CENTRE FOR INVASIVE SPECIES SOLUTIONS

DEVELOPMENT OF INTEGRATED PASSIVE AND ACTIVE SURVEILLANCE

FINAL REPORT FOR PROJECT P01-I-003

AUTHORS

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DEVELOPMENT OF INTEGRATED PASSIVE AND ACTIVE SURVEILLANCE TOOLS AND NETWORKS

FINAL PROJECT REPORT FOR P01-I-003

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EXECUTIVE SUMMARY

The mode of entry of exotic vertebrates into Australia has changed. Historical incursions typically arose from deliberate introductions by authorities, industry and acclimatisation societies with a focus on mammals. Future introductions will be mainly though through the escape and release of exotic species kept as pets, particularly birds, reptiles, amphibians and fish as opposed to mammals. This strong urban component to future introductions means that citizens with an interest in wildlife and the world around them are ideally placed to undertake surveillance.

We use case studies, a literature review, reasoning and analytics to highlight the effective role citizens play in the surveillance for exotic vertebrates. The effectiveness of citizen surveillance arises largely from deliberate image sharing to document, and/or to crowdsource species identification. Within what are essentially communities of practice, the chances than an exotic species will be recognised by at least one member is high, and this underpins the surveillance sensitivity. Knowing where and for what animal groups citizens are already providing effective surveillance affords considerable benefit by allowing surveillance resources to be devoted to the gaps in citizen surveillance cover.

The online data streams of sightings shared by citizens open up the opportunity for species alert systems based on simple matching algorithms. Traditionally such matching would be based on 'alert' lists of species of biosecurity concern. However, as a first step in identifying exotic species, we argue that it makes more sense to use a 'permitted' list approach to identify possible exotics, with a second process to determine whether management action is required. We additionally explore the value of data-mining techniques for detecting exotic vertebrate pests through social media, and conclude that such an approach would be unlikely to lead to significant improvements in surveillance sensitivity without adding significant costs. Putting resources into education campaigns around the importance of reporting sightings of exotic species could be beneficial, though only if done in concert with improving citizens' identification skills to avoid wasting valuable resources on pursuing misidentifications.

While citizen surveillance is effective for detecting incursions of most vertebrate groups in most areas, this is not always the case. Images play a central role in motivating the sharing of animal sightings and in crowdsourcing their identification. This means that aquatic environments and nocturnal species are not well sampled. Hence citizen surveillance for invasive fish may not be adequate for their timely detection. Areas adjacent to ports and international freight handling considered high-risk for hitchhiking/stowaway species of concern often have limited access for citizens to undertake surveillance activities. Likewise, for specific pest threats such as the spread of the common starling into Western Australia, there are gaps in citizen surveillance effort in key locations. In these areas we illustrate how targeted surveillance that deploys detection devices, such as remote acoustic detection devices for known pest species (e.g. common starlings and traps for exotic toad species of concern) have considerable utility.

Australia's best defence against future invasions of vertebrate pests involves the eyes, ears, knowledge, cameras and phones of its citizens, in combination with targeted surveillance when citizen surveillance is inadequate.

INTRODUCTION

CONTEXT

Invasive exotic vertebrate pests are responsible for considerable environmental, amenity and agricultural damage (Bradshaw et al. 2021). To make matters worse, there are many more species with the potential to become pests in Australia given the opportunity. Because of this, preventing the naturalisation of additional species is highly desirable. Two approaches to achieve this objective are: (1) Using legislation and compliance activities to prevent the import, postborder possession and sale of potentially invasive species, and (2) Detecting and eradicating embryonic populations early, where feasible and realistic.

Early detection of new incursions is challenging for authorities as incursion pathways are often diffuse and spread across an array of possible entry points. Furthermore, identifying which of the numerous exotic vertebrate species will become invasive if introduced remains problematic (notwithstanding surveys of stakeholders in this report).

However, certain high-risk species have been introduced into multiple countries via reasonably consistent entry pathways, making their entry into Australia somewhat more predictable. Moreover, their biology sometimes makes them more vulnerable to detection at specific places. For these species, there is still an important role for carefully designed, pre-emptive surveillance at high-risk points of entry (so-called 'active surveillance'). Provided we have a good understanding of a target species' invasion history elsewhere in the world, there is scope to design a strategic, active surveillance program that increases the probability of early detection in Australia.

While a relatively small number of high-risk species are worthy targets for active surveillance, authorities charged with biosecurity responsibilities will always be heavily reliant on what is known as 'general surveillance' (sometimes referred to as 'passive' surveillance) as a means of early detection. Most of this general surveillance involves encouraging the general public (i.e. citizens), or sometimes specific interest groups, to report suspected sightings of target species. The importance of general surveillance is perhaps best recognised in plant biosecurity, where it is acknowledged that it accounts for most detections of plant pests and pathogens (Epanchin-Niell et al. 2021).

Despite this, there has been little evaluation of the vertebrate pest biosecurity information content of citizen/community surveillance data streams, and how these could contribute to the early detection of incursions of invasive exotic vertebrates into Australia. Harnessing the observational powers of community surveillance activities has the potential to dramatically increase the scale and sensitivity of surveillance efforts, assuming of course that the observational power isn't already being effectively used. Understanding the effectiveness of existing citizen surveillance helps inform how best to deploy scarce surveillance resources. *A priori*, we might expect that the effectiveness of surveillance may differ between the main groups of vertebrates (mammals, birds, amphibians, reptiles and fish) though such differences have been subject to little examination.

Identifying gaps in the spatial coverage of surveillance by citizens in areas of high likelihood of pest introduction is of particular interest. Advances in sensor and genetic sampling technology may enable more cost-effective surveillance by industry and government, particularly in areas where citizen surveillance is lacking.

OBJECTIVES

The broad aim of this research was to evaluate the performance of citizen surveillance for exotic vertebrate pests, and to develop guidelines for how to best combine passive and active surveillance tools with citizen surveillance in a complementary manner. The intended outcome was to enable the early detection of invasive vertebrates and hence prevent additional vertebrate pests establishing in Australia.

Specific objectives of the project were to:

- Evaluate the effectiveness of citizen surveillance for the main vertebrate pest groups focusing on taxa identified by relevant agencies within 'of concern' jurisdictions.
- Identify gaps in the surveillance coverage provided by citizens that relate to taxonomy (which types of organisms are they likely to observe) and space (where do they undertake effective surveillance?).
- Explore ways that we can improve information capture from citizen observations, including the use of modern analytical tools such as data mining of social media.
- Develop remote acoustic monitoring capability for starlings.
- Develop active surveillance methods for Asian black-spined toads.

In this report, we address the effectiveness of citizen observations in providing surveillance for exotic vertebrates, with an emphasis on Australia. We next characterise where citizen surveillance sits within the broader range of surveillance activities. We then document examples of exotic pest incursions that have been detected by citizens as part of general surveillance activities, and make reasoned arguments as to how effective the citizen surveillance system may be. We then describe quantitative analytical methods for assessing the effectiveness of existing citizen surveillance. This involves developing a taxonomy for describing general surveillance activity such that it can be incorporated into quantitative models. We then explore how we could extract more useful surveillance data from citizen-generated sightings, including better detection of exotic pests from sightings that are intentionally shared by citizens, and the pros and cons of data mining of social media. We then demonstrate how gaps in citizen surveillance coverage can be filled using targeted approaches. Finally, we summarise our major findings, including implications for the effective surveillance of exotic vertebrate pests of concern, benefits to existing management and the logical next steps in this field.

METHODS

We employed a number of approaches, including:

- reviewing citizen reports of vertebrate pests incursions
- analysing all citizen sightings that are reported through accessible online platforms to identify taxonomic groups for which citizen surveillance is adequate, including spatial gaps in coverage
- critiquing the value of bringing modern analytical tools, such as image recognition and natural language processing, to data mining of social media feeds
- describing the components of citizen surveillance leading to citizen reports
- outlining how to infer pest presence/absence using general surveillance
- developing remote acoustic survey methods for common starlings (*Sturnus vulgaris*)
- developing an acoustic trap methodology for Asian black-spined toads (*Duttaphyrnus melanostictus*). James Cook University Animal Ethics Committee Approval ‘A2767–Ecology and bioacoustics of the Asian black-spined toad (*Duttaphrynus melanostictus*)’.

END-USER ENGAGEMENT

At the start of the project we surveyed primary industry, conservation and NGO organisations across the jurisdictions to identify their:

1. high-priority *established* vertebrate pests
2. high-priority *non-established* vertebrate pests
3. high-priority vertebrate pests for which acoustic surveillance is considered applicable.

The key to a summary of the results is shown in Figure 1. Priority *established* pests by jurisdiction are shown in Figure 2. Priority *non-established* pests by jurisdiction are shown in Figure 3.

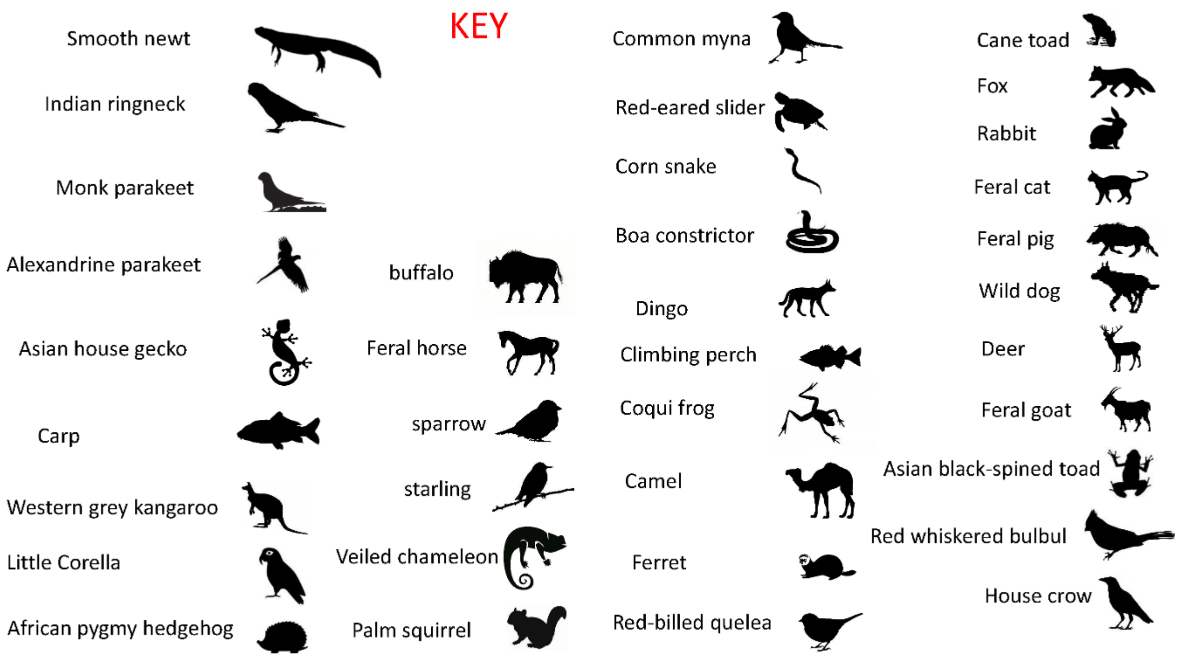

Figure 1. Key for species identified in vertebrate pest prioritisation exercise with state and territory industry and conservation agencies.

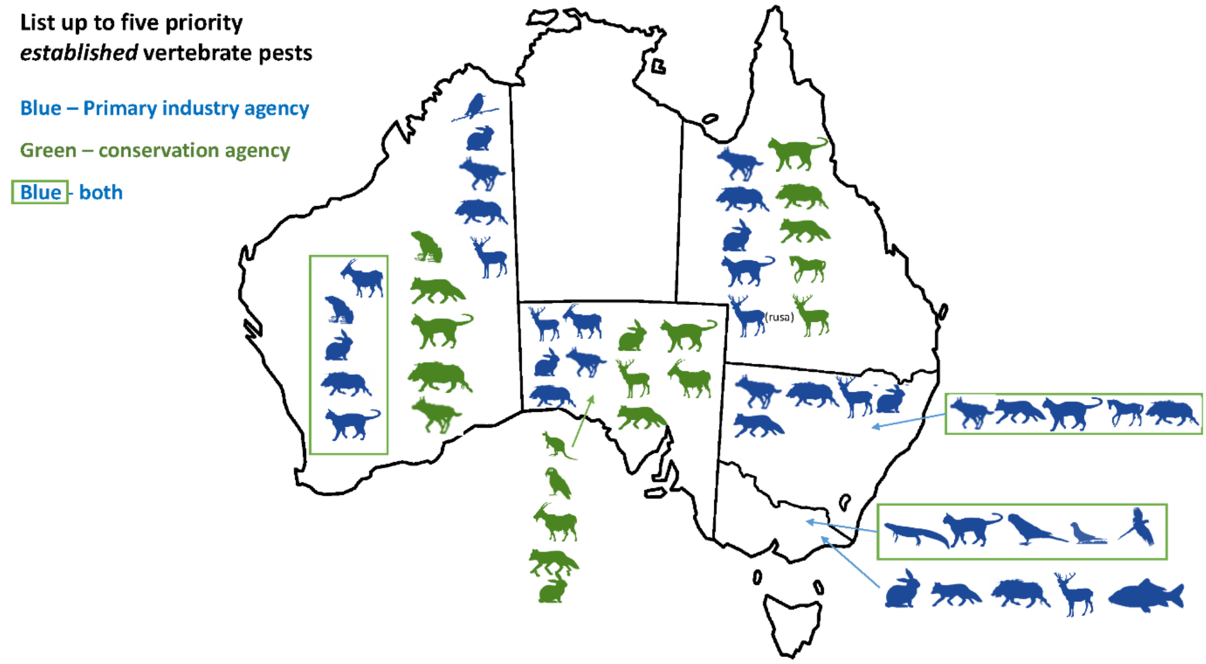

Figure 2. The results of surveying primary industry (blue) and conservation (green) agencies for a list of priority established vertebrate pests.

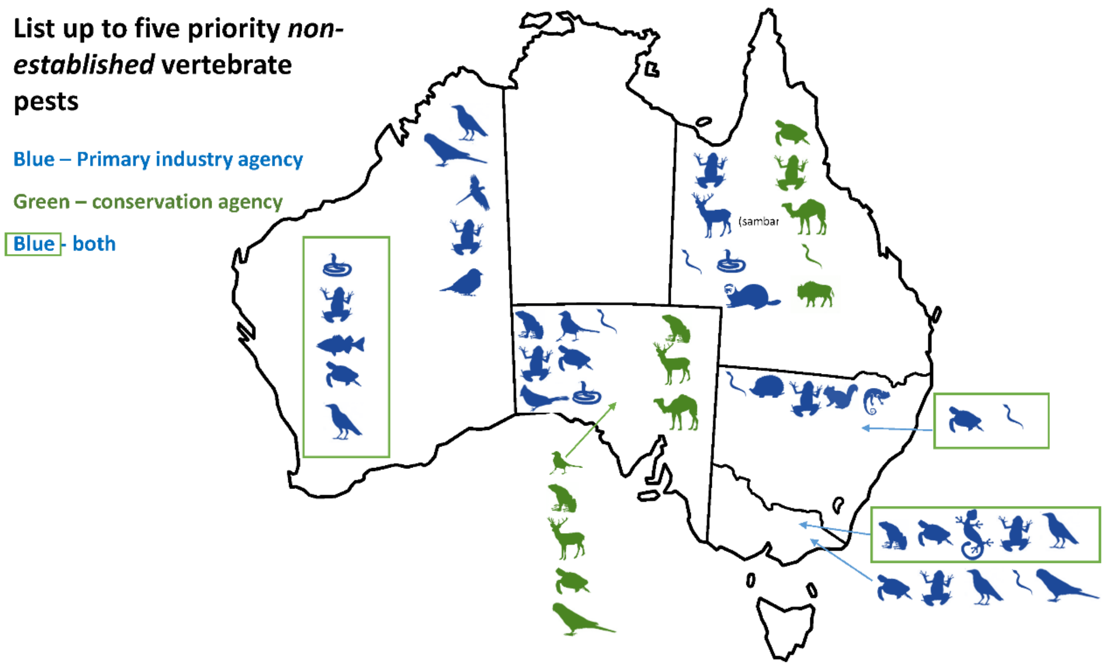

Figure 3. The results of surveying primary industry (blue) and conservation (green) agencies for a list of priority non-established vertebrate pests. Species for which there is an overlap between the industry and conservation agencies are shown in the green-lined boxes.

High-priority species for which acoustic surveillance was considered applicable by at least one organisation included starling (WA), sparrow (WA), Asian house gecko (WA, Vic), Asian black-spined toads (WA, Qld, SA, NSW, Vic), house crow (WA, Vic), coquin frog (WA), deer spp. (WA, NSW), goat (WA), red-whiskered bulbul (SA, Qld), common myna (SA), dingo/wild dog (SA, NSW), red-billed quelea (Qld), cane toad (SA, NSW, Vic), camel (Vic), fox (WA, NSW), Indian ringneck (Vic) and Alexandrine parakeet (Vic) (Figure 4).

This list excludes species for which we are unaware that acoustic monitoring would be possible, though they were listed. The frequency with which the species were listed across the jurisdictions is summarised in Figure 5.

Regarding citizen surveillance, the project engaged scientifically with Dr Phill Cassey (Adelaide University, co-author of this report) on: (1) knowledge of incursion pathways for the introduction of exotic vertebrate pests, and how effective citizen surveillance is for these pathways, and (2) the feasibility of applying data-mining methods to detect incursions of exotic vertebrates in social media data streams. We also engaged with Dr Dave Ramsey (Arthur Rylah Institute) around how citizen-reporting probabilities for key species (wild deer and wild pigs in particular) can be incorporated into decision-support models developed as part of Project PO1-I-005 (Tools for developing cost-effective decisions for managing invasive pest eradications).

The project liaised regularly with key staff from the Atlas of Living Australia (ALA), particularly on naming conventions of citizen reports incorporated into the ALA, and the possibility for generating biosecurity alerts for sightings of exotic vertebrate pest species uploaded to the ALA. As end users, both SA Biosecurity and Biosecurity Queensland provided lists of species of biosecurity concern. This led to discussions with the custodians (then Department of Agriculture, Water & Environment) of the Australian Faunal Directory on how the checklist of species considered established within Australia should be accessed and used to identify exotic species with citizen data streams. NSW Biosecurity was contacted for an assessment of their pest hotlines; their improving detection of illegally kept reptiles was of particular interest.

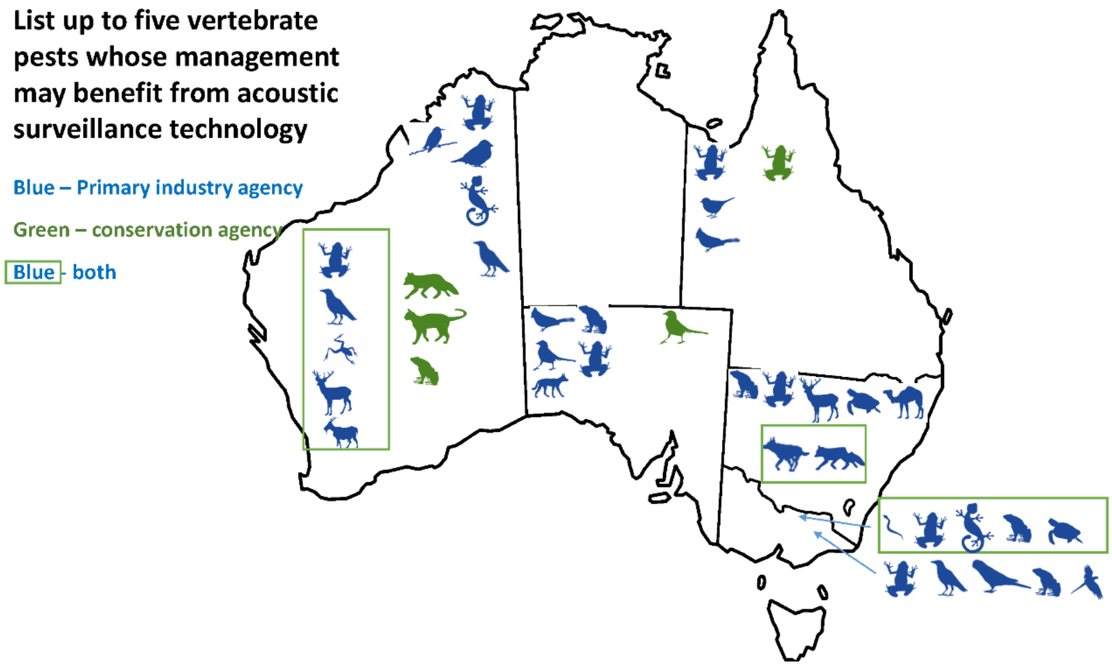

Figure 4. Vertebrate pests identified by industry and conservation groups as being of high priority, and whose management could benefit from acoustic technology.

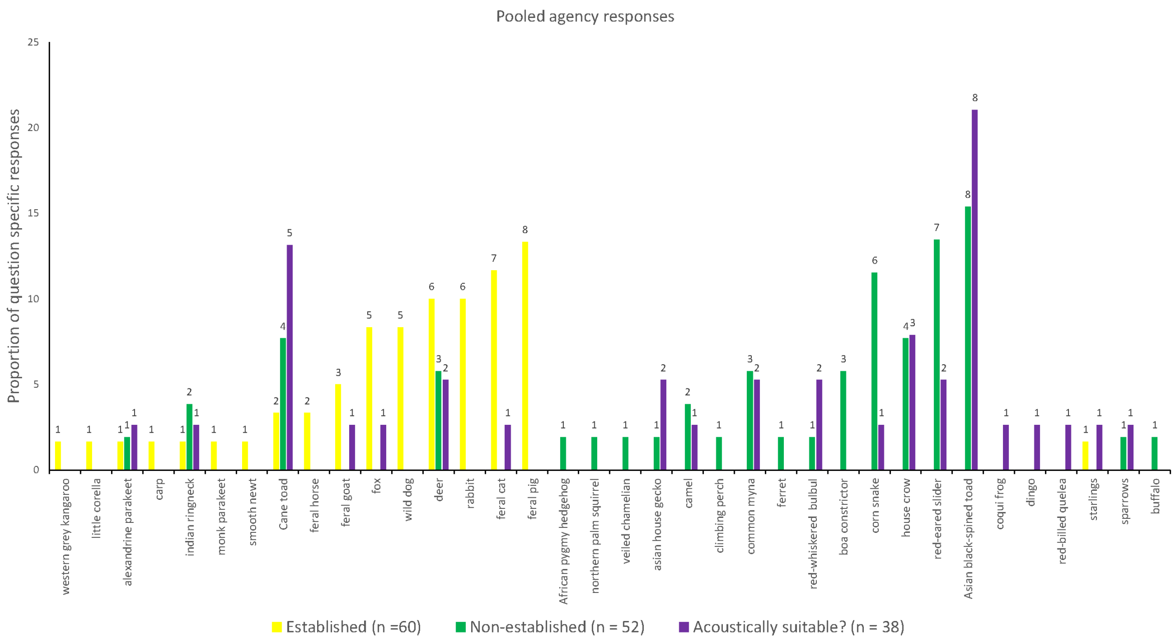

Figure 5. Pooled industry and conservation agency responses to vertebrate pests deemed established (yellow), non-established (green) and possibly suitable for acoustic detection (purple). Note no responses were received from NT, ACT and Tas.

CHARACTERISING CITIZEN SURVEILLANCE ACTIVITIES

A FRAMEWORK FOR EVALUATING CITIZEN SURVEILLANCE

The risk of introducing exotic pests is typically diffuse, being spread across diverse points of entry, multiple modes of entry, and involving multitudes (tens of thousands) of possible taxa (see Caley and Cassey 2022 and references therein). This makes targeted, structured surveillance programs impractical for all but a few high-priority pests, typically trade related, and means that authorities charged with biosecurity responsibilities are heavily reliant on what is known as 'general surveillance' for early detection of high-risk pests. Most of this general surveillance relates to sightings made by members of the public ('citizens') undertaking a broad range of activities often described as 'science' but usually not in the true sense of the word (Welvaert and Caley 2016).

The important role of general surveillance is perhaps best recognised in plant biosecurity, with the International Plant Protection Convention ISPM 6 report on 'Guidelines for Surveillance' (IPPC Secretariat 1997) defining general surveillance as 'a process whereby information on particular pests which are of concern for an area is gathered from many sources'. The other recognised type of surveillance system is 'Specific surveys' (IPPC Secretariat 1997). General surveillance is further defined as providing a level of confidence that 'the pest, if present, would have been detected and notified'. Detections from general surveillance forms a large proportion of all detections of exotic insects (Carnegie and Nahrung 2019), plants (Epanchin-Niell et al. 2021), and unwanted biosecurity organisms in general (e.g. Beale et al. 2008; Froud et al. 2008; Pawson et al. 2020), but there has been little attention given to its role in detecting exotic vertebrate species.

As the name 'general surveillance' suggests, the types of observations and observational processes made are, by their nature, very broad, and span the passive/active and unintentional/intentional dimensions of the reporting process (see Welvaert and Caley 2016). General surveillance is considered separate to surveillance from 'Specific surveys' (see IPPC Secretariat 1997), that involve structured searching (i.e. intentional and structured) for target pest species. Surveillance implicitly and explicitly undertaken by citizens that is not targeted, and is hence 'general' is often described as 'passive' surveillance (e.g. see Hester and Cacho 2017). This is somewhat of a misnomer in that a citizen observation can be both quite active and intentional as an activity (e.g. a birdwatcher actively seeking to record and share all the birds at a specific location), but not targeted in the sense of seeking to detect (or check for the presence of) a particular exotic bird species of concern. It is clear, however, that the general surveillance 'activity' is the key component that needs to be considered. There is a possibility, depending on the activity parameters, that the exotic species of concern would be detected if present.

While it is reasonably straightforward to list the organisms that have been detected by general surveillance, and demonstrate its relative importance in biosecurity detections (e.g. responsible for the majority of biosecurity detections), it is more difficult to evaluate the power (surveillance sensitivity) that general surveillance provides. A particular challenge is a pervasive feature of general surveillance in that negative survey results (e.g. surveillance zeros) are rarely recorded. Recording absences is an important aspect of any surveillance program but, by definition, it is not usually done systematically under general surveillance. Typically, only positive reporting occurs. That is, people may report what they do see (a 'sighting') but will rarely if ever report on what is not sighted, unless explicitly requested to do so. Furthermore, efforts to get people to voluntarily report this are generally in vain. Within Australia for example, regarding general surveillance for vertebrate species, citizens are simply not going to record 'No elephants, meerkats or macaws were sighted' as these are highly unlikely. In practice, there are tens (actually hundreds) of thousands of other theoretical species sighting possibilities if all possible vertebrate species were considered. Hence these data take the form of implicit (unrecorded) 'zeros'. As such, it is difficult to apply traditional statistical approaches to estimate the value of these systems. Data analysts confronted with making inference based on general surveillance activities are typically slow to recognise and accept this, and invariably ask that general surveillance programs record whether the species they are interested in were present. This almost invariably doesn't happen (due to the very nature of general surveillance) and has led to a widely held view that it is not possible to objectively discern the properties of a general surveillance system.

The notion that we cannot make quantitative statements arising from general surveillance (especially when a species is not reported) is at odds with accepted wisdom for the current distribution of much of the world's vertebrate biodiversity. For example, it is almost universally accepted (cryptozoology adherents aside) that there are no wild (free-living) striped skunks *Mephitis mephitis* in Australia, nor kangaroos (*Macropus* spp.) hopping across the Great Plains of the United States. This acceptance comes despite that fact that in neither country are there any structured surveys for either species providing targeted surveillance. If we accept that this inference from general surveillance holds for tens of thousands of vertebrate species, then we are recognising that there is an underlying structure to this reasoning (mental reckoning) that arises from general surveillance activities. This becomes more important where inference from general surveillance is needed in less contrived situations. For example, assessing whether a pest-eradication program has been successful, or assessing pre-emptively how sensitive general surveillance may be for a particular incursion threat (e.g. wild pigs *Sus scrofa* spreading into new areas of the United States).

Making useful inference from a general surveillance activity and the implicit zeros that it contains requires that the underlying observation process is described/captured in such a way that: (1) the probability of a sighting, given pest presence, can be estimated, and (2) a reasoned estimate of the probability of the sighting being reported can be made. Note that 'sighting' subsumes all recognised methods of detection (e.g. physical sample, verified photograph, audio recording). The sighting model of (Solow 1993) and the many that followed this seminal paper are essentially models using data from general surveillance activities in its simplest form (marginalised to a non-spatial annual probability of at least one sighting). Caley and Barry (2014) pointed out some of the limitations of this excessively simple assumption with respect to sighting probability and how it relates to population size.

TAXONOMIC COVERAGE VIA CITIZEN REPORTING

The taxonomic coverage of vertebrates (and hence potential exotic vertebrate pests) reported by citizens appears to be very good. On social media, for example, there are numerous Facebook groups that specialise in identifying birds, reptiles and amphibians (see Table 1 for examples). The groups are initiated entirely by and for citizens and operate as communities of practice with various levels of complexity. A universal purpose of the groups is the crowdsourcing of species' identification. Most engagement by citizens with online platforms, such as sharing sightings and seeking identification of sightings, arises from an interest in natural history. Some engagement, however, arises out of necessity. For example, through their desire to have reptiles (snakes in particular) removed from their homes, the public often unintentionally bring taxonomic expertise to their sightings by calling on the services of wildlife rescue agencies (Shine and Koenig 2001). Likewise, the 'Snake Identification Australia' Facebook group seeks to assist citizens by rapidly identifying snakes when the citizen may need to make decisions around personal safety.

Table 1. Examples of Facebook groups from Australia dedicated to identifying vertebrates, including the number of members (as of July 2022), and their stated purpose.

GROUP	MEMBERS	PURPOSE
Australian Bird Identification (ABID)	51,000	Bird species identification
Snake Identification Australia	71,000	Snake species identification, education and wildlife advocacy
Australian Reptile/Amphibian Identification	9,000	Species identification for any reptile/amphibian found within Australia
Frogs And Toads Identification Australia	27,000	Species identification of frogs and toads

Dedicated smartphone apps and linked platforms cater to either a different form of identification (e.g. audio), or to citizens with different identification skills and motivations. For example, FrogId taps into specialist knowledge from the Australian Museum to identify frogs from their calls (as submitted by the user). iNaturalist provides a general platform for sharing and crowdsourcing the identification of all biota, and enables the user to keep and curate a record of their sightings, create projects and join other projects of interest. Platforms such as eBird operate on the assumption that the observer will make the correct identification, though undertake moderation of sightings. Historically there were few images of sightings on eBird but that is rapidly changing with advances in digital camera technology.

SPECIES-DEPENDENT REPORTING PROBABILITIES

The propensity for a citizen to generate a general surveillance report of a sighting is highly contextual. As a general rule, citizens are more likely to post sightings of species that: (1) are unfamiliar to them (i.e. seeking identification), or (2) they know to be rare, and hence they are sharing a special occurrence with others, or (3) they consider it to be physically interesting by being ornate, brightly coloured, large, 'cute' etc. (in which case they are sharing an experience they feel others may like also). In contrast, birdwatchers contributing to platforms such as eBird are often interested in the diversity of their sightings (i.e. list length), hence they intentionally report on all species sighted, regardless of their physical features. For social media platforms (e.g. Twitter, TikTok), uploaded material will be heavily biased towards the 'big, bold, bright and beautiful'.

For detecting an exotic vertebrate incursion, only one report of a sighting is required. It is instructive to highlight the mechanics by which sharing observations increases the likelihood of a sighting of an invasive species being reported. For an incursion comprising of *N* individuals, each with probability p_i of being detected (i.e. sighted and reported), the probability of at least one detection is:

$$\begin{aligned} P(\text{At least one detection}) &= 1 - P(\text{No detections}) \\ &= 1 - \prod_{i=1}^{N} (1 - p_i). \end{aligned} \tag{1}$$

Under the often-used simplifying assumption that the p_is are equal, Equation 1 simplifies to a form that can be termed the 'first law of biosecurity risk analysis':

$$P(\text{At least one detection}) = 1 - (1 - p)^N. \tag{2}$$

The formulation in Equation 2, with the combined sighting and detection probability for each individual assumed a constant, overly emphasises the influence of the population size *N* on the probability of a report of a positive sighting. In reality, however, p_i subsumes both the sighting probability and the probability of reporting given sighting(s), and may be highly variable. A single high p_i will ensure a high probablity of at least one detection. The sighting probability for individuals within the invading population will clearly vary, depending on the intersection between the general surveillance activity and the distribution of the *N* individuals. Likewise, the probability of reporting a given sighting will vary with individual citizens and the nature of the species in question. Importantly when considering typical general surveillance activities undertaken by citizens, this report could either be from the original observer making a primary sighting, or by any of the individuals that the sighting has been shared and reshared with (secondary and higher order sightings). The total number of sightings from which a surveillance report may arise is thus a combination of several components (some of which are random variables themselves), involving both primary and shared (secondary) sightings. To understand how this affects citizen surveillance sensitivity, let *S* be a random variable denoting the total number of sightings relating to an incursion, that includes shares and reshares of the primary sighting. Furthermore, if we make the simplifying assumption (for illustrative purposes) that the probability of any one of these sightings being reported is a constant (ρ), then:

$$\begin{aligned} P(\text{At least one sighting reported}) &= 1 - P(\text{No sightings reported}) \\ &= 1 - E_S\left[\text{No sightings reported} \mid S = s\right] \\ &= 1 - \sum_S (1-\rho)^s P(S = s). \end{aligned} \tag{3}$$

The key feature to note in Equation 3 is that increasing the probability of having at least one reported sighting can be achieved by either increasing the reporting probability and/or increasing the number of sightings (either as primary observations or by crowdsharing).

SPATIAL COVERAGE AVAILABLE

It is well-known that the locations where citizens generate their observations is strongly biased, based on where they live (e.g. around their homes) and where they can access (e.g. along public roads and publicly accessible areas), and where they like to visit (e.g. nature parks and reserves) (Figure 6). Sites of known high diversity may also targeted by nature lovers, particularly within the birding community. There is also bias in the temporal pattern of observations towards daytime and weekend observations. For exotic species detection this weekday temporal bias is inconsequential, but the lack of night-time observations is potentially an issue as many exotic vertebrates are predominantly active at night.

A feature of all citizen reported information is that along with no record of what wasn't seen, there will typically be no record of the underlying activity that leads to sightings that underpin reports. This unrecorded information relates to all the locations (private yards, urban streets and parks, reserves etc.), times and movement modes (e.g. sitting, walking, riding, driving). As a consequence the spatial extent of the surveillance effort is typically greater than the sightings suggest. Quantitative methods to treat this problem are explored in another section.

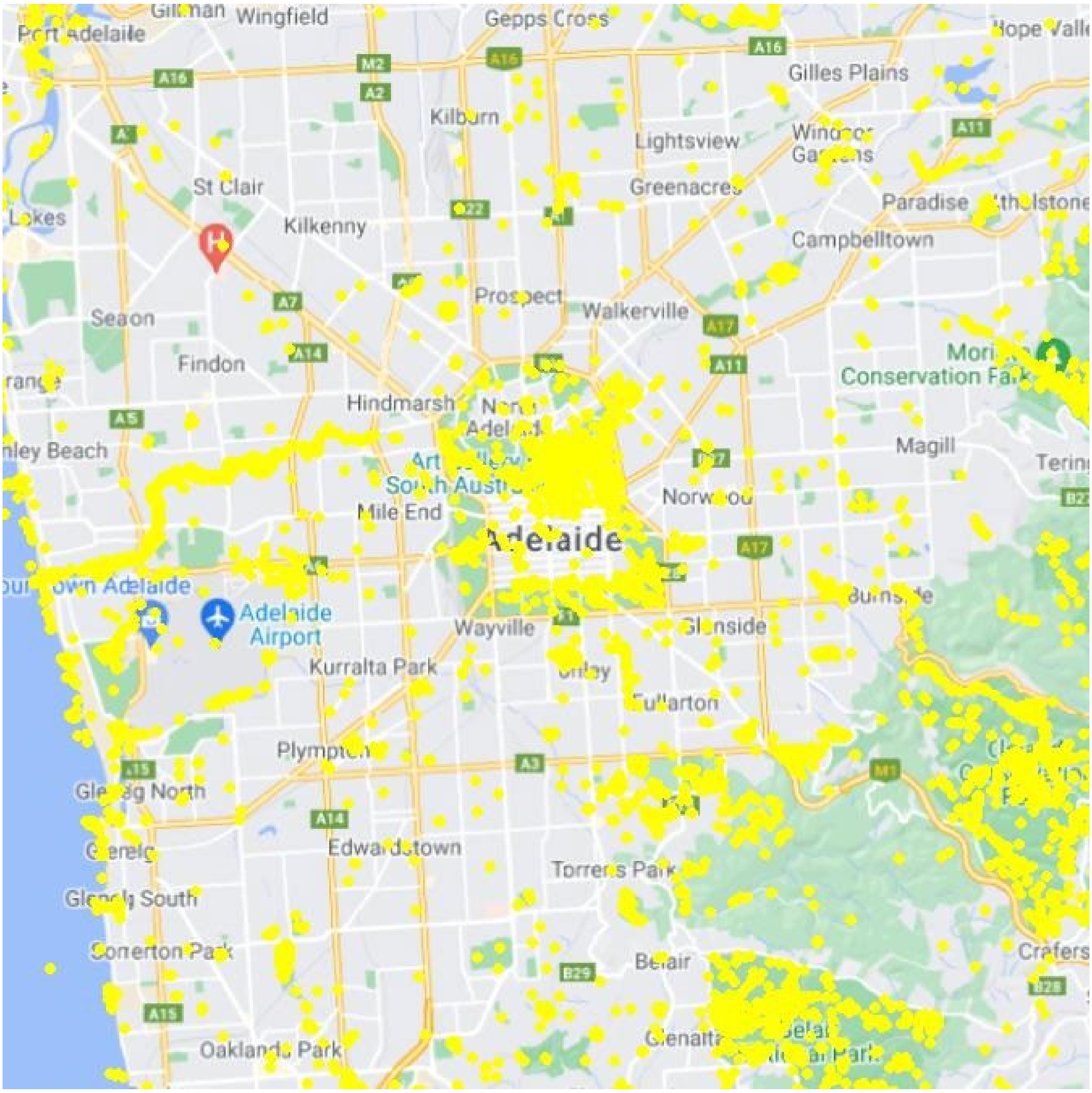

Figure 6. Distribution of citizen observations of birds centred on the city of Adelaide that were uploaded to the Atlas of Living Australia for the period 2016–2021.

ACCESSING DATA ARISING FROM GENERAL SURVEILLANCE ACTIVITIES

For platforms for which storage and retrieval of citizen sighting records is one of their core purposes (e.g. eBird), data storage is comprehensive and full retrieval possible on request (if approved). Likewise, within Australia, most of the major reporting platforms for citizen biodiversity observations are ultimately incorporated into the ALA, and basic sighting information (e.g. date, location, taxon) is available on request. Accessing and analysing records is facilitated in several ways (e.g. a GUI), but also the R software (R Core Team 2021) package 'galah' (Stevenson et al. 2022).

For social media platforms (e.g. Facebook, Twitter) automated information retrieval is considerably more challenging for many reasons. Firstly, these platforms are not designed for record biological sightings, so there is no record structure. Hence, digital identification of species of interest needs to be based on either natural language processing or image recognition. Both these approaches contain considerable logistical challenges and their value proposition seems dubious in comparison to the business-as-usual case. The business-as-usual case is to simply rely on social media users to report sightings that may be a biosecurity concern to the relevant authorities for a possible response. The next level approach is to directly engage (i.e.

participate and monitor) with particular focused groups (e.g. Facebook groups dedicated to animal identification).

Many citizens, who would not necessarily contribute sightings to any platform (dedicated or social), may instead instigate a report if they saw something they thought worth notifying authorities about (e.g. via a pest reporting hotline). They are contributing to general surveillance as they go about their everyday lives. Reports from these sources are typically held by authorities, and may be accessible on request.

EXAMPLES OF DETECTIONS OF EXOTIC PEST INCURSIONS BY CITIZENS

Citizens are routinely sighting and reporting exotic vertebrate pests (Table 2). What follows are examples of general surveillance activities of citizens that have detected exotic vertebrate pests.

Table 2. Examples of public detections of vertebrate pests.

SPECIES	MODE OF REPORTING	SOURCE
Cane toad (*Rhinella marina*)	Citizen report to authorities	https://www.canberratimes.com.au/national/act/two-cane-toads-detected-in-canberra-20181016-p509xf.html
Boa constrictor (*Boa constrictor*)	Citizen report to police*	https://www.abc.net.au/news/2015-04-07/police-release-boa-constrictor-by-mistake-on-gold-coast/6374398
Boa constrictor (*Boa constrictor*)	Citizen report to snake catcher	https://www.dailymercury.com.au/news/blimey-massive-boa-constrictor-found-in-mackay/3087029/
Asian black-spined toad (*Duttaphrynus melanostictus*)	Citizen report to authorities	https://www.communitynews.com.au/southern-gazette/news/cloverdale-discovery-of-asian-black-spined-toad-sparks-request-from-authorities-to-be-on-look-out/
Asian black-spined toad (*Duttaphrynus melanostictus*)	Citizen report to authorities	https://www.abc.net.au/news/2018-11-27/asian-black-spined-toad-sneaks-into-australia/10557252
Boa imperator	Facebook post	Fast Snake Identification Group

*Released after being mistaken for a carpet python (*Morelia spilota*)

SELF-INTRODUCED EXOTIC GEESE

Citizen surveillance through amateur birdwatching detected and ultimately eradicated an incursion of the exotic and potentially invasive Canada goose (*Branta canadensis*) into New South Wales, Australia (Table 3). Through the observations of a number of independent birdwatchers spanning a large stretch of coastline, the incursion of four birds was successfully detected, identified and reported as they moved between wetlands on the South Coast of New South Wales, prior to their successful elimination by authorities (see Boles et al. 2016). It is presumed that the birds had flown from New Zealand where they are an established pest following deliberate introduction from North America last century. Previously, amateur birdwatchers had detected the entry of a lone individual (Carter 2006). The subsequent incursion demonstrated this was not a one-off event. More generally, sightings of vagrants (species uncommonly seen in Australia, and assumed not to breed here) are reported almost daily on eBird.

Table 3. Timeline of successful citizen surveillance that detected Canada geese in 2007 on the South Coast of New South Wales. Source: Boles et al. (2016).

Date	Source	Location and details
26 Dec. 2007	Local birdwatchers	Milton local area – 4 geese sighted
29 Dec. 2007	Eremaea Birds (Birdline New South Wales)	Burrill Lake, south of Ulladulla – 4 geese sighted
4 Jan. 2008	Newspaper story	Condie, K. (2008). Birdwatchers flock to Milton for gander at Canada Geese. Friend or foe? *Milton Ulladulla Times*, 4 January 2008
< 23 Jan. 2008	Birdlife Australia	Locally around Milton – 4 geese sighted
9 Mar. 2008	Birdo via Birdlife Australia	Lagoon at Killalea State Park, Shellharbour, NSW (*c*. 90 km north) – 4 geese sighted

ESCAPED EXOTIC SNAKES

Escaped pets are the major source of vertebrate introductions, and a recent example of an escaped *Boa imperator* (native to Central and South America) in Sydney, Australia is a case in point. The escaped animal was sighted by a neighbour, who realising that it was unusual, posted an image onto an Australian Facebook group (Snake Identification Australia) dedicated to snake identification.

Through one of the Facebook group's moderators, a reptile relocation expert was mobilised, authorities notified, and the illegally kept reptile ultimately impounded, all in a matter of hours. This particular Facebook group is one of many that leverages crowdsourced species identification, including moderation by members considered to have sufficient identification skills. Interestingly, the group appears to deal effectively with fake images (e.g. photos from overseas purporting to be from within Australia), with members searching reverse image to identify the source of the fake material. The moderators are also, however, by their own admission, struggling to cope with the increasing workload of such an effective (and free) service. Group membership as of June 2022 was in the order or 71,000 and increasing rapidly.

AQUATIC AND SEMI-AQUATIC PESTS

Citizens have been responsible for most of the sightings of red-eared slider turtles (*Trachemys scripta elegans*), but that hasn't prevented them becoming established in various locations in eastern Australia (Burgin 2007). Early detection is necessary, but on its own not always sufficient to prevent exotic vertebrates establishing. Prompt and effective management is also needed. This can be challenging for several reasons, including ongoing introductions (as can occur when large numbers of animals are being kept illegally), and difficulties in effecting removal. Low detection probability and capture rates make eradicating populations of red-eared slider turtles challenging (García-Díaz et al. 2017). Furthermore, in the case of red-eared sliders, the sheer volume of introductions from escapes and releases from captivity could, in combination with the lack of effective response, have jeopardised any opportunity to prevent naturalisation.

The incursion of the European newt (*Lissotriton vulgaris*) into Australia was first reported by a member of the public (general surveillance again), though subsequent surveys revealed is was already well established (Tingley et al. 2015). It is a similar story for the Siamese fighting fish (*Betta splendens*) in the Adelaide River floodplains of Northern Australia, where the first confirmed sighting was by a member of the public (Hammer et al. 2019), though the population was already well established.

HOW GOOD IS EXISTING SURVEILLANCE?

EVALUATING GENERAL SURVEILLANCE ACTIVITIES BY REASONED ARGUMENT

The previous examples have highlighted retrospective examples of general surveillance detecting exotic vertebrate species, often in time to prevent establishment. The obvious question that arises is how effective will citizen surveillance be in the prospective sense? For example, returning to the case of the Canada goose, its population in New Zealand is currently uncontrolled, so we reasonably expect there will be further incursions of Canada geese into Australia originating from this source population. Can we rely on the general surveillance provided by the birdwatching community as being adequate for our needs, or do we need a targeted 'Canada goose surveillance program'? It appears reasonable that having previously been effective enough to detect an incursion within a sufficient time frame, there is no reason that citizen surveillance couldn't be effective again. It also seems reasonable to extend such apparent surveillance sensitivity to exotic bird species more generally for which conformation and colour patterning are distinctive.

Given the high number of exotic vertebrate species that could potentially be introduced if they had an introduction pathway, it makes sense to restrict the evaluation of citizen surveillance to those species with a non-trivial probability of mounting an incursion. Other than birds, which are clearly capable of self-introduction in some cases, exotic vertebrates will typically need to be inadvertently transported as stowaways/hitchhikers or be imported deliberately by humans. The deliberate introduction of vertebrates, either by acclimatisation societies or for attempted biological control, has now largely ceased. Future exotic vertebrate incursions will originate mainly from captive individuals (Lockwood et al. 2019), mirroring the more recent role of ornamental garden plants as a source of future invasive plants (Groves et al. 2005). Indeed, research has shown that humans are the biggest direct source of alien invasions (e.g. from escaped pets kept legally or otherwise) (Lockwood et al. 2019; Vall-llosera and Cassey 2017). This has implications for the effectiveness of citizens as surveillance agents for invasive pests, in that they are central to the process of both introduction and hence (potentially) detection. This means that having citizen surveillance effort biased towards where the most humans are is not a bad thing. In fact, if adopting a risk-based approach, such stratification of surveillance effort would be considered ideal.

It is worthwhile considering how timely citizen surveillance needs to be. The need for surveillance to provide 'early detection' has essentially become a mantra in the field of biosecurity surveillance, but 'early detection' is rarely defined. What is actually needed is 'timely' detection. That is, detection needs to occur so that options such as eradication or containment remain logistically and economically viable. The interplay of a range of factors (e.g. immigration rate, detectability, vulnerability to control, benefit-cost ratio, sociopolitical considerations) determine the feasibility of eradication, but the first criterion listed by Bomford and O'Brien (1995) is that the rate of removal (through control actions) exceeds the rate of increase over all densities. In a worst-case scenario (for which we want to be prepared) where we expect an invading population to be growing, the relevant measure is the intrinsic rate of population increase (r_m) (Caughley and Birch 1971). For different species, the acceptable delay before detection will vary enormously. For large, conspicuous vertebrates with a low r_m, the acceptable delay from incursion to detection could be in the order of years to decades (e.g. in the case of elephants), whereas for cryptic species (e.g. snakes) or species with a very high r_m, a successful eradication campaign would require the incursion to be detected very early with a small invasion footprint involving few individuals.

EVALUATING GENERAL SURVEILLANCE ACTIVITIES QUANTITATIVELY

We can conceptualise a model for general surveillance as comprising components of *entry*, *population*, *activity* and *detections*. Consider an exotic species with an approach rate that can lead to *entry*, dispersal mechanisms and population dynamics that generate a *population*, and citizen surveillance *activity* methods that result in *detections* (or lack thereof).

In general Bayesian statistical terms, we can write down an expression for the distribution of the size of population given surveillance detections (noting that detections can also implicitly be a series of 'zero' surveillance outcomes) as follows, where the square parentheses ([ ]) indicate some appropriate probability distribution.

$$\begin{aligned}[\text{population}|\text{detections, activity, entry}] \propto\ & [\text{detections}|\text{population, activity}] \\ & \times [\text{population}|\text{entry}] \\ & \times [\text{activity}] \times [\text{entry}]\end{aligned} \quad (4)$$

A key feature of Equation 4 is that the prior belief of entry, as captured by the distribution [entry], can effectively reduce the likelihood of a population being present to zero, regardless of survey effort and detections. For example, if it is believed that the unseen entry of a particular exotic species is effectively zero (e.g. striped skunks in Australia), then it follows that the belief in the probability of a population being present, regardless of the surveillance effort, is also effectively zero. If, however, entry is considered possible, then making inference on the population size on the basis of general surveillance requires quantitative treatment of all the components in Equation 4. That is, modelling the population size given entry, in conjunction with the detections given surveillance effort and population, and the underlying surveillance activity and prior belief of entry. This represents the 'Entry, Establishment and Spread' (EES) component of an invasive species risk analysis (Andersen et al. 2004). Likewise, the likely distribution of detections given the population also requires that the distribution of the activity is characterised.

QUANTIFYING GENERAL SURVEILLANCE EXAMPLE – FULLY CHARACTERISING ACTIVITIES

Authorities were rightfully concerned when rumours surfaced in the late 1990s of the introduction of the red fox (*Vulpes vulpes*) to Australia's island state Tasmania, as the small mammal fauna would be highly vulnerable to this predator (Johnson 2006). The inference of an already widespread and expanding population was based on the extraction of red fox mitochondrial DNA from predator scats assumed to have been collected from Tasmania (Sarre et al. 2013). The reasoned argument from a substantial proportion of citizens, however, was that no such widespread population existed. Following an initial cluster of confirmed specimens of actual foxes (a single individual purportedly shot by a hunter, and three individuals purportedly killed by vehicle collisions), there had been no further specimens considered reliable (though see Marks et al. 2014), despite the DNA evidence indicating a persisting and spreading population.

The Tasmanian fox incursion data necessitated applying Equation 4 in an explicitly spatial and temporal manner. The space-time distribution of *entry* was constructed from news reports of the rumoured deliberate introduction, and the corroborated sightings of a fox jumping from a container boat. The general surveillance activity 'vehicle collision' was defined by the distribution of roads, and 'hunter kill' was defined by the hunting distribution based on the demonstrated high intensity of hunting in Tasmania with detection efficacy informed from the literature of surveying for foxes where they are known to occur on the Australian mainland. All calculations and associated dynamics were abstracted to a 5 km by 5 km raster with a one-year time step. These steps are similar to those undertaken when constructing a Bayesian hierarchical model to describe the dynamics of a partially observed population process; however, standard likelihood methods become impossible to use as the complexity (of what is still a reasonably simple observation and population process) makes the likelihood intractable. The problem of the intractable likelihood was solved by using Approximate Bayesian Computational methods (Toni et al. 2009).

The resulting inference from what was then considered verifiable data arising from general surveillance (i.e. lack of confirmed roadkills and hunter kills) provided compelling inference that the postulated widespread distribution of red foxes was very unlikely to be true, and in fact the most likely population size was zero (Caley et al. 2015); a result that has so far stood the test of time. It should be noted, however, that the uncertain provenance of the carcasses observed and reported by citizens (see Marks et al. 2014) highlights the risk of false-positive citizen observations. A high rate of false-positive visual sightings is a given; it is intrinsic to human nature. However, deliberate fabrication of observations is more difficult to detect, and potentially more costly if it triggers an expensive response, as may well have been the case for the postulated fox incursion into Tasmania (Anon. 2017).

Caley et al. (2017) note other forms of general surveillance activity that add further to the inference. For example, searching the prey remains ('orts') associated with wedge-tailed eagle (*Aquila audax*) nests in Tasmania (for which the locations are in-the-main known to authorities). Like their northern hemisphere cousins, the golden eagle (*Aquila chrysaetos*), wedge-tailed eagles regularly kill red foxes and red fox remains are consistently found at non-trivial percentages in wedge-tailed eagle diets in a wide range of habitats wherever foxes are present (Glen et al. 2017). Codifying the surveillance 'activity' of wedge-tailed eagles would require quantifying the foraging radius of an eagle pair, and calibrating the predation rate from the numerous locations on the Australian mainland where the eagles and foxes coexist. Yet other forms of general surveillance activities could also be added for which calibration would be easier, including extensive camera trapping studies of Tasmanian fauna (e.g. Thalmann et al. 2014) and statewide spotlight count transects undertaken since 1975 (Lazenby et al. 2018). Neither has recorded a fox sighting, though it is safe to assume that if a sighting were made it would be reported. Adding additional forms of observation to the general surveillance inference need not increase the computational burden of such a model if each activity can be essentially marginalised to an activity layer with the same spatio-temporal scale.

QUANTIFYING GENERAL SURVEILLANCE SENSITIVITY EXAMPLE – USE OF COVARIANCE

A way of quantifying the observation sensitivity (for the possible population sizes that haven't been observed) is via statistical expectation after conditioning on a variable that the population of species in question is known to co-vary with. The covariance need not be linear. For example, Caley et al. (2017)

showed how the numerical response relationship between a predator (in this case the red fox) and its prey (hares and rabbits) could be used to quantitatively infer the population size of the predator from a location where there hadn't been any sightings. The data in question were airport runway strike data collected by the Australian Transport Safety Bureau. These are typical industry data arising from general surveillance, whereby there is a clear process of recording all positive 'sightings', that is, all incidents of animals being struck on runways and their identification if possible but nothing else (excluding near misses). For these types of activities, the assumption that if a species has not been recorded then it has not been detected by the surveillance activity, is by no means an onerous one.

de Groot et al. (2022) use knowledge about a set of species detectable through general surveillance activity combined with the reporting motivations of individual observers, to infer 'constrained' pseudo-absences. They do this by conditioning citizen observations on: (1) observers that had previously reported sightings of the target species, and (2) locations where this subset of observers had observed at least one other species expected to be observable using the surveillance activity in question. The first conditioning step ensures that observer possesses the necessary identification skills, while the second step confirms that the surveillance activity has occurred at the location in question. de Groot et al. (2022) use this approach of generating pseudo-absences to feed into a species distribution for an invasive species; however, it can also be used to quantify the distribution of the surveillance activity in Equation 4.

QUANTIFYING GENERAL SURVEILLANCE SENSITIVITY EXAMPLE – DIRECT EMPIRICAL

In an ideal situation, the distribution of the population of interest is known, as is the distribution of the surveillance activity. This enables the sensitivity of the surveillance activity to be calculated directly using empirical methods. This requires independent ground 'truth' data of the population of interest to evaluate citizen sightings against. That is: the probability distribution of detections, given population size and surveillance activity (as described by the component [detections|population, activity] in Equation 4), can be calibrated. This direct calibration clearly can't be applied to exotic species that aren't yet present where the surveillance activity is occurring. Again, statistical conditioning can be useful to overcome this problem. It requires features (not necessarily only physical ones) that influence the combined sighting and reporting probability of endemic species that can be used to develop a model-based estimate of sensitivity for exotic species of interest. For example, Caley et al. (2020) used a case-control design combined with physical covariate features to estimate the reporting probabilities of citizen surveillance. The resulting model was then used to estimate the probability of an incursion being reported by general surveillance for the exotic species of interest, conditional on covariates that predict observation and reporting, and the spatial extent of the population incursion.

DISCUSSION

In this section we have argued that understanding and using the general surveillance information inherent in citizen reporting requires characterising the activities that will generate reports from positive sightings (if any). Once the activities are adequately described, the surveillance information they provide, including that arising from the implicit zeros/absences, can be calibrated by a range of methods and hence quantitatively evaluated. This is important, as there appears to be both a lack of scientific understanding and accepted methodology for dealing with the implicit absences within data generated by general surveillance activities. This is exemplified by the polemic surrounding the true number of foxes associated with the putative incursions into Tasmania (see later section in this report), with critics of the inference in Caley et al. (2015) [that the size of the fox population was most likely zero or failing that, very small] reasoning that there was insufficient evidence from only four fox carcasses to make such sweeping conclusions. This reasoning that information comes only from detections (positive sightings) is a recurring theme. An implicit contradiction within the reasoning is that to have increased confidence that there are no individuals (in this case foxes) you need to have first detected numerous individuals. Furthermore, by extension, if you have not detected any individuals, then you have no information on whether any individuals are present. Such arguments are often presented in conjunction with the maxim that 'Absence of evidence is not evidence of absence'. We have argued that there is indeed inference to be had from the 'absence of evidence', providing the citizen activity capable of generating positive sightings can be described in a way that enables quantitative treatment, and that a non-trivial reporting probability of the sighting can be reasonably assumed.

The case studies we present for the detection of vertebrate pests entering Australia support the assumption that there is a high reporting probability of many exotic vertebrate pest species given a positive sighting. The manner in which sightings by citizens are typically shared within a community of practice increases the probability of a sighting being reported; the probability of the sighting remaining unreported declines exponentially with the increase in the number of people that view the sighting. The internet plays an important role in sharing sightings, and for the bird and mammal animal groups it appears that citizen-based general surveillance provides sensitivity adequate to prevent incursions. This assumes, of course, that an effective incursion response is mounted; timely surveillance can only lead to useful outcomes if acted on. For species from more cryptic groups, such as reptiles, and those inhabiting aquatic habitats (e.g. amphibians and fish) it appears that although citizens are again providing the bulk of the surveillance effort, the detections may not always be timely enough to prevent establishment. For example, while community sightings comprise the biggest source of reports of corn snakes (*Elaphe guttata*) in Australia, the increasing pattern of detections suggests they have established free-living populations that are increasing (McFadden et al. 2017; Mo and Mo 2021). Such cryptic species are difficult to eradicate, and when individuals are found, the uncertainty as to whether the individual is free-living or simply an escaped specimen introduces uncertainty to the decision-making process. As noted previously, citizen surveillance of aquatic habitats is hampered by the obvious challenges of access and visibility (including the difficulty of obtaining images).

We note that increased surveillance sensitivity arising from citizen activities may require more decision-making around the sighting information generated. The adage 'Be careful measuring what you cannot manage' has relevance. Deciding the level of response warranted by a reported incursion of an exotic vertebrate species is beyond the scope of this report, though clearly not all species that establish will have undesirable invasive traits (and hence be a 'pest' to some part of society). Indeed, what society considers 'a pest' can be subjective. For example, in Western Australia, established laughing kookaburras (*Dacelo novaeguineae*) are generally accepted and not considered a pest species despite being exotic (deliberately introduced). Species that are already on alert lists would be expected to generate an immediate response. For species of uncertain invasive potential, a prudent response could be effective containment while the likely impacts are assessed. For some species, the desired outcome could be no management action (c.f. eradication, containment, managed spread), especially regarding the treatment of vagrants and self-introductions in the case of birds. Others may require a response to prevent establishment.

The decision to eliminate Canada geese detected in south-eastern Australia, on the assumption they had travelled from New Zealand where they are introduced (as opposed to self-introducing all the way across the Pacific Ocean from North America), points to a grey area in responding to detections of alien species. Can we distinguish a 'natural' self-introduction from one that is not part of the 'natural' order? For example, the cattle egret (*Bubulcus ibis*) is now widespread and endemic across much of Australia and New Zealand after self-introducing during the mid-20th century as part of a bigger worldwide expansion, no doubt facilitated by the spread of pastoral systems for domestic cattle (*Bos* spp.). The extensive network of birdwatchers across Australia is now regularly reporting on sightings for species classified as vagrants. Which ones should be worried about (if any) and why?

Repeated sightings of a free-living ostrich (*Struthio* spp.) near Dulkinnia Bore on the Birdsville Track occurred from 2018 until at least 2021 (Figure 7), including news items in the mainstream media (e.g. this ABC article). This did not appear to have prompted any action from authorities. In their defence, being a solitary male may have influenced the hands-off decision of authorities, along with the obvious tourism drawcard (particularly with the birdwatching fraternity) that this individual presented.

Figure 7. One of several posts on Twitter of an ostrich on the Birdsville Track. Repeated sightings occurred over the period 2018–2019.

GETTING MORE FROM EXISTING CITIZEN DATA STREAMS

We have previously highlighted the substantial reporting effort provided by citizens, largely in the form of passive surveillance, whereby citizens take the initiative to report a sighting of species they consider of interest to authorities. In this section we explore approaches to identifying exotic vertebrates from within: (1) animal sightings that are posted onto platforms such as iNaturalist with the intention of seeking species identification and/or sharing biological knowledge, and (2) animal sightings that are contained within social media posts (e.g. Facebook) for which the purpose of posting is more varied.

AUTOMATED DETECTION AMONG DEDICATED CITIZEN DATA STREAMS

There are two broad approaches to successfully identify a reported sighting as an invasive species. First and most traditional is to check the sighting identification for matches against a list of species of concern (e.g. a 'priority list' or 'declared list'). Such lists can be at different taxonomic levels (e.g. genera), and the criterion for inclusion is often prior evidence of the species or the genera being invasive elsewhere (in this context typically meaning outside of Australia). The second approach is to check the sighting identification against species known to already be established (and not under attempted suppression/eradication action) in the recipient area (a 'permitted list' approach). Both approaches have strengths and weakness.

One of the primary risks of the 'priority list' approach is that it doesn't actually contain all the high-risk species in terms of their invasiveness, and that an ultimately invasive species will fail to be identified because of this. Unfortunately, and despite our best efforts, reliably predicting which species will become invasive when introduced to new environments remains challenging (Hayes and Barry 2008), echoing the earlier doubts of Crawley (1987). The best predictor of successful invasion relates to the introduction effort, that is, the number of introduction attempts including the number of individuals involved in each attempt (Cassey et al. 2018; Lockwood et al. 2009) and is a measure unrelated to the intrinsic invasive potential of a species. This is useful in risk management as it predicts that species known to be introduced more often (such as appears to be the case of the Asian black-spined toad) will have a greater likelihood of establishing. Inferring that the more you introduce the more likely you will get a successful invasion does not hold in every case. In fact, if repeated introductions occur without successful establishment then the likelihood that the species is actually capable of mounting an invasion *decreases* (see Heersink et al. 2020). The failure of domestic ferrets (*Mustela furo*) to establish despite numerous ongoing introductions in the vicinity of their preferred rabbit prey (a result of individuals not being retrieved when ferreting for rabbits) is increasingly looking like an example of this. The barriers to ferrets establishing are not clear, but agonistic interactions with intraguild predators, such as the red fox, would be a candidate hypothesis. It would be unwise, however, to proceed from hypothesis to inference without supporting data. For example, at least 1,000 introduced mongoose (most likely the small Indian mongoose *Herpestes auropunctatus*) were introduced over 14 occasions during the late 1800s, yet failed to establish any populations (Peacock and Abbott 2010), despite the probable absence of foxes from most of the release locations (Abbott 2011). Rolls (1984) suggests that removal by rabbiters may have led to their demise.

The other predictor of invasiveness used to populate priority lists is evidence of invasiveness elsewhere. While this undoubtedly contains some predictive power, and hence some use, the method provides no useful information on species that have not had the chance to demonstrate their invasiveness elsewhere (i.e. haven't been introduced outside their native range in large numbers). The number of species in this category (and hence this size of the blind spot in the method) is potentially large.

Advantages of the 'priority list' approach include the reduced number of taxa that sighting reports need to be matched against (though note that modern computing power makes this inexpensive) and the ability to target a limited number of species of special importance in community outreach activities. Indeed, for species that are believed to be highly invasive (in comparison to others), targeted surveillance would appear in order.

The ‘permitted list’ approach aims to generate alerts based on identifying any species that is not established in the recipient region of interest. Note that:

- there is more work in generating the permitted list
- there are considerably more species for a reported sighting to be matched against.

However, matching is now inexpensive (done by computers) so the major effort is in generating the permitted list. The Australian Faunal Directory provides an obvious place to start.

MINING SOCIAL MEDIA FEEDS

Not all potentially useful observations find their way directly or expediently into the public realm of biodiversity records where they would be amenable to direct querying and online surveillance. In particular, social media platforms (Facebook, Twitter, Instagram etc.) host numerous groups relating to aspects of wildlife survey (e.g. identification, photography, nature appreciation, husbandry and pet-keeping). These groups harness the collective observation and identification skills of hundreds of thousands of individuals; they connect people and provide online training in animal identification. Short of having a biosecurity practitioner join all the relevant groups and/or following feeds and accounts (and to be on the lookout for more), and spending much of their work time trawling through this material, how can we tap into the massive surveillance resource this presents? Is it possible to automate the process through data mining (image recognition and/or natural language processing), and would these users be happy about this approach? Furthermore, do we actually need to extract surveillance information out of these data streams, or is the self-reporting by the citizens sufficient?

In this section we explore the utility of mining social media data to detect postborder incursions of exotic vertebrate pests. This is different from looking at illegal trade which relates to law enforcement. Using Australia as an example, we illustrate the scale of the problem, in terms of the number of alien vertebrate species potentially involved, the scope for effective data mining, and the effectiveness of surveillance provided by citizen-generated data.

DO WE NEED TO?

Do we actually need to get better at detecting incursions of alien vertebrate species, either before they have escaped into the wild to be free-living (i.e. still within captivity), or following escape? This is the first question to be addressed, before we launch into developing methodology. Here we consider mammals, birds, reptiles and amphibians, and freshwater fish in turn.

Mammals: For mammalian invasive alien species (IAS), for Australia at least (being an island), the majority of successful invasions to date (other than small commensal rodents) are largely the result of deliberate (and often repeated) introductions by acclimatisation societies (Rolls 1984) or as attempts at biocontrol. These include the repeated introduction, though ultimately failed establishment, of the Indian mongoose (*Herpestes auropunctatus*) in the belief they may control introduced European rabbits (*Oryctolagus cuniculus*) (Peacock and Abbott 2010). Such deliberate introductions are now subject to considerable restrictions and risk analyses and have virtually ceased. With ongoing heavy restrictions around deliberate importation (for release into the wild) and strict border biosecurity around trade and visitation, the future approach rate of alien mammals from external sources will be negligible. Hence future postborder incursions that do occur will be as a result of escapes from captivity, particularly pets, though also potentially from zoos (for which importations continue). Note, however, that zoo escapes will typically be quickly identified by their owners/keepers and relayed to authorities (e.g. the recent red panda escape from the Adelaide Zoo), or be a non-viable breeding population such as the solitary pygmy hippopotamus (*Choeropsis liberiensis*) that escaped a private exotic animal collection in the Northern Territory before living in the wild for about six years (Mo 2022). Exceptions could include small, cryptic and highly mobile species, particularly in situations where a zoo is located adjacent to large tracts of forest (e.g. the wet tropics of northern Queensland). We note that although new introductions of alien mammals are rare, there is still considerable demand for new mammalian exotic pets in Australia, many of which are recognised as highly invasive species (Toomes et al. 2020b). Even if there were pathways of entry for the exotic mammal species (e.g. pygmy marmosets *Cebuella* spp. and raccoon dogs *Nyctereutes procyonoides* are highly popular internationally), we argue there is no need for data mining citizen’s social media feeds, as a sighting of such an exotic species will quickly trigger a report to authorities through existing general surveillance channels. For example, the land manager who accidentally shot the aforesaid pygmy hippopotamus promptly reported it to authorities (see this ABC article).

Birds: Participants in the age-old hobby of birdwatching, through platforms such as eBird, have embraced sharing their sightings with such enthusiasm that the need to physically mine their social media data for sightings of exotic species of concern is largely redundant. Members of the online birding community take the process of correct species identification very seriously, and platforms such as eBird apply moderation to all sightings. For example, eBird provides an email alert system for rarities and vagrants at the spatial resolution from county/province/state to country level. A recent incursion of an exotic species that could be considered undesirable (both exotic and potentially invasive), was a group of Canada geese (*Branta canadensis*) sighted by birdwatchers on the South Coast of New South Wales. The sightings quickly found their way to an online birding portal (Birdline New South Wales), and continued to be sighted and reported online as they moved between wetlands over a considerable distance, before being removed (euthanised) by authorities (Boles et al. 2016). There is a much higher uptake of online reporting apps by the birdwatching community than 15 years ago. The surveillance provided now would be even more sensitive, and prompt. Thus, the current citizen-reporting system appears adequate for detecting introductions in a timely manner. Sightings of escaped pets in particular are easily accessed (Vall-llosera and Cassey 2017). It could be argued that what is needed to stop incursions is most probably more effective responses, rather than improved surveillance.

Reptiles and amphibians: As with mammals and birds, deliberate introductions of reptiles and amphibians have largely ceased. The most infamous deliberate introduction and release of a vertebrate biocontrol agent (that ultimately failed in this regard) was that of the cane toad (*Rhinella marina*) in 1935 (Easteal 1981). However, as with birds, escaped pets are identified as a real and significant risk (Toomes et al. 2020b). Recent examples of species that have escaped and established free-living populations include the red-eared slider turtle (*Trachemys scripta elegans*) (Burgin 2007), the European newt (*Lissotriton vulgaris*) (Tingley et al. 2015), and quite possibly European corn snakes (*Elaphe guttata*) (McFadden et al. 2017; Mo and Mo 2021). In all cases the source of these establishments was animals released from captivity either deliberately or accidentally. We expect incursions from the escaped exotic pet trade (including many illegally kept reptiles and amphibians) to continue at non-trivial rates (Stringham et al. 2021a; Toomes et al. 2020a). We also expect ongoing introductions, despite stringent biosecurity measures, of hitchhiking species such as the black-spined toads (*Duttaphrynus melanosticus*) that may be difficult to detect if entrapped within cargoes or shipping containers (Tingley et al. 2018).

Fish: The aquarium trade sees numerous exotic fish species brought into Australia in the recent decades (García-Díaz et al. 2018), and there appears to be a steady stream of incursions arising from escapees, and in some cases deliberate releases. Recent incursions include several species of tilapia (e.g. Mozambique tilapia *Oreochromis mossambicus* and the spotted tilapia *Tilapia mariae*) in eastern Australia, and Siamese fighting fish (*Betta splendens*) in the Northern Territory (Hammer et al. 2019). Nearly all the detections of exotic fish incursions arise from citizen reporting. The problem is that the same factors that hinder the ability of citizens to observe and identify fish (i.e. being aquatic) also limit the ability to acquire images that can be subject to data mining. Within iNaturalist, along with other strong biases in reporting (e.g. over reporting of birds in relation to their diversity) fishes are strongly under-sampled relative to their diversity (Mesaglio and Callaghan 2021).

CAN WE ACTUALLY DO IT?

Is the signal there?: Citizens' social media posts will almost certainly contain images and/or text relating to IAS, though only a proportion of social media postings will be public and hence accessible. Many citizens are motivated to share images and accounts of animal species that are novel to them, whether they are thought to be exotic or not. It has been clearly demonstrated when it comes to uploading images of animals that morphology, colour, pattern and size all matter (Caley et al. 2020). Hence people are more likely to go to the effort of sharing sightings of organisms that are bigger, brighter, more colourful, patterned ornately, morphologically unusual and/or exquisite. Many exotic vertebrate pests will tick at least one of these boxes, especially those of the escaped pet variety, that are considered desirable for these very attributes. For example, the adult female *Iguana iguana* identified by a kayaker on Ross River, Townsville, Queensland, in April 2011 (Henderson et al. 2011). So yes, it appears very likely that conditional on being sighted, and in particular if photographed, that information (image, description) of an alien species will find its way onto social media and/or a dedicated reporting platform. The key issue then becomes whether the signal can be identified efficiently, and correctly.

Issues of scale: If the full set of possibilities is to be addressed, there are literally tens of thousands of potential species for a classifier to consider. From Australia's perspective, worldwide there are approximately

60,000 species of mammals, birds, reptiles, amphibians and fishes considered alien. This is approximately three orders of magnitude greater than the largest image recognition study of free-living wild vertebrate animals to date, of which about 5,000 species are endemic to Australia.

Natural language processing: Mining social media feeds for alien animal species of biosecurity concern is extremely challenging (Welvaert et al. 2017). This is particularly so in the majority of cases where the sampling is largely unintentional from a scientific viewpoint (Welvaert and Caley 2016), as this influences the scale, aspect and quality of photographs, and the type of language used. Even for IAS sightings where the reporting is intentional, the observer often won't know either the scientific (binomial) or common name for the species in question. This is exacerbated by the frequent use of a large number of trade names for many exotic pet species. For example, more than 20 names were found for the potentially invasive monk parakeet (*Myiopsitta monachus*) in the aviculture (bird-keeping) trade (Stringham et al. 2021b). This means that identification from social media feeds (without images) has to be made by natural language processing. There is a surprising amount of noise in the social media landscape, and it can come from a surprising number of causes. For example, when (Welvaert et al. 2017) set about evaluating whether there was a signal in Twitter to indicate the arrival of the migratory eastern koel (*Eudynamys orientalis*) into eastern Australia, noise resulted from 'koel' being a Dutch word for 'cool', as well as the name of a popular Bollywood actress with a strong Australian following. Of note, if the observer does know (or strongly suspects) what the species is, and if it is alien (e.g. a boa constrictor in the case of Australia), then the chances are high that this information will reach someone who cares enough to make the effort to report the sighting to authorities. Of course, there is no guarantee this will lead to the desired consequences, as in the case of the boa constrictor mistakenly released by Gold Coast police after responding to a call from the public.

Image recognition: Successes to date arise from analysing camera-trap images to identify a limited number of study species of interest. For example, when classifying images from the Snapshot Serengeti dataset (Swanson et al. 2015), Norouzzadeh et al. (2018) had only 48 classes of animals to classify, of which many exhibit unique conformation arising from natural selection for local ecological niches. Such morphological differentiation often disappears in physically separated populations where convergent evolution has taken place. Even in this limited choice image classification study with extensive training available, the mis-classification rate was a non-trivial eight per cent (Norouzzadeh et al. 2018). Impressive as this is (equal with human volunteers), trawling through social media data for alien species would result in mis-classifications and generate an impossibly high workload on account of the sheer number of images to be classified. When the number of species to potentially identify increases dramatically, so does the error rate. Given the number of images involved, the number of false alarms (natives classified as alien) will be considerable (Lamba et al. 2019), resulting in the online equivalent of 'wild goose chases' in citizen's social media data if followed up.

Who thought zoos and holiday snaps were a problem?: Dealing with social media posts lacking geolocation data will be logistically problematic when determining native or alien status. The feed of good quality images of alien species in particular could well be essentially 'spammed' by people visiting the zoo. People sharing images of their pets on social media, along with advertising exotic pet animals for sale will generate (if the image classifier is working) a large quantity of true positives of species identification but in the wrong context (i.e. not a free-living specimen in the wild). Posts pertaining to IAS that are associated with trade (either 'wanted' or 'for sale') can almost certainly be effectively filtered (e.g. Stringham et al. 2021b), but those relating to pets in particular will be harder to identify. Not only is keeping pets a major source of unwanted introductions, it would also be a major source of noise that will hinder the application of digital methods to help identify and respond to these introductions.

WILL IT BE BETTER THAN BUSINESS AS USUAL?

Any new surveillance system should improve the existing surveillance under business as usual (BAU) – the comparative value proposition. Without descending into detailed cost-benefit considerations, this means that our data mining needs to at least generate additional reports of alien species from social media feeds, over and above what are already detected. Otherwise, we will be simply discovering, through potentially intensive analytics, what is already adequately reported by word-of-mouth. Also, human vision, processing, and word-of-mouth is demonstrably powerful, as a recent case of an alien *Boa imperator* (native to South and Central America) in Sydney demonstrated. A citizen posted a picture (not particularly detailed, with the head obscured) to a Facebook group dedicated to the fast identification of snakes; a licensed reptile handler was notified (pinged), the snake safely captured and handed over to authorities (Figure 8). This all occurred over a timescale of hours. The lack of resolution and features in the picture would make image recognition challenging, whereas the human brains involved provided the correct classification: a potentially alien species in need of further investigation. Such a crowdsourced classification and notification system is demonstrably powerful. It can also, through messaging, resolve contextual issues that an automated image classifier may struggle with, such as country (e.g. occasionally people outside Australia mistakenly post an image to the 'Snake Identification Australia' Facebook group seeking identification) or location (e.g. captivity or wild?).

Of course, as the quality of photos improves, along with training data, the quality of classifications improves. A subsequent high-quality photo (Figure 9) of the snake shown in Figure 8, when presented to the iNaturalist classifier (van Horn et al. 2018), is much more encouraging. The classifier reckons 'We're pretty sure this is in the genus Boa Constrictors' [sic] with *Boa imperator* being its second highest choice. The point is that the citizen surveillance ecosystem had already made this identification and alerted authorities several days earlier.

Figure 8. Post to Facebook group Snake Identification Australia with a photograph of what transpired to be a Boa imperator. The illegally kept pet was captured by a licensed snake handler and impounded by the appropriate authorities within hours. A simple Google image search of this image will return pictures of houses only. The iNaturalist classifier admits to being unsure (suggestions range from cats to carpet pythons). Source: Facebook.

Figure 9. Follow-up photo of Boa imperator captured from western Sydney. Source: Facebook.

The previously mentioned example of citizen birdwatchers effectively detecting an incursion of Canada geese into Australia, in combination with the knowledge of just how interested the birding community is in the identification of exotic and/or vagrant species, leads to the conclusion that data mining social media feeds is unnecessary to achieve adequate surveillance for alien birds. Put simply, citizens are willingly sharing sighting data on publicly accessible platforms.

Citizen surveillance for purely aquatic species, while still the primary form of reported observations for IAS, doesn't appear to be timely enough for preventing the establishment of IAS in this environment. However, the factors limiting the effectiveness of the surveillance are not the propensity to report an IAS given detected, but the process of detection and hence signal generation itself.

In contrast, amphibians such as frogs, are more likely to be physically sighted as they are not confined to aquatic habitats, but more importantly are easily detectable by their typically prolonged calling behaviour that makes them detectable by the citizen-driven FrogId.

WHAT IS WARRANTED IN PURSUING?

For Australia, it appears sensible to prioritise for which species data mining will be beneficial based on the risk of introduction (approach rate) and effectiveness of existing general surveillance provided by citizens. This enables us to narrow the problem space considerably by excluding mammals (too few incursions expected), birds (BAU surveillance provided by birdwatching enthusiasts appears adequate), or fish (lack of sightings worth mining). This leaves reptiles and amphibians as the group that are the source of most new vertebrate incursions, and where improved incursion response appears to be needed the most.

The global list of possible reptile and amphibians (tens of thousands) is logistically too large for highly accurate image recognition, hence further filtering of the species of interest is needed. Disappointingly, science hasn't been overly successful in identifying intrinsic biological traits that are consistent predictors of invasive potential (see Hayes and Barry 2008). However, the role of propagule pressure influencing establishment success is clear (Cassey et al. 2018), and there are data available on interceptions that can identify which species are most likely to pose the greatest risk of establishment. Indeed, (Toomes et al. 2020a) show that a handful species account for about half of all border interceptions. It makes sense to start to target these species which include red-eared slider turtles, corn snakes and boa constrictors, all highly desirable (though illegal) pets in Australia, as well as the Asian black-spined toad (*Duttaphrynus melanostictus*) which is frequently detected as stowaways (Tingley et al. 2018).

Both red-eared slider turtles and corn snakes are probably permanently established in Australia, whereas boa constrictors are not. A good starting point for narrowing the species of interest would be to focus on those that are highly desirable across the globe to keep and breed. The propensity of collectors to breed exotic snakes (mainly pythons and boas) means the escape of a single individual (a gravid female) can initiate an invasion, with potentially major environmental impacts (e.g. Dorcas et al. 2012). Moreover, certain reptile species are capable of parthenogenesis (asexual reproduction). Australia is home to several species of large python with considerable colour variation, so discriminating between native pythons (e.g. the carpet python *Morelia spilota* with all its colour morphs) and unwanted exotic python (e.g. reticulated python *Malayopython reticulatus*) is a challenge for some citizens (as evidenced by the release of the boa constrictor on the Gold Coast), but may not be a major challenge for an image classifier if the deep learning algorithm can discover features that are sufficiently discriminatory.

Citizens easily mistake Asian black-spined toads for the already invasive cane toad, so there is utility in developing a classifier to distinguish the two. Again, we are reasonably certain that someone who's interested enough to take a photo of a toad will probably be posting to a site (e.g. iNaturalist) where the identification will be crowdsourced. This raises the obvious question of how much image identification should be automated, versus relying on the collective taxonomic skills of the crowd? Platforms such as iNaturalist, already facilitate alerts for sightings of selected taxa within user-specified geographical regions. Furthermore, if we are happy that: (1) sightings are being classified with sufficient accuracy, and (2) that the naming system is also workable, then we no longer need to employ high-powered semantic-style natural language processing. Simple queries based on the taxa of concern become straightforward.

WHAT ARE THE COSTS?

A large part of the argument for employing data mining of social media to detect IAS incursions is that it will be comprehensive and cheap (or at least cost-effective). Given the scale of the problem in terms of the potential number of species, and the likely number of mis-classifications involved, this is unlikely to be the case.

One of the longer-term issues of data mining is the curation and storage of large datasets. Previous data-rich information systems such as the Australian Biosecurity Intelligence Network (ABIN) and International Biosecurity Intelligence System (IBIS) have either been discontinued (or taken offline), or were unsuccessful, because they were inaccessible and could not secure recurrent funding.

The loss of societal trust through unsolicited data mining of social media content is an obvious potential cost. Many people would be unhappy to know that their social media posts are being scrutinised by authorities. Any benefit in improved surveillance sensitivity would need to more than compensate for this. It is likely that some people that have posted material that could be an IAS incursion may by unwilling (somewhat understandably) to state exactly where the observation was and the context, making the extraction of useful information difficult. Finally, nefarious posts are a real possibility, whereby individuals deliberately construct sightings of IAS in an attempt to frustrate and embarrass authorities. Such postings can consume considerable resources to resolve. Moreover, people who keep illegal reptiles occasionally attempt to generate a public perception that private possession is 'out of control' and, therefore, needs to be legalised (the latter being a clumsy attempt to remove effective laws, for the financial benefit of a few people).

CAN WE RESOURCE ALTERNATIVE APPROACHES?

An obvious alternative to investing in the data mining of people's social media posts is to direct resources into improving the existing surveillance provided by citizens arising from their intentionally shared sighting information. That is, rather than scrutinising social media posts that will have extremely low signal-to-noise ratios, we take measures to help citizens improve the signal within posts that they are already willingly sharing on purpose-designed platforms. For citizen data streams that are curated online (e.g. eBird, iNaturalist) or aggregators of biodiversity data such as the ALA, it should be possible to work directly with the curator to provide the generated alerts for potential IAS sightings of concern from within. Understanding the processes by which citizens are reporting IAS is a precursor to identifying how the reporting process can be improved through investment. The components of an IAS incursion being reported include:

1. Observation: Citizens having an interest in and awareness of the living world around them.
2. Identification: Citizens with (a) a good working knowledge of endemic/native species, and/or (b) the skills to identify a species unknown to them, and/or (c) the interest to try to identify a species unknown to them (e.g. crowdsourcing).
3. Reporting: Citizens knowing who and how to contact the appropriate authority in the event of sighting an IAS.

Fostering an interest in the natural world can be achieved through the education system, at all levels. This will invariably lead to improvements in all the components of the reporting process listed above.

Harnessing the passion of people for collecting things (whether animate or not) towards the biological is a clear opportunity to improve biodiversity reporting and hence IAS surveillance. For example, it may be possible to encourage the users of augmented reality games such as Pokemon Go to engage with real-world nature (see Dorward et al. 2017). A challenge in getting citizens to undertake surveillance for IAS is that, by definition, the IAS will be absent or uncommon most of the time. Hence to maintain interest (and hence build a collection) necessitates that people are observing and cataloguing what is predominantly non-alien biodiversity, with alien species 'detection' an incidental event. There remains the possibility that biodiversity 'collection' and alien species 'detection' could be much better 'gamified'. That said, many people are already using one or several of the many readily available platforms to record and store their sightings of animals in the world around them, and there is no market failure in the availability of suitable apps and associated platforms for collating, comparing and sharing lists of taxa.

Improving the coverage and quality of citizens' identifications could be achieved by improving the access and awareness of platforms to facilitate identification (e.g. crowdsourcing platforms, online keys, image classifiers). An alternative to the unsolicited use of image classification on peoples' social media posts is to put the image recognition tools in people's hands to do their own investigations, with sufficient natural history information (e.g. 'native to this region') for people to make an informed choice as to whether they should notify authorities. A good example is provided by Queensland's 'Weedspotter Network', which has over 1,800 members, all specifically trained to look for high-risk invasive plants while they go about their daily fieldwork.

Finally, we can improve the direct detection and reporting on IAS by citizens. For example, agencies charged with managing biosecurity could invest in targeted advertising on social media, encouraging people to report exotic species, or search in particular areas. For example, the city of Adelaide is currently asking members of the public to report sightings of rose-ringed and Alexandrine parakeets (*Psittacula eupatria*) and Biosecurity Queensland routinely invites people to report certain high-risk species on monthly Facebook feeds. This technique appears highly successful, not only at detecting pests but also raising awareness of the value of prevention generally. Advantages of this approach include the possibility of actually influencing the citizen sampling and reporting process. We have described how escaped pets are a major pathway of introductions of IAS, and websites and social media groups devoted to reporting on lost pets and sightings of suspected escaped pets are now common and heavily used. These are an important source for potentially detecting escapes of the more common species (the escape of a highly valuable and/or illegal species may not be advertised), and act as a form of self-regulatory surveillance system.

COMBINING PASSIVE AND ACTIVE SURVEILLANCE – IDENTIFYING AND PLUGGING THE GAPS

An important outcome of evaluating the effectiveness of the passive surveillance by citizens is to help identify whether active surveillance is needed, and if so, exactly where.

CASE STUDY 1 – DETECTING INCURSIONS OF COMMON STARLINGS

Through considerable ongoing effort, Western Australia has managed to prevent the common starling (*Sturnus vulgaris*) establishing, despite ongoing self-introduction pressure from the long-established populations in eastern Australia. Starlings are considered highly invasive, and to be a serious pest, with a cost-benefit analysis suggesting that considerable effort is warranted to keep Western Australia free of the species (Campbell et al. 2016). Removing all individuals from incursions of starling populations is labour intensive (see Campbell et al. 2012), hence there is value in detecting incursions at a very early stage while small in numbers.

SPATIAL GAPS IN SURVEILLANCE

Detecting starlings in Western Australia in the areas where they are likely to (and do) invade is logistically difficult using standard methods including direct (active) human observations. Furthermore, the passive surveillance provided by citizen birdwatchers in the areas of interest around the South Australian border with Western Australia is low (Figure 10).

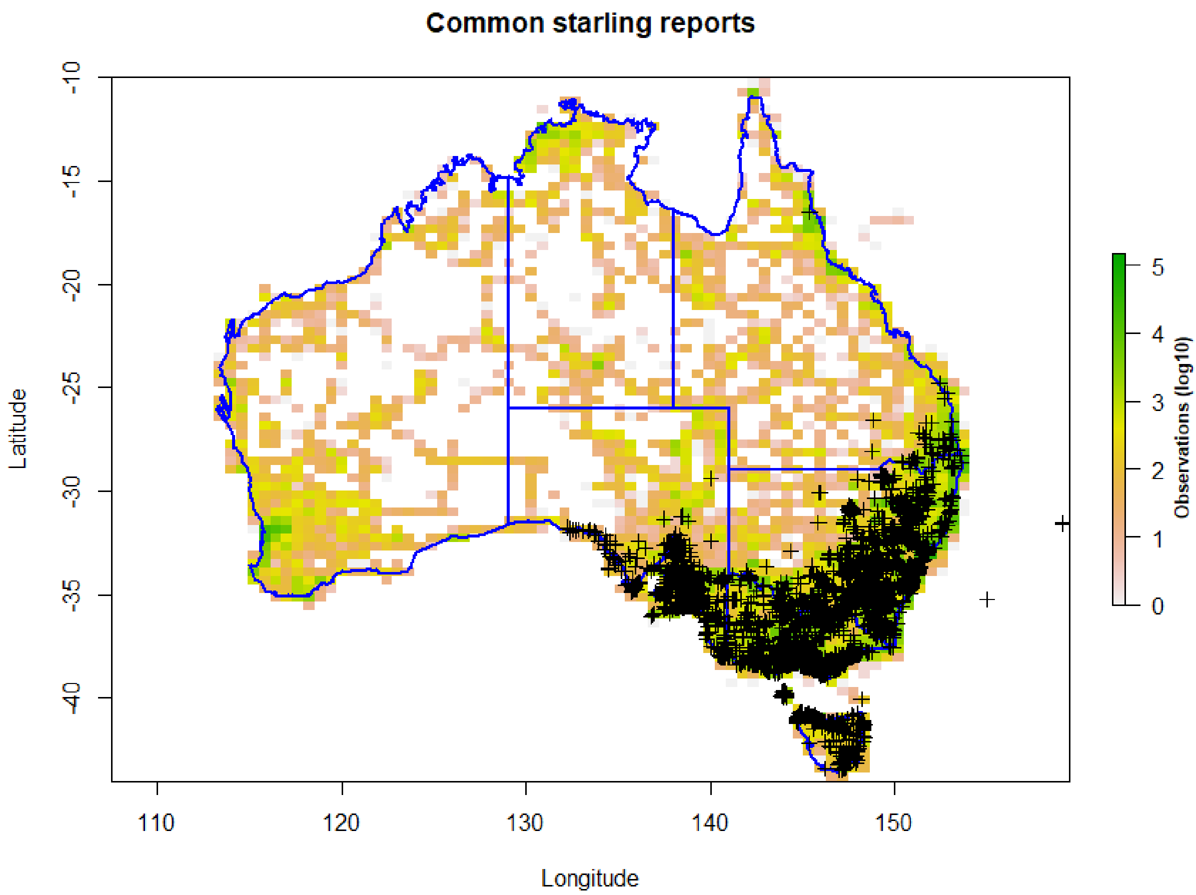

Figure 10. Intensity of bird sightings (all species) from Birdlife Australia over the past five years (coloured squares), with sightings of common starlings (Sturnus vulgaris) overlaid (crosses). Note the large area of low reporting around the border between South Australia and Western Australia. Note that the scale is logarithmic (base 10). Raster is at 0.5-degree resolution.

DEVELOPMENT AND DESCRIPTION OF ACOUSTIC SURVEILLANCE

This project and project 'Automated detection: triggering smarter, faster, better response to incursions' (P01-T-002) have developed passive acoustic surveillance (PAS) technology for detecting common starlings, a key development in filling the identified surveillance gaps. Note that although described as 'passive', the technology as deployed in surveillance is very much 'active'. To elaborate, it involves active and targeted deployment of a sound-recording pest-recognition surveillance device. The system provides remote connection to devices for algorithm and firmware updates, microphone testing and soundscape recordings. A highly accurate and precise bioacoustics-based starling call recording and recognition system has been produced and field tested. The detection algorithm is based on the one-dimensional Convolutional Neural Network (CNN) method and is embedded in a routine that records signals from the microphone, classifies signals within the audio stream in real time, and outputs results and example snippets of putative target signals ready for communication back to base. The algorithm is being refined using training from real sound recordings from PAS devices in Western Australia. Results

The recording units have been tested and validated through playback trials, with microphones detecting starling playback calls at up to 130 m. PAS towers were successfully deployed for ongoing starling surveillance at Bremer Bay and Gibson — sites of previously recorded incursions of starlings into Western Australia. The deployments have demonstrated successful end-to-end communication of acoustic signals over an internet of things (IoT) network to cloud servers, accessible via a user interface. The CNN algorithm has been retrained for Asian black-spined toad and also made available to other conservation practitioners for detection of acoustically identifiable threatened species.

CASE STUDY 2 – DETECTING INCURSIONS OF ASIAN BLACK-SPINED TOADS

The Asian black-spined toad (*Duttaphrynus melanostictus*) is a species of biosecurity concern to Australia, with a high approach rate as a hitchhiking stowaway (Tingley et al. 2018). There are no known populations of the toads in Australia. An assessment identified areas along the northern and eastern coastlines as being most suitable for establishment, although the extent of competition with existing cane toad (*Rhinella marina*) is unclear. The ABST has a poison gland much like the cane toad.

LIKELY POINTS OF ENTRY

ABST are regularly detected at our border, after hitchhiking within imported baggage and shipping containers. Port surrounds and container handling facilities have been identified as high-risk areas for the introduction of ABST. Such container handling facilities are not necessarily adjacent to ports, and in the case of Brisbane, occur in industrial areas adjacent to the wetlands of Oxley Creek, an area of apparently optimal habitat.

SPATIAL GAPS IN SURVEILLANCE

Through citizen science initiatives such as FrogId we have some confidence that a new incursion of ABST will be detected eventually, but perhaps only once it spreads to within earshot of suburban areas. The trigger for this to occur would most likely be a citizen user of FrogId who is familiar enough ('in tune') with the frog fauna of their neighbourhood to notice an unfamiliar call, and to then use the FrogId reporting app to make and submit a sound recording. Port surrounds are generally not accessible for surveying by citizens, either because of issues of trespass, or limited walking infrastructure. Wetlands are also often difficult to access, either on foot or via watercraft, and this limits the citizen surveillance possible. An exploration of citizen reporting of amphibians in the western suburbs of Brisbane reveals strong spatial clustering, with clusters of observations seen at the Brisbane Botanic Gardens and Karawatha Forest in the south-east (Figure 11). The gap in the observations of particular note encompasses the industrial areas of Rocklea and the wetlands of lower Oxley Creek (in the centre of Figure 11). Hence it appears that an ABST incursion arising from what we think are some of the most likely entry and establishment points could pass undetected through a passive citizen-based surveillance network. Hence, more sophisticated and targeted detection tools are needed.

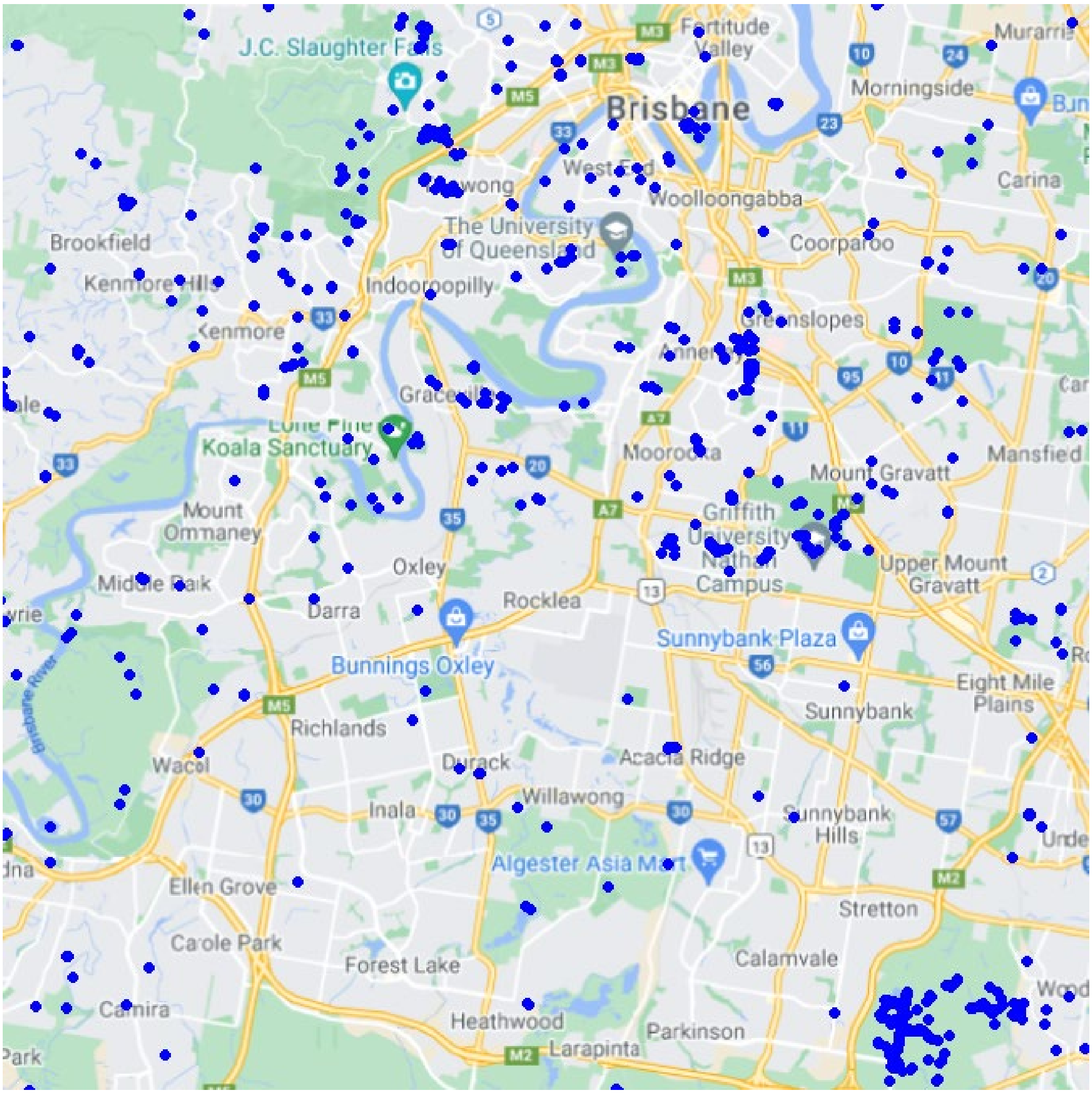

Figure 11. Distribution of ALA citizen-generated amphibian records across south-west Brisbane over the past five years.

DEVELOPING TARGETED APPROACHES

The project has explored two forms of active surveillance for ABST. First, an extension of the PAS approach applied to starlings, and second the development of acoustic cage traps based on a modified form of the Toadinator®. This was a collaborative research partnership with Bogor Agricultural Institute (IPB) University in Indonesia and James Cook University.

In deploying the acoustic cage traps in Queensland, attention focused on major ports and industrial areas where shipping containers are first opened within Queensland (where the habitat is most likely suitable for ABST). Twenty traps were deployed during the most favourable (wet) seasonal conditions for ABST breeding, and spread across the Torres Strait (considering ABST is naturalised in Papua New Guinea and movement of goods south into Qld is high risk), Port of Mackay, Port of Brisbane, Oxley industrial area (Brisbane), and the Oxley Wetlands (Brisbane). Traps at the last location were partly managed by volunteers. No ABST were detected, providing a degree of confidence that the species is not yet present in Queensland, although the traps were not optimally configured. Indeed, subsequent research in Indonesia (where the toad is native and abundant) found that the wire mesh used in the prototype acoustic traps was too coarse and allowed toads to escape. Hence, traps need to be retrofitted with finer scale (10 mm x 10 mm) wire mesh. Trials of the prototype trap in Indonesia with average frequency and high frequency toad call lures, coupled with camera traps showed that toads responded to the lures, although capture rates were low and comparable to non-target species. Comparing toad responses to average and low frequency audio lures also showed low responses. Toad activity in proximity to audio lures was highest in close proximity to water bodies, suggesting that traps need to be located very close to water or preferably placed in shallow water (if animal welfare compliant) to be most effective. Research also suggested that camera traps be used with acoustic traps to detect movement and that visual searching of high-risk sites during summer rainfall events is worthwhile. Trap and audio lure refinement, studies of toad movement and breeding and characteristics of breeding sites is ongoing in Madagascar in a collaboration between Biosecurity Queensland and the Madagascar Flora and Fauna Group. The research in Indonesia developed a library of 219 toad calls from 30 animals. These were used to characterise the acoustic properties of the calls and generate audio lures based on local calls for the prototype traps. These calls also contributed to the automated artificial intelligence (AI)-based acoustic recognition for toads using the CNN used for common starlings (previous section).

The modified Toadinator® Trap provides an active surveillance mechanism that can be deployed by authorities in high-risk locations. The ABST research and monitoring by Biosecurity Queensland is being promoted via the 'Pest Prevention StoryMap' (https://qgsp.maps.arcgis.com/apps/MapSeries/index.html?appid=3a402e3c72af42259c7c30a87395d398). We note that there were no FrogId submissions specifically arising from the locations and nights that the acoustic traps were in place emitting (loudly) ABST calls. This confirms that these locations, considered to have a higher risk of entry, are not subject to adequate surveillance by citizens. That is not to say that citizens cannot play a more active role in providing surveillance in these areas. Indeed, citizens were used to monitor the traps in the Oxley Wetlands as part of this study.

SUMMARY AND CONCLUSIONS

MAJOR FINDINGS

The surveillance provided by citizens would be considered effective for detecting and reporting exotic vertebrate pests from most taxonomic groups and in most locations considered to have a high risk of entry to Australia. Citizens have already formed self-organised communities of practice that are dedicated to sharing sightings and identifying most of Australia's vertebrate species. This provides good surveillance for exotic pests, should they enter. Indeed, we found that citizen surveillance has successfully prevented a number of incursions of exotic pests, and we expect that to continue. Regarding the risk of invasive vertebrates, we found that although the potential number of exotic vertebrates not yet in Australia is very large, an analysis of entry pathways demonstrates that the expected type of pest likely in new incursions and the location of entry are actually much more constrained. In fact, now and into the future, unassisted self-introductions to Australia will be uncommon (stowaway Asian black-spined toads an exception). The human hand will again play a major role in new introductions, as with the past deliberate release efforts of acclimatisation societies. However, most future incursions will be vertebrate species kept as pets that have escaped or been deliberately released. The range of species kept legally is diverse (e.g. from exotic African fish to Indian parakeets), and in the case of the reptiles often includes illegally kept species (e.g. boa constrictors). The number of cases of illegal keeping is probably heavily determined by the quantum of compliance effort invested across all jurisdictions.

As most new incursions of exotic vertebrate pests will arise from humans, the strongly spatially biased observation effort of passive citizen surveillance around where people live is nearly optimal. We also found that the process by which sightings are shared within what are essentially communities of practice dedicated to species identification greatly increases the likelihood that a genuinely exotic species will get reported to authorities at least once. This leads to our argument that there is a limited set of situation/species combinations where it appears that data mining social media could improve existing citizen surveillance. Data mining social media presents numerous challenges ranging from technical feasibility through to the social licence to operate. If we are to data mine social media data to help detect introductions of vertebrates, it needs to add value and be trusted. Developing and provisioning open-source tools for people to use for species identification seems like a good place to start. Indeed, we argue it is probably better to invest resources to improve the quality of voluntary contributions, including efforts to reduce the number of false-positive sightings, which can waste scarce resources.

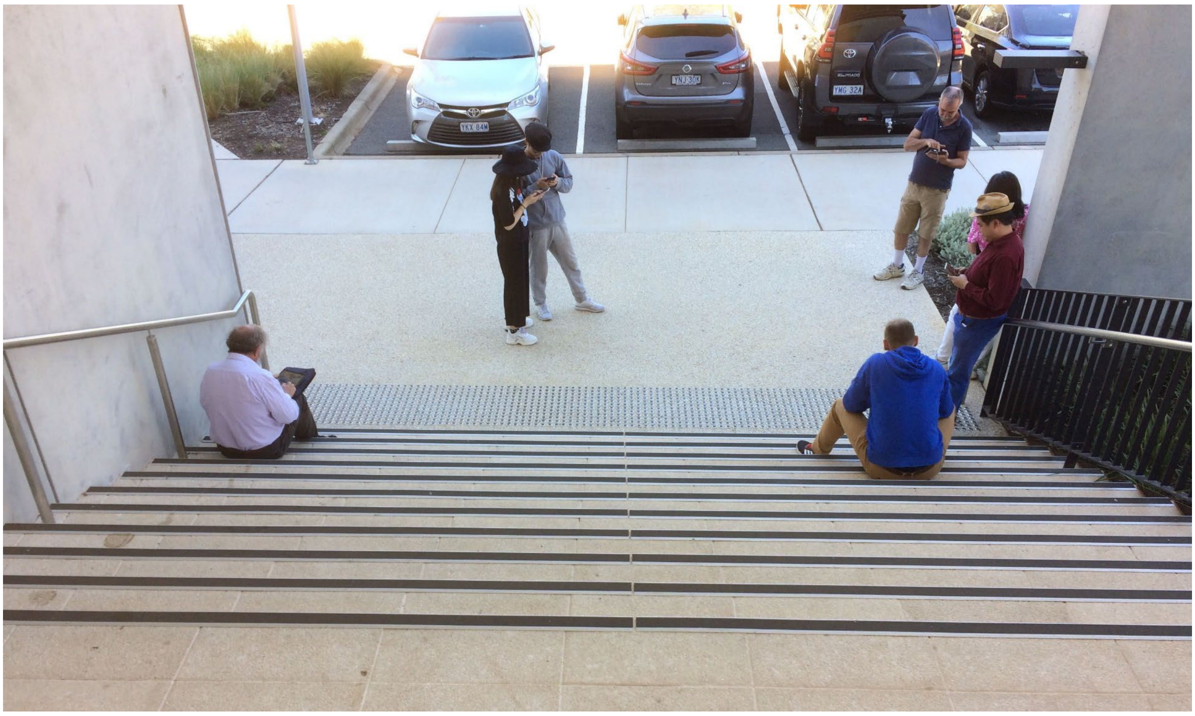

Figure 12. Citizens deeply engrossed in the hunting of Pokemon. An obvious question is whether we can redeploy these energies to searching for vertebrate pests out in the 'real' world? Source: Peter Caley.

Despite the massive observational capability that citizens offer, there remain some notable surveillance gaps relating to physical species detectability, sighting reporting probability, and citizen access to locations. First to detectability. Citizen-reporting platforms are particularly focused on sharing photographic images, both sharing the sighting but also crowdsourcing species identification. This generates a strong bias against sampling species that are difficult to photograph despite being seen (e.g. difficult photographic conditions such as night-time), difficult to see (e.g. shy and cryptic species), or in environments that are difficult to access. Aquatic environments are particularly challenging to access and see potentially invasive species, let alone obtain high-resolution wildlife photographs. This hampers the surveillance power of citizens to detect incursions of invasive fish. That said, citizens have been the first detectors in most cases of exotic invasive fish, but not in a timely enough manner. Wild deer and wild pigs are invasive species that are difficult to photograph, as sightings are often fleeting and at night. Frogs are an exception, in that although they are generally nocturnal and often difficult to see and photograph, but they are readily identified by their calls, and the FrogId App capitalises on this.

Second, the issue of the probability of a sighting (or audio record) being reported. This is a function of a number of factors, including the motivation to share, that in turn is influenced by a range of factors including aesthetics (reporting biased towards the big, bright and beautiful), novelty of species (‘you won’t believe what I just spotted’), and seeking taxonomic identification (‘What is this, could it be an exotic?’). The number of shares is a key driver of whether a report of the sighting makes its way to authorities. The more people who view the sighting, the higher the chances at least one person will act. In the case of wild deer and pigs, for many people the novelty value of a sighting is low as these species are abundant and widespread in Australia. So although management agencies are still very interested in effective surveillance, the reporting probabilities of citizen sightings appears low. In contrast, truly exotic species are more like to generate a citizen report (even if a photo is not obtained) given a sighting. The FrogId App takes the audio recording directly to the taxonomic experts for species identification.

Third, legal access for citizens to undertake observations can be limited. In many cases this is not a biosecurity surveillance issue, as the area in question is not a high risk for entry of exotic species. The lack of access to areas adjacent to high-risk points of entry such as around ports and container handling facilities can be an issue. We found this to be the case for the risk of entry of Asian black-spined toads.

In terms of the effectiveness of existing citizen surveillance for the mammal, bird, reptile and amphibian and fish vertebrate groups, we found the following for mainland Australia. For truly exotic mammals, we expect few if any future self-introductions to occur, as the days of deliberate introductions by acclimatisation societies are well and truly gone. Those introductions that do occur will be due to escapes from captivity. These will almost inevitably be in close proximity to civilisation with its associated high human observation intensity. Furthermore, the novelty of the exotic taxa will ensure a very high reporting rate. In short, citizen surveillance has the timely detection of exotic mammal incursions well covered. As noted previously, for invasive mammalian pests that are well established and no longer considered exotic (e.g. wild deer and pigs), citizen surveillance is not as sensitive for detecting new incursions. We note that pest-free offshore islands (e.g. Barrow Island off the coast of WA) are special cases in terms of their vulnerability to invasion and the coverage the citizen surveillance provides, and our findings won’t necessarily apply.

For exotic birds, self-introductions of pest species are clearly possible either as hitchhikers (e.g. Indian house crows arriving on ships and drill rigs) or flying unassisted (e.g. Canada geese from New Zealand). Birds, however, are the one group for which the spatial intensity of citizen surveillance extends well beyond the urban environments. The network of citizen birdwatchers is far-reaching, and regularly reports on sighting of vagrants, of which nearly all are of no biosecurity concern. The network has previously demonstrated that it has the ability to detect incursions of unwanted pest species such as Canada geese in a timely manner, and to track their movements sufficiently closely to enable an effective biosecurity response. The data streams arising from the birdwatching community are regularly detecting escaped aviary birds, for which the citizen observation effort is optimised for risk management. The question for authorities is really one of knowing when to act on sightings, rather than questioning whether such citizen surveillance is adequate. It almost certainly is for most cases.

An example of demonstrable ‘market failure’ in the surveillance sensitivity of citizens for detecting exotic birds is the spatial gap in citizen surveillance for common starlings entering Western Australia. This underpins the need to develop targeted acoustic surveillance tools. There are also costs associated with the numerous citizen observers and their variable identification skills, in that limited government resources can be diverted in following up and responding to false-positive reports arising from species misidentifications from relatively untrained citizens. Education campaigns that assist with the correct identification of invasive species of concern, and the correct identification of vertebrates in general could help reduce such wasted resources while improving the surveillance sensitivity of citizen observations.

The PAS technology being developed in this project for starlings (with more details available from sibling project P01-T-002) is a key development in filling such a surveillance gap. This has involved the successful deployment of permanent PAS towers for starling surveillance achieved at Bremer Bay and Gibson – sites of previously recorded incursions of starlings into Western Australia. The deployments have demonstrated successful end-to-end communication of acoustic signals over an internet of things network to cloud servers, accessible to managers via a user interface, therefore enabling a timely control response to detected incursions. The CNN has been retrained to detect Asian black-spined toad calls to assist in surveillance efforts for this invasive pest.

For reptiles and amphibians, again the surveillance effort of citizens is largely optimal for detecting the most likely areas of incursions. Citizens are highly engaged in the surveillance of frog species, for which using audio identification by FrogId overcomes challenges of obtaining sightings and photographs (the preferred sharing medium). Through citizen science initiatives such as FrogId we have some confidence that an incursion of *D. melanostictus* will be detected, but perhaps only if it occurs within earshot of an urban incursion point. The modified Toadinator® Trap developed as part of this project can be deployed to provide a more active and targeted surveillance in locations considered to be high introduction risk. Trap refinement and deployment is ongoing, as is the collation of a library of toad calls. The research and monitoring by Biosecurity Queensland is being promoted via the 'Pest Prevention StoryMap' (https://qgsp.maps.arcgis.com/apps/MapSeries/index.html?appid=3a402e3c72af42259c7c30a87395d398).

The contribution by citizens to our knowledge of the world's biota is increasingly recognised (Chandler et al. 2017). Here we have highlighted the important role of citizens, through their contribution to general surveillance activities. Furthermore, we have described and illustrated methods for making quantitative statements based on such general surveillance activities.

IMPLICATIONS

Australia's best defences against future invasions of exotic vertebrate pests involve harnessing the eyes, ears, knowledge, cameras, microphones and smartphones of its citizens. The combined surveillance power of these methods of detection is immense, but only if the detections are converted into timely reports and false-positive identifications are kept at a manageable rate (see caveat above). This relies on citizens being in touch with the natural world, and aware of the importance of reporting what they reasonably suspect to be exotic species to the appropriate authorities. It may appear tempting to remove the onus on reporting from citizens by data mining social media feeds, though we consider this to be of questionable value over the existing situation.

Citizen surveillance, powerful though it is, doesn't provide surveillance of sufficient sensitivity for all species in all situations. For example, authorities can't rely on citizen surveillance for the timely detection of incursions of vertebrate pests such as wild deer and feral pigs that are cryptic and difficult to photograph. Furthermore, many citizens would consider observations of wild deer and feral pigs to be trivial and not worth reporting.

In difficult-to-access aquatic environments, where the entry of exotic pests is sufficiently high, there is a need for targeted, active surveillance measures. Monitoring eDNA in high-risk locations would be the obvious first port of call. Likewise, the deploying remote acoustic monitoring devices for starlings and other audible invasive pests in high-risk locations where citizen surveillance is sparse, and devices for trapping exotic toads in high-risk locations where citizens can't access.

BENEFITS AND CHANGES TO ON-GROUND MANAGEMENT

Our research provides considerable benefit in demonstrating where and for what animal groups citizens are already doing a surprisingly good job of undertaking surveillance for exotic vertebrate pest species. This is of considerable benefit in that it allows precious surveillance resources to be devoted to the gaps in the surveillance cover citizens provide. The research into the habitat preferences of *D. melanostictus* and developing acoustic trapping technology is helping Queensland to target surveillance effort spatially, and to deploy effective surveillance within these areas. Deploying acoustic detection devices for the common starling in Western Australia will assist that state to remain starling free.

NEXT STEPS

With regard to citizen surveillance activities, in the short term authorities can put efforts into:

- Awareness raising of the importance of reporting sightings of suspected exotic vertebrate species. As well as promoting the existing hotlines, this could take the form of advertising on social media, or establishing a social media presence that would be appealing/engaging enough to generate a significant number of followers. Citizen engagement around 'blind spots' for pest entry (such as identified for ABST and the Oxley Creek wetlands in Brisbane) would seem sensible while targeted devices continue to be developed. More work is required to fully use a network of frog watchers.
- Engaging with the custodians of online data streams to streamline the reporting of sightings of exotic vertebrate pest species. The ALA, iNaturalist and eBird are obvious organisations to start conversations with. Authorities should be focusing on a both an alert' and 'permitted' list approach for identifying incursions of exotic vertebrate pests from citizen reports. The permitted list, as a first cut, should be based on the Australian Faunal Directory. It makes most sense for the screening of data streams that are incorporated into the ALA to occur in-house, based on an agreed method of alerts. We advise against using an alert list in isolation, as history strongly suggests we are not particularly good at predicting which species will be pests and which won't.

In the longer term, the ability of citizens to identify and the willingness to report potentially exotic vertebrate species is strongly influenced by their interest in the natural world around them. This can be increased by:

- fostering an interest in natural history through the public awareness campaigns and the education system
- improving the coverage and quality of citizens' identifications (and hence ability to detect exotic invasive species) by improving the access and awareness of platforms to aid identification (e.g. crowdsourcing platforms, online keys, image classifiers).

With regard to targeted surveillance activities, from a technological viewpoint, decisions need to be made on whether to continue development of the modified Toadinator® trap (e.g. testing different acoustics and trap design) for targeting *D. melanostictus*, or whether to put more effort into developing more sophisticated acoustic surveillance devices for deployment into high-risk areas. Automation is particularly desirable as capacity for on-ground deployment of biosecurity staff is limited. There appears to be exciting scope to use technology being developed to detect starling calls to ABST, particularly using artificial intelligence technology. A network of automated acoustic devices, located at key high-risk points of entry, could provide a much-needed boost to our ABST detection capability. When combined with eDNA and passive citizen-based surveillance, the probability of early detection of ABST could be significant.

With regard to remote acoustic monitoring of starlings, for locations where citizens aren't providing adequate surveillance for starlings in south-eastern Western Australia, deployment of PAS towers would seem prudent. Some refinement of the of the method is required, including:

- completing statistical modelling to investigate influence of abiotic variables on detection radius
- undertaking ongoing verification of false-positive signals from Bremer Bay and Gibson towers, such as investigating the source and possible fix of 'noise' returned intermittently from towers.

NEW KNOWLEDGE GAINED

The project has demonstrated that remote acoustic surveillance for common starlings is possible. This is a major development as the calls of starlings are particularly challenging. There have been many learnings in getting to this stage, with key highlights including:

- successful installation of permanent passive acoustic surveillance towers for surveillance of the common starling achieved at Bremer Bay (April 2022) and Gibson (May 2022)
- PAS towers operational from day of installation, with proven end-to-end communication of acoustic signals over Telstra NB IoT network to cloud servers and available via the user interface as per design
- sensitivity (detection range) of recording units investigated through playback trials, with microphones detecting starling playback calls up to 130 m
- proven remote connection to both devices for algorithm and firmware updates, microphone (gain) testing and soundscape recordings. We remotely downloaded about two hours of field recording over NB IoT network to cloud to validate playback investigations. These represent additional features beyond the original scope and delivered by project partner DKB Solutions Australia for no additional cost.
- a highly accurate and precise bioacoustics-based starling call recording and recognition system has been produced and field tested. Key to this was the design and implementation from a Senior Research Engineer (Thomas Rowntree) at the Australian Institute of Machine Learning. The detection model was produced by the one-dimensional CNN method and is embedded in a routine that records signals from the microphone, classifies signals within the audio stream in real time, and outputs results and example snippets of putative target signals ready for communication back to base.
- installation of desktop run-time CNN code in Adelaide enabling ongoing retraining of Model_2 with ‘real life’ false positives returned from PAS towers in Western Australia and archived recordings from SongMeter units
- the first version of a similar bioacoustics-based detection system for the Asian black-spined toad has been trained on recordings provided by a global network of collaborators. These include recordings made in India, Indonesia and Madagascar. The output model (‘Model_0’) is ready for a small-scale field test in a habitat where it will be challenged with the calls of other frogs and signal sources, as well as overlapping calls of the target species.

The research into using acoustic cage traps targeting *D. melanostictus* has shown that the method works despite a low success rate in preliminary trials in Indonesia. Refinements such as smaller mesh size, better placement of traps (closer to water) and use of camera traps and/or sound recording devices could greatly improve trap success.

The research has identified just how effective citizens are for reporting sightings of exotic vertebrate pests, particularly from areas near where they live, for which the risk of introductions of new pest species is often greatest. The communities of practice that have grown around the ability to share sightings online strongly suggests that recognising citizens as the best form of surveillance will likely continue for many pests in numerous locations.

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*Note: bold references indicate project outputs. Other CISS and IA CRC publications are marked with an **

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