Expanding general surveillance of invasive species by integrating citizens as both observers and identifiers

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Abstract

Expanding general surveillance activities can improve the detection of invasive species when eradication remains feasible. Traditionally citizens report observations to government agencies and mobile-phone-based tools provide incremental submission and processing efficiencies. However, citizen-reported data has a high proportion of false positives and diagnostics labs are not resourced to process large observation volumes.

We demonstrate 'Find-A-Pest' a partnership model whereby citizens, including Māori groups, and industry representatives both contribute observations and undertake identifications. We combine a mobile-phone-based app, database, and content management system with data linked to iNaturalist NZ. We present data from a 3.5-month period of case studies that assessed the effectiveness at delivering improved general surveillance outcomes.

Installed by 497 users, there were 471 observations of 176 taxa submitted by 74 individuals. In combination citizen and industry identifiers processed 99% of observations with only 1% (5 submissions) forwarded to Biosecurity New Zealand. Citizens' identifications were comprehensive and rapid: 79.4% of submitted observations were identified by citizens with 57.3% and 95.4% of these processed within an hour or day, respectively. Citizen identifications were correct 95.5% of the time. Many observations (56.1%) were of high priority species profiled as in app fact sheets.

Find-A-Pest demonstrates that general surveillance partnership can effectively distribute identification effort thereby reducing false positive loads within government diagnostics labs. Find-A-pest was stable, robust, and endorsed as fit for purpose by users. Achieving biosecurity outcomes, such as early detection to facilitate eradication, will require a much larger scale participation in Find-A-Pest. We suggest applying Behaviour Change Theory to expand participation across diverse groups in the future.

Keywords: Biosecurity; Passive surveillance; Citizen engagement; Invasive species; Information systems; Phone applications; Crowdsourcing data

Author contribution: SP conceived the project, all authors contributed to stakeholder design. SP/JS designed and analysed case studies. SP wrote manuscript with contributions from all authors.

Key message:

- Biosecurity surveillance is vital to protect natural, productive, and urban environments from invasive species. General surveillance by the public is an important component of the surveillance system but it can be resource intensive.
- We co-designed (with government, industry, and Māori) a mobile phone-based general surveillance tool called Find-A-Pest. This involves the public in both the submission and identification of samples.
- Case studies show that in-app fact sheets concentrated public effort on species of interest. The public, via iNaturalist, were capable of quickly and accurately identify observations.
- Find-A-Pest has shown that new integrated mobile phone-based apps can effectively support general surveillance outcomes and reduce pressure on government funded surveillance services.

Introduction

Biosecurity is vitally important to protect natural, productive and urban environments from new invasive pests. As an island nation New Zealand can implement a strict biosecurity system that is not feasible in continental situations. Public contributions to the biosecurity system of New Zealand are fostered by the concept of a ‘team of 4.7 million’ as part of the Biosecurity 2025 strategy (MPI 2016). Pest surveillance is an important activity that contributes positive outcomes at different stages of the biosecurity continuum, i.e., to prevent the entry, establishment, and subsequent spread of invasive species (Hulme 2014). Here we discuss surveillance in the context of the International Plant Protection Convention’s (IPPC) surveillance standard (ISPM 6. 2018) that defines surveillance activities as either specific or general. S*pecific surveillance* (sometimes referred to as active) includes official activities by a National Plant Protection Organisation (NPPO) whereby data is actively gathered about specific pests or pathways of concern over defined periods of time. For example, Biosecurity New Zealand (a business unit of the New Zealand Ministry for Primary Industries with responsibility for biosecurity) conducts 13 specific surveillance programmes that target risk taxa or pathways, such as gypsy moth (*Lymantria* spp.) (MPI 2012). *General surveillance* is the process by which information about a pest species (e.g., its presence at a location) is acquired by an NPPO from a variety of sources, e.g., government agencies, research institutions, industry, general public, or published/unpublished literature. Hester and Cacho (2017) go further and describe general surveillance as a continuum with public reports defined as ‘passive surveillance’, reports from community groups or citizen science groups as ‘citizen science’, and reports from the primary sector producers or associated intermediaries, such as consultants, as ‘general surveillance’. Whilst we appreciate the benefits of segmenting and targeting audiences with appropriate surveillance messaging and tools, here we use the IPPC definition of general surveillance in our description of co-developing a tool, called Find-A-Pest. Hence, we include the passive, citizen science, and general surveillance user groups of Hester and Cacho (2017) within our working definition of general surveillance.

General surveillance has been adopted in other countries to monitor the spread of a diverse assemblage of recently established high-profile invasive species. Examples include brown marmorated stink bug (*Halyomorpha halys*) (Hancock et al. 2019; Maistrello et al. 2018; Malek et al. 2018), Asian tiger mosquito (*Ades albopictus*), Rose-ringed parakeet (*Psittacula krameria*) (Vall-llosera et al. 2017), Sudden Oak Death (*Phytophthora ramorum*) (Meentemeyer et al. 2015), and as well as various pest plants (Gallo and Waitt 2011; Laidlaw et al. 2016) in terrestrial environments. Most projects rely on visual observations by an observer, but some have been highly successful at incorporating sample collection to facilitate molecular identification (Biggs et al. 2015; Meentemeyer et al. 2015; Meyer et al. 2019). Some programmes do not target the public but empower organisational employees to contribute to biosecurity surveillance. These have also proven successful with employee general surveillance effort responsible for 95% of all new organism detections on Barrow Island (Australia) (Thomas et al. 2017).

Beyond monitoring established pests, general surveillance supports the detection of new incursions of exotic species to a country or region/state within a country. For example, 25 of 34 post-border detections of new forestry pests in Australia were made through general surveillance, seven as the direct result of public reports (Carnegie and Nahrung 2019). Similarly, between July 2005 and June 2008 the general public generated 355 of the 728 exotic organism detections (these do not represent establishments) reported via the Pest and Disease Hotline in New Zealand (Froud et al. 2008). This rate was closely matched in 2008 and 2009 where 205 of the 453 reports were from the general public (Froud and Bullians 2010). Clearly a large proportion of new detections are created via general surveillance, however the process is often inefficient. The 355 observations reported between 2005 and 2008 (Froud et al. 2008) represent a 2.4% positive rate from 14,546 reports submitted. New Zealand's NPPO had valid concerns that new technologies that enhanced the efficiency of observation submission could overwhelm their diagnostic resources. Furthermore, there are inherent public reporting biases towards species that are visually distinctive, e.g., large and colourful (Caley et al. 2019). Hence, the value of general surveillance to the overall biosecurity system is context dependent. For example, general surveillance is likely to be more successful for monitoring the spread of a recently established highly distinctive species, but less likely to be successful at detecting a non-descript exotic pest early enough to facilitate eradication. Carnegie and Nahrung (2019) note that most exotic pests or pathogens of trees detected in Australia between 1996 and 2017 were detected after the point that eradication could have been contemplated. But, there are also examples where high impact pests reported by the public have led to effective eradication, such as fall webworm (*Hyphantria cunea*) and red imported fire ant (*Solenopsis invicta*) in New Zealand (Froud et al. 2008). Early detection is crucial as it is the most important predictor of eradication success (Brockerhoff et al. 2010). Maximising the beneficial outcomes from general surveillance requires a simple process that both focuses the attention of the observer on high-priority species and reduces the identification burden posed by the high false positive rate of public reporting.

New Zealand had 4.963 million mobile handset connections to the internet in 2018 (Statistics New Zealand. 2018), more than its resident population which is probably a function of international tourist visitors. Mobile phones can increase the speed and quality of surveillance reporting by automating information transfer to minimise potential user error, e.g., date/time, location, and image are provided by the device (Newman et al. 2012). Many mobile-phone-based general surveillance tools are now available for monitoring the spread of established species or detecting new incursions of exotic species, e.g., bugMap (Malek et al. 2018). When conceptualising Find-A-Pest in 2016 all current biosecurity surveillance applications that we were aware of relied on expert validation of data by the project owner (individual or company). This was a task often delegated to a team of expert diagnosticians, often paid public-sector employees (e.g., Observatree and MyPestGuide™ Reporter) or a closed group of experts (e.g., iRecord (Roy et al. 2015)). To overcome this challenge we proposed a partnership model (Grant et al. 2019), whereby government, industry and the community contributed to both the submission and validation of observations submitted. A variant of this approach now seems to be considered by others, e.g., Mosquito Alert, who are developing a community identification approach (Palmer et al. 2017).

Here, we report on the design, development and case-study testing of Find-A-Pest in New Zealand. Find-A-Pest is a biosecurity surveillance tool designed as a partnership between government, industry, and community groups. Its objectives were to test whether mobile phone technology can be used to increase the accuracy, consistency, focus (on high priority invasive species), and eventually the volume, of general surveillance in New Zealand. Importantly we trialled a distributed system of diagnostics to reduce the pressure on professional diagnostic services within New Zealand's NPPO. We report on the outcomes of a series of case studies and evaluate the performance of the tool and feedback from users.

Methods

Find-A-Pest Partnership

Find-A-Pest is a partnership between central and regional government, primary producers, Te Tira Whakamātaki (Māori Biosecurity Network, Māori are the indigenous people of Aotearoa/New Zealand) and iNaturalist NZ, to improve general surveillance reporting (Grant et al. 2019). The partnership increases public and industry participation in biosecurity, which is an aim of the Biosecurity 2025 strategy (MPI 2016). Specifically, primary producers, regional government staff and their contractors, and the public are the target audience to contribute observations of potential biosecurity threats. Furthermore, Find-A-Pest works with citizens and industry representatives to identify these observations at different levels depending on the potential sensitivity of the data. Firstly, Find-A-Pest works in close collaboration with iNaturalist NZ (https://inaturalist.nz/) that is an open community of individuals interested in natural history that already contribute and identify biodiversity observations throughout New Zealand. iNaturalist NZ users can view observations that are likely to represent a low biosecurity risk and provide identifications and commentary that are returned via Find-A-Pest to the user. Industry and regional government biosecurity managers contribute by screening observations of unknown or higher priority threats (see below for dataflow). Screening sends suspected positives of high priority threats to Biosecurity New Zealand as the NPPO and low risk observations can be forwarded to the iNaturalist NZ community for further identification. This partnership was designed to reduce the burden on the professional diagnostic services of the NPPO so that higher volume general surveillance could be sustained in the future.

Technology of Find-A-Pest

Find-A-Pest is modelled on the concept of a single ‘skeleton’ for all, that uses different ‘content skins’ depending on the users’ subscription to available sectors within the app. This approach allows delivery of fit for purpose content that meets the information need of a wide variety of stakeholders. Conceptually there are three types of users within Find-A-Pest: 1) site administrators, 2) identifiers, and 3) app users. Site administrators are Find-A-Pest project staff who control the content and dataflow within Find-A-Pest, which includes:

- Adding species profiles and determining the data flow of any observations submitted via the profile page of a species (see data flow below)
- Creating and modifying individual sector profiles (e.g., forestry, kiwifruit, weeds) and populating these with relevant species profiles.
- Creating geographic areas and assigning species profiles so that content reflects regional priorities.
- Assigning users rights to the identifier website.

Identifiers from industry have access to an identifier website that is a private website tool for rapid assessment of potential biosecurity risk (see data flow below). Most industry identifiers are biosecurity managers with their respective organisations; they are not taxonomists but have varying levels of domain knowledge about high priority pests relevant to their industry. Users are those that install the Find-A-Pest app and submit observations via their iOS or Android phone. Example screen shots of core Find-A-Pest functionality are shown in Figure 1.

The core of the Find-A-Pest structure is a Couchbase database that is hosted by Amazon Web Services (Figure 2). The Couchbase is the ultimate repository of observations and app content. A Find-A-Pest user hosts a subset of the database on their phone (in Couchlite) that is updated by a sync gateway when data coverage is available. Couchlite ensures that full offline functionality is available to the user, which was an important consideration of stakeholders who often work in areas with patchy cell phone coverage. Content is created and managed using Directus (https://directus.io/) an open source headless Content Management System (CMS). Within Directus a 'content skin' can be created and the fact sheets of species assigned to that 'content skin' will be visible to those users that have subscribed to it. Species fact sheets are created in Directus and include an image and text grouped under the following headings: Identification, Habitats, Similar species, Origin, and Damage. Content updates to the user's phone, data transfer between the users and the identifier website, and interactions with iNaturalist NZ, are controlled by an Application Programming Interface (API). Identity and access management are controlled by Keycloak (open source identity and access management software). Conceptually the system is designed to be specific to an individual country to ensure data integrity of potentially sensitive biosecurity observations. Currently deployed in New Zealand, the tool could work in any other country that was happy to work collaboratively with a local iNaturalist node (as we do in New Zealand) or with the iNaturalist global community.

Find-A-Pest Dataflow

Users can submit a photo of an observation via three methods; 1) via a species profile page (fact sheet) when they believe they may have seen that particular species, 2) via a blue 'camera' button that facilitates submission of photographs of anything seen by the user, or 3) by typing in a species name into a search bar to select from the list of species in the Find-A-Pest system. To guide users on what is most important to report, species profiles are organised into "content skins" of pests specific to the user's region and specified sector(s) or interest (e.g., forestry, weeds). All users additionally see the 'content skin' for the highest priority pests nationally and for their region. These species are defined by Biosecurity New Zealand and New

Zealand's regional councils that have statutory responsibilities for biosecurity at the national and regional scales, respectively. These high priority pest species can be updated in real-time whereby changes (additions, deletions, and modifications) to individual species factsheets or groups of fact sheets (i.e., a 'content skin') in the Directus CMS are immediately visible to the user if they have wifi or cellphone data coverage. This is important to ensure users can be alerted quickly towards new high priority threats that are identified.

When creating a species profile an administrator determines the dataflow of observations submitted via that species profile. Observations from profiles of new-to-New Zealand species are routed to the Find-A-Pest identifier website for pre-screening, along with unknown observations taken using the 'camera' button. The identifier then has the option to provide an identification and mark the observation as 1) complete and do not forward, 2) forward to iNaturalist NZ for further identification, or 3) send to Biosecurity New Zealand for formal identification. For the case studies (see below), our partner institutions identified 233 high priority pests (including many weeds) for inclusion on the appropriate "content skin" along with a species profile (fact sheet) page. These were a mix of high risk species not established in NZ, new to NZ species, and established but spreading species. Identifiers provide a screening service to filter out obvious biosecurity threats from existing pests and native species. They can provide a species identification or simply tag the observation with a higher rank, e.g., Kingdom, Class, Order etc, to focus the attention of subsequent citizen identifiers on iNaturalist NZ.

Observations submitted via a species profile of a taxa that is already present in New Zealand are typically routed from the user directly to iNaturalist NZ and do not appear in the Find-A-Pest identifier website. The few exceptions were pest taxa absent from some regions that are of value to some members of the public (e.g. deer, coarse fish). In these cases, regional council biosecurity staff did not want to risk further spread by making new incursions immediately public on iNaturalist NZ. All observations submitted by Find-A-Pest to iNaturalist NZ are automatically placed in the Find-A-Pest observation project (https://inaturalist.nz/projects/find-a-pest-observations). For potential new incursions to New Zealand, all information collected by Find-A-Pest about an observation is collated into an email and forwarded to Biosecurity New Zealand's Pest and Disease Hotline provider who then integrates the observation into current formal surveillance processes. In all cases, comments and identifications made by Find-A-Pest identifiers and citizen identifiers from iNaturalist NZ appear to the Find-A-Pest user on their app. This includes comments encouraging the user to add additional, more diagnostic photos to confirm an identification. Note: Observations submitted by a user following the link within a factsheet are tagged with that species name as a suggested identification. These initial identifications can be confirmed or updated by a Find-A-Pest identifier or citizen identifier from iNaturalist NZ.

Case studies

The availability of Find-A-Pest was restricted to iOS and Android users in New Zealand due to the geographic scope of the project, the relevance of the species included in the "content skins", and the participating identifiers. Find-A-Pest was trialled between February and April 2019 as part of a series of case studies involving the plantation forestry and kiwifruit industries and three local government agencies with an interest in weed surveillance (Northland Regional Council, Auckland Council, and Environment Southland). The format of each case study was designed in conjunction with each of the case study partners (Forestry and Kiwifruit and the general public via regional councils). A brief description of each case study and associated communication activities are provided in supplementary material: Appendix A.

Segmenting involved a process of identifying groups within the scope of each case study that scored (low, medium, or high) with respect to access, suitability and motivation to report via Find-A-Pest. Our process aligns with the capability, opportunity, and motivation model (COM-B) developed by Michie et al. (2011). Access was defined as people that were regularly present in areas where observations of potential pests were likely. For example, a field-based employee in a forestry company would be preferred over a desk-based position. Suitability was assessed as individuals/groups that were likely to be regular users of mobile phones or may have one as part of their job. Motivation assessed the importance a user/group might place on biosecurity and the role of surveillance. High motivation was reflected in traits such as biosecurity being a core part of their professional or volunteer work or that they were the owner of a primary production facility, e.g., farm or forest and hence it was in their self-interest to be biosecurity aware. A process of targeting and cultivating relationships was used to define who would partake in each case study and how communications with these groups would be managed. Targeting exercises were undertaken with the stakeholders of each case study group to identify the most relevant participants to include in each case study. An email request was made to all individuals that had submitted at least one observation to solicit feedback via a questionnaire (see Supplementary material: Appendix A) on their experience using Find-A-Pest and to suggest future improvements.

Uptake and system performance during case studies

Find-A-Pest was tested with an invite only beta-test group in December 2018 and made publicly available in New Zealand on 12 February 2019 via both the Apple App and Google Play stores to support the case studies. While publicly available, it was only promoted to our small case study communities. There was an almost equal split between Apple and Android users with 497 installations of Find-A-Pest (excluding beta testers as they were invited).

Analysis of results from case studies

All data collected by the Find-A-Pest app and its identifier website during the case study period was analysed in R (R Development Core Team 2017) alongside all iNaturalist NZ data (comments and identifications on the Find-A-Pest observations) from the same period. The speed and accuracy of identifications were assessed by calculating the time between submission and first identification, and the accuracy of both the first and final consensus identification (on iNaturalist NZ multiple users can contribute identifications to an observation, producing a consensus “community ID”). The accuracy of final identifications was assessed by the authors (SMP for invertebrates, JJS for plants and vertebrates). The fungal observations were identified on iNaturalist NZ by a volunteer user who is a professional mycologist and recognised New Zealand expert. Find-A-Pest identifications (user ID, initial ID, and consensus ID) were considered correct if they were the same taxon, at the taxonomic level appropriate for the provided photographic evidence. Identifications at a correct higher taxonomic level (e.g., a correct genus ID for a species), or a plausible lower taxonomic level (e.g., a plausible species ID when the photo only supports the genus), were separated from incorrect identifications. The summary of observations by New Zealand biostatus (endemic, non-endemic indigenous, naturalised) used the biostatus provided by the New Zealand Organisms Register (http://nzor.org.nz/).

Results

Outcomes from case studies

In total 471 observations were submitted by 74 users (excluding observations made by the authors and developers) during the case study period (20 December 2018 to 4 June 2019). Observation submissions were dominated by plants (78.9%) with insects, mammals, arachnids and fungi represented by 14.3, 4.1, 0.5, and 0.5% respectively (1.7% were other animal/pathogen groups and one unidentifiable photo). User observations were automatically passed to the Find-A-Pest project on iNaturalist NZ 63% of the time, pre-screened by the Find-A-Pest identifier website before forwarding to iNaturalist NZ for further identifications 33% of the time, and pre-screened and retained in the Find-A-Pest identifier website 3%, or forwarded to Biosecurity New Zealand 1%. The latter comprised five observations, which included one *Cermatulus nasalis* (a native stink bug that superficially resembles *Halyomorpha halys* (brown marmorated stink bug)), one *Monistria?* sp. (a grasshopper found dead in imported grapes), and three exotic species that were already established in New Zealand. These were an observation of a larva found in a peach (suspected to be *Coscinoptycha improbana* (Australian guava moth)), a *Harmonia axyridis* (Harlequin ladybird beetle, first detected in NZ in 2016), and *Abutilon theophrasti* (Velvet leaf, the subject of a 2016 biosecurity incursion response in NZ).

Users suggested an identification for 63.9% of the observations they submitted. By the end of the case studies, the iNaturalist NZ community had provided identifications for 79.4% of the observations that had been forwarded to iNaturalist NZ. Comments were made in addition to identifications on 17.5% of these observations and 2.2% received comments from iNaturalist NZ users but no identification. In cases where the iNaturalist NZ community moderated an identification provided by the user, this was confirmed 86.0% of the time and corrected or improved 14% of the time. Of those observations that received an identification, more than half (57.3%) of observations submitted received their first identification by iNaturalist NZ within one hour of submission and 95.4% of observations within 24 hours (Figure 4). Many (34.6%) of observations forwarded to iNaturalist NZ received two or more identifications (Figure 5). Of the Find-A-Pest observations identified on iNaturalist NZ, their consensus ("community") identifications were 85.6% at a species level, a further 7.8% at the subgenus or genus level, 2.8% at the subfamily or family level, and the remaining 3.9% at higher taxonomic levels.

There were 176 taxa recorded during the case studies using Find-A-Pest, 136 of which were identified to species or below. Of these, 54 were of high priority species selected by our partner institutions to include as species profile pages on the Find-A-Pest app as part of the different "content skins". A majority of observations (56.1%) submitted by Find-A-Pest users were confirmed to be one these high priority pest species. Of the 176 unique taxa recorded, 147 (representing 456 of the observations) could be unambiguously categorised as introduced or indigenous to New Zealand. Of these, 75.5% of the identified taxa, from 78.5% of the observations, were of introduced species that were already established in New Zealand.

We manually assessed the identification accuracy of all Find-A-Pest observations submitted to and subsequently identified on iNaturalist NZ. The great majority (95.5%) were completely correct. Of those correctly identified observations, 92.9% were identified at the species level, 5.0% at the genus level, and 1.2% at the subfamily or family level (the remainder were at higher levels, usually due to low quality submitted photos). Of the incorrectly identified observations, 15 were identifications correct at the genus level, but the species identifications given, while plausible, were not possible to confirm with the submitted photos. Another two observations had plausibly correct species or genus identifications with comments specifying that they could otherwise be relatives in another genus. One citizen identified observation was the wrong species in the correct genus (identified as *Buddleja davidii* but was another *Buddleja* species), and another was the wrong species in the correct tribe (identified as *Carduus nutans* but was another thistle, *Cirsium vulgare*). Importantly, only one observation had completely the wrong ID (a vegetative weed tentatively identified by one citizen identifier as *Viola odorata* but likely to be *Petasites fragrans*).

Feedback from users

The feedback survey was completed by 55 of the 74 people that submitted observations. Two responses were clearly attempts to obfuscate the purposes of the survey and were removed prior to summarising the results. The majority (71%) of respondents agreed/strongly agreed that Find-A-Pest was easy to use with 10% disagreeing with this statement and one individual strongly disagreeing (Figure 6). Most users (66%) agreed or strongly agreed that the ability to focus on pests relevant to their sector of interest or region was useful with 12% disagreeing with this statement (Figure 6). Similarly, 65% of users agreed/strongly agreed that Find-A-Pest was useful for learning about important pests (Figure 6). The ability to submit random observation of any species using the blue camera button deemed useful to 79% of respondents (Figure 7). Many respondents (64%) indicated they would not have submitted their observation to Biosecurity New Zealand if Find-A-Pest was not available (Figure 7). Feedback from Find-A-Pest (via industry identifiers or the iNaturalist NZ community of identifiers) did encourage 54% of respondents to submit additional observations (Figure 7). Most (75%) of industry identifiers found the tools for processing observations in the Find-A-Pest identification systems to be suitable for their needs (Figure 7).

All of the six improvements suggested by the survey (see Supplementary material: Appendix A) were considered to be either essential or somewhat essential by at least 84% of respondents with three improvements having 98% support (Figure 8). The functionality deemed most essential was the ability to receive alerts via the app of new biosecurity incursions. The suggested improvement that had the highest non-essential rating (still thought non-essential by only 16% of respondents) was the ability to reply to comments on observations directly from within the Find-A-Pest app.

Not all survey respondents completed the demographic section, however of those that did there was little ethnic diversity with 48 people identifying at NZ European or European and one as Māori (Figure 9). There was greater diversity in the age of respondents with relatively even participation between those aged 20 to 50 years and lower participation in older age cohorts (Figure 9). Most (84%) respondents had a tertiary qualification, with 34% working for a government agency, 28% within the primary sectors, 30% indicating a general interest in biosecurity and 12% identifying as self-employed (Figure 9). Most survey respondents did not live in a major urban centre with 50% from regional towns, 30% identifying as rural, and a combined 20% from Auckland, Wellington, and Christchurch (Figure 9).

Discussion

General surveillance is one of the various channels of intelligence gathering of the National Plant Protection Organisation (NPPO). To increase the scale (and potential success) of general surveillance without overwhelming NPPO resources requires the distribution of effort. Our approach to this is to incorporate citizens (via iNaturalist NZ) and industry representatives in the screening process for observations submitted. This approach reduced the number of false positives received by NPPO diagnosticians and an overall improvement in the quality of reports was achieved by targeting user attention via in-app factsheets.

Scale: Reducing the number of false positives received by an NPPO?

Our screening approach was very successful and reduced the identification burden on the official diagnostic service of Biosecurity New Zealand to just 1.1% of observations submitted to Find-A-Pest. This differentiates us from most other mobile-phone-based general surveillance initiatives where citizen involvement is limited to the role of observers/reporters or a closed group of invited 'experts'. We implemented a tiered approach where an open community of volunteer citizen identifiers (via iNaturalist NZ) screen low-risk reports of species known to be present in New Zealand. Such reports were submitted via the pest profile within Find-A-Pest, hence observers had self-identified an initial diagnosis that the citizen identifiers could then review. Such species profiles were included as educational material to improve user knowledge about current pests. Find-A-Pest identifiers were members of the primary sectors or regional councils with biosecurity training. They screened the unknown observations that were submitted from the generic camera button or potentially higher-risk observations submitted from a fact sheet of a species not present in New Zealand. iNaturalist NZ was critical to the success of this process. In particular, its open membership represents a broad and largely self-sustaining community of interest with experts in all domains of life, e.g., fungi, insects and plants, hence they provide expertise for the full range of observations submitted. Hence, they were an ideal partner to assist observers who have limited taxonomic knowledge or only knowledge in specific taxonomic domains that wanted to participate in biosecurity by reporting a broader range of potential threats. The iNaturalist NZ community self-moderates and thus a consensus of opinion can be reached amongst multiple observers. Furthermore, the open nature of the iNaturalist NZ platform with the contribution of comments and identification is an ideal method to gradually increase the collective identification skills of all participants.

Citizen identifiers responded to observations very quickly with the majority of observations that received an identification doing so within 24 hours. The validation exercise indicated that accuracy was also high (95.5%) with only one observation indicating a completely wrong identification. However, identification errors on iNaturalist NZ are often discovered by others at a future date and corrected by the user community over time. Hence, our identification error estimates from citizen identifiers here will be conservative and long-term future comments/identifications will flow from iNaturalist NZ into Find-A-Pest. Identification accuracy was impressive given that they were based solely on submitted images and that no original specimens were provided for analysis. The speed and accuracy of identifications underscored both the knowledge of the citizen identifiers and the skill of Find-A-Pest users that were supplying images suitable for a diagnosis. This can be difficult for small, obscure taxa, e.g., insects, however with time and encouragement it is hoped that regular users will improve their photography skills further allowing for an increase in the identification rate. In the few cases where citizen identification was uncertain it was either because species identification was not possible for an insect larval stage (https://inaturalist.nz/observations/25137030) or that the image did not illustrate a key diagnostic feature or was of insufficient quality (https://inaturalist.nz/observations/25927144). Hence, Find-A-Pest users would benefit from feedback through the app to encourage better image capture.

Identifications were only provided by citizen identifiers for 79.4% of observations submitted. To achieve 100% coverage of identifications would therefore require some investment in additional diagnostic services, i.e., paid staff to identify observations not dealt with by citizen/industry identifiers. One potential long-term risk of incorporating citizen identifiers is fatigue whereby volunteers stop identifying observations as they feel their contribution is undervalued. We cannot ascertain the extent of this potential issue as part of our current project, however maintaining motivation and avoiding volunteer fatigue is a known risk for citizen-based projects (Deutsch and Ruiz-Córdova 2015). Despite this we note that iNaturalist NZ has been running since 2012 and has developed a large, sustained community of identifiers that are identifying without any explicit institutional encouragement or feedback. That’s not to say that Find-A-Pest would not get more engagement from identifiers if there was some form of encouragement.

Improving the quality of general surveillance reporting

There are clear biases in the type of organisms that initiate the submission of a voluntary observation as part of biosecurity reporting. Organisms that are large, distinctive/colourful are known to be over reported (Caley et al. 2019), yet many biosecurity threats do not fit such categories. It may be possible to use these initial submissions of distinctive low priority species as a point of engagement that may result in longer-term interactions whereby a motivated group can be encouraged to report additional specific threats.

Our approach to improve the quality of general surveillance reporting focussed on the provision of factsheets within Find-A-Pest that aim to focus the users' attention on high priority invasive species. Factsheets included a mixture of high-priority pests species that are not present in New Zealand (e.g., species from Biosecurity New Zealand's priority pest and disease list (Biosecurity New Zealand. 2019)), total control weeds from regional council pest management plans, and a range of relatively wide spread common pests that affect crops of primary industry stakeholders. The inclusion of the latter was to enhance user knowledge of current pests such that they could distinguish these from invasive species not currently present in New Zealand. Over time, knowledge gained, should reduce the false positive surveillance rate of reporting common existing pest species. Furthermore, encouraging such observations may identify new host associations or distributions that are relevant to other aspects of biosecurity, e.g., long-term pest management (Froud et al. 2008). The Find-A-Pest case studies included profiles of 233 species. The majority (56.1%) of observations submitted during the case study period were species for which Find-A-Pest included a species profile. This suggests that our approach is effective at targeting user attention to species that are of most relevance to those that manage invasive species. Find-A-Pest does not currently include a messaging service to inform users about new invasive species threats in real-time. This functionality was ranked by users as an essential item for further development and is an obvious extension to the species profiles as a method for targeting user effort at high priority species.

Promoting wide-spread adoption

A biosecurity team of 4.7 Million is the catch phrase of Biosecurity New Zealand's current ten year strategy that wants all New Zealanders to do their bit for biosecurity (MPI 2016). Clearly the identification capacities within Find-A-Pest would be overwhelmed at such a scale, however greater participation is required to improve the odds that new organisms will be detected within the early stage of the invasion curve when eradication is possible. Past experience of general surveillance indicates that early detection does occur (Froud et al. 2008), but does not occur as frequently as we would like (Carnegie and Nahrung 2019). Looking forward, Find-A-Pest now needs to engage with behaviour change specialists to understand both the motivations that underpin general surveillance reporting.

User feedback

Survey respondents were generally supportive of Find-A-Pest with the majority agreeing or strongly agreeing with statements that the app was easy to use, useful for learning about pests, and that it was useful to focus on pests of interest to their region or sector. Being able to simply send random photos via the phone camera was seen as highly useful. The Find-A-Pest survey of respondents found that 54% indicated that feedback was influential and encouraged further reporting. Others have also found that feedback on the quality of citizen contributions and how such efforts contribute to project outcomes is an important motivational factor that influences on-going participation (Baruch et al. 2016). A more thorough survey of motivations after Find-A-Pest has been operational for a longer period would be beneficial, however the work to date indicates that feedback is a potentially important motivator to users and further work should look to ascertain what type of feedback is most important to users.

Case studies have shown that Find-A-Pest encourages wider and more engaged participation in biosecurity surveillance and that feedback is an important component when building engagement. This shows that Find-A-Pest has the potential to play an important complementary role to the hotline by providing an avenue to collect additional surveillance data. Most participants indicated that they would not have reported the observation directly to Biosecurity

NZ via the national pest and disease hotline. The survey did not explore the rationale for why people would not have reported in the absence of Find-A-Pest. In part, this may have resulted from the large number of pest plant observations that were of species already present in New Zealand but formally controlled by regional government agencies. Hence, observers submitting such records are providing excellent surveillance information, but this is not relevant to Biosecurity NZ that manage the national Pest and Disease Hotline.

Conclusions

General surveillance is an important component of any national surveillance system, however reports often occur once a species has established beyond the point where eradication is feasible. Improving the scale and quality of general surveillance reports is likely to improve options for eradication. Find-A-Pest is a new information and communication tool that incorporates citizens and industry representatives as both observers and identifiers of biosecurity threats. Our approach reduced the burden of identifying false positives by professional diagnosticians at the NPPO and encouraged reporting by observers that would not have engaged (for reasons as yet unknown) via existing communication channels. Our case studies have shown that our approach can increase the efficiency of general surveillance and over time may contribute to improved early detection as engagement builds. However, Find-A-Pest will only result in improved general surveillance outcomes if there is strong engagement and uptake of the tool by users. This is often a challenge for new technologies – how to encourage adoption. The Behaviour Change Wheel developed by Michie et al. (2011) has been proposed by McLeod et al. (2015) as an appropriate behaviour change system that incorporates a Capability, Opportunity, Motivation - Behaviour (COM-B) approach to improve adoption of new biosecurity practices and thus achieve desired outcomes amongst communities of interest. We believe that there is benefit in applying such behaviour change science to ensure the long-term delivery of this tool results in strong engagement across a broad cross-section of target audiences.

Acknowledgements

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Figure captions

Figure 1. Screenshots from the Find-A-Pest app. The left screen shows part of the "content skin" highlighting the highest priority weeds in the Canterbury region of New Zealand. From this screen, users can also access galleries of the highest priority national and regional pests, and switch between different sectors that they have joined. The second screen from the left shows the top of the species profile page for the wetland weed, purple loosestrife (*Lythrum salicaria*). Second from right is the observation submission screen, in this example taking a photo of a suspected purple loosestrife plant after using the "Report This Pest" button from the species profile page. Users can select to use multiple photos and can either take photos or choose them from their photo library. The coordinates of observations can be obscured with the toggle switch to hide the exact location from public view if shared on iNaturalist NZ. The right screen is the Activity screen. Selecting an observation here displays a page with the identifications(s) and comment(s), sourced from iNaturalist NZ, Find-A-Pest identifiers, or Biosecurity NZ diagnostics staff (depending on the species).

Figure 2. Overview of the components of the system designed by Cucumber (design and software company based in Tauranga, New Zealand) to run Find-A-Pest. API = Application Programming Interface, CMS = Content Management System, RDB = Relational Database, Keycloak is an authentication service that allows Find-A-Pest to anonymously store user credentials.

Figure 3. Number of app units downloaded from the Apple store and number of active app installations from Android Play store during the case study period from 12 February to end of May 2019. For the Apple store this includes all first-time downloads of Find-A-Pest but does not include app updates, multiple downloads from the same Apple ID, and redownloads to the same device.

Figure 4. Time in hours before the first identification provided by iNaturalist NZ users. Most (95.4%) observations were identified in the first day, however the inset shows the extended identification tail with time in days to the first identification with Y-axis truncated to values ≤5% of observations.

Figure 5. Percentage of observations with, Top) Number of identifications, and Bottom) Number of comments from iNaturalist NZ users.

Figure 6. Percentage of respondents (total 54) that agree or disagree with the following statements. Q1) Do you find it useful that the app focuses on just the pests relevant to your region and area(s) of interest? Q2) The Find-A-Pest app was a useful way to learn about the most important pests to look for in your area and interests, and Q3) The Find-A-Pest app was easy to use.

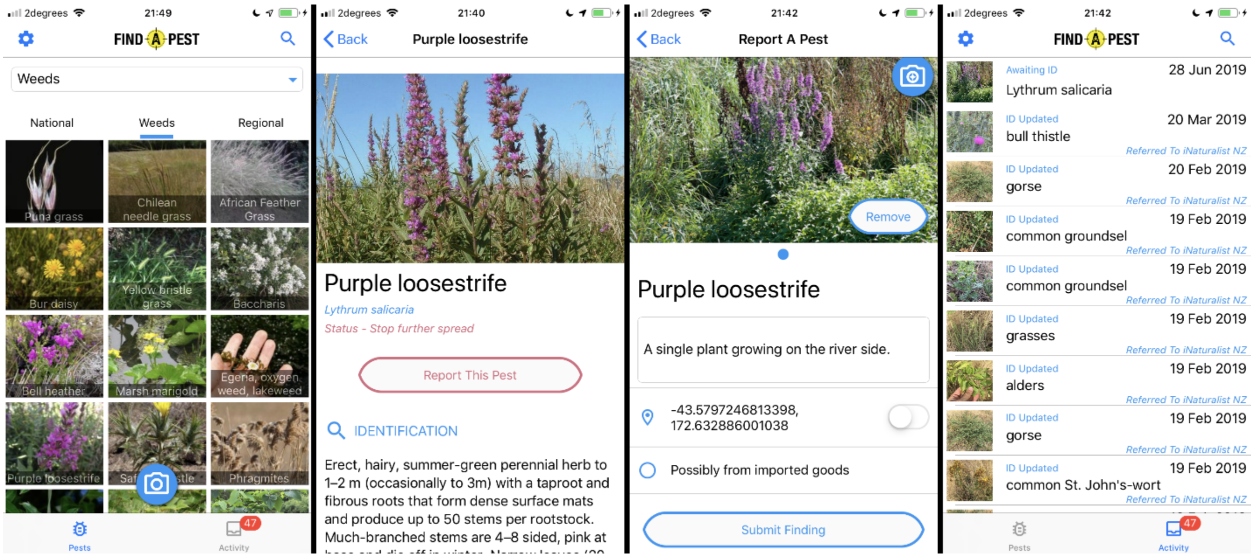
Figure 7. Percentage respondents indicating yes or no to the statements. Q1) Did you find the blue camera icon a useful and quick way to take a photo for anything you didn't know? (respondents 49), Q2) If Find-A-Pest wasn’t available, do you think you would have reported your observations via the Biosecurity New Zealand 0800 pest hot line? (respondents 52) Q3) Did the feedback you received via Find-A-Pest encourage you to make multiple reports? (respondents 48) Q4) Was the Find-A-Pest Identifier website suitable for you to process and identify the observations submitted from your sector? (respondents 18).

Figure 8: Percentage of respondents who ranked the importance of the following potential developments of Find-A-Pest in the future as essential, somewhat essential or not essential. Q1) Instant identification suggestions using computer vision machine learning, Q2) Ability to reply to comments made by identifiers directly from the Find-A-Pest app, Q3) Alerts of new biosecurity incursions as notifications on your phone, Q4) News of biosecurity discoveries and

events relevant to your area and interests, Q5) See a map of all observations of pests made near you, and Q6) Automatic suggests of what to look for based on the current location of your phone

Figure 9. Demographics of users that responded to survey. Respondents varied between question, age and ethnicity = 49, education, employment, and place of residence = 50.

Figures



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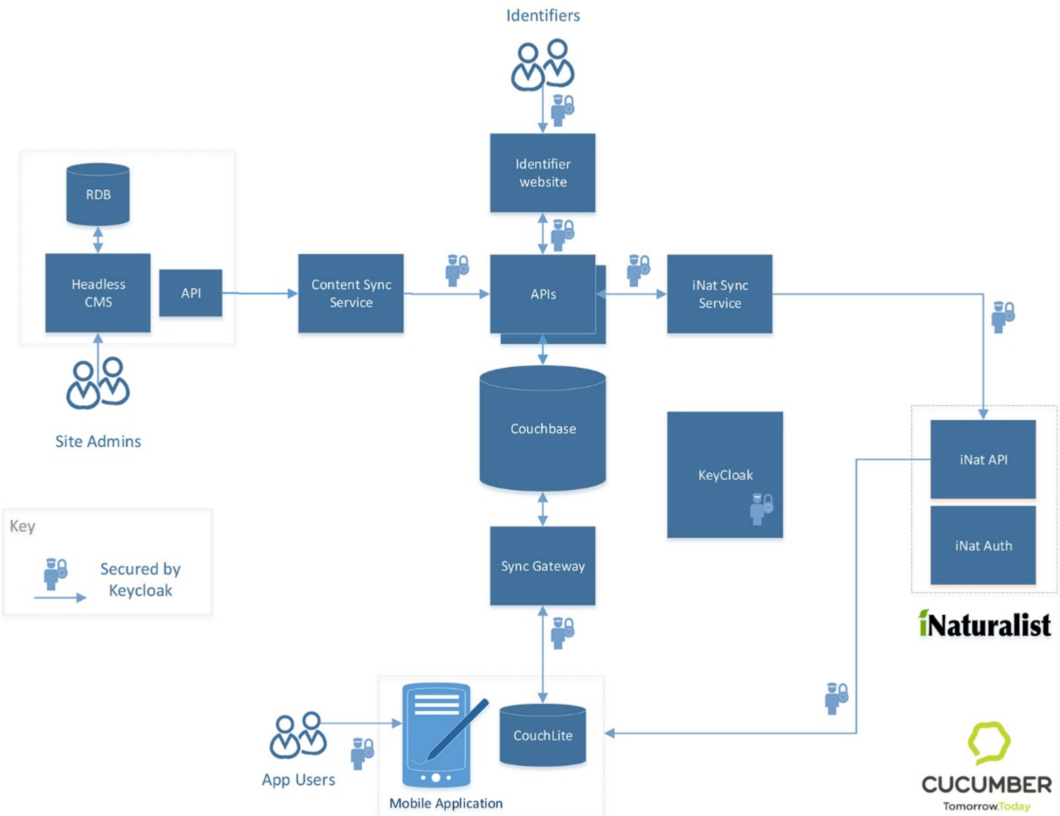

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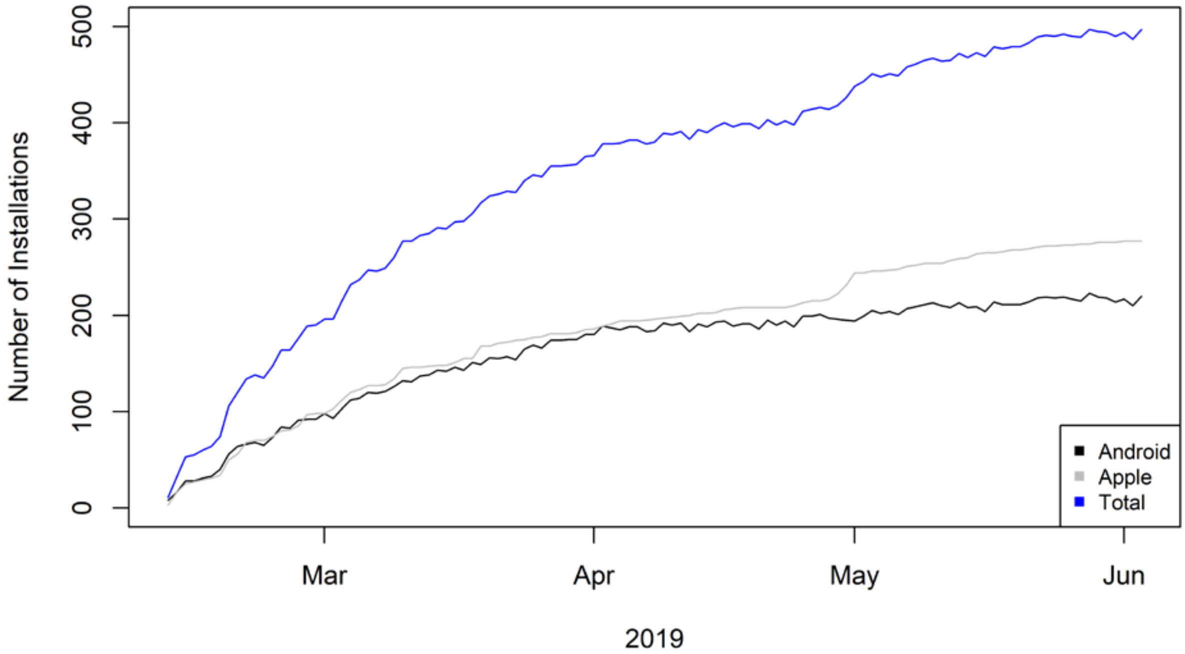

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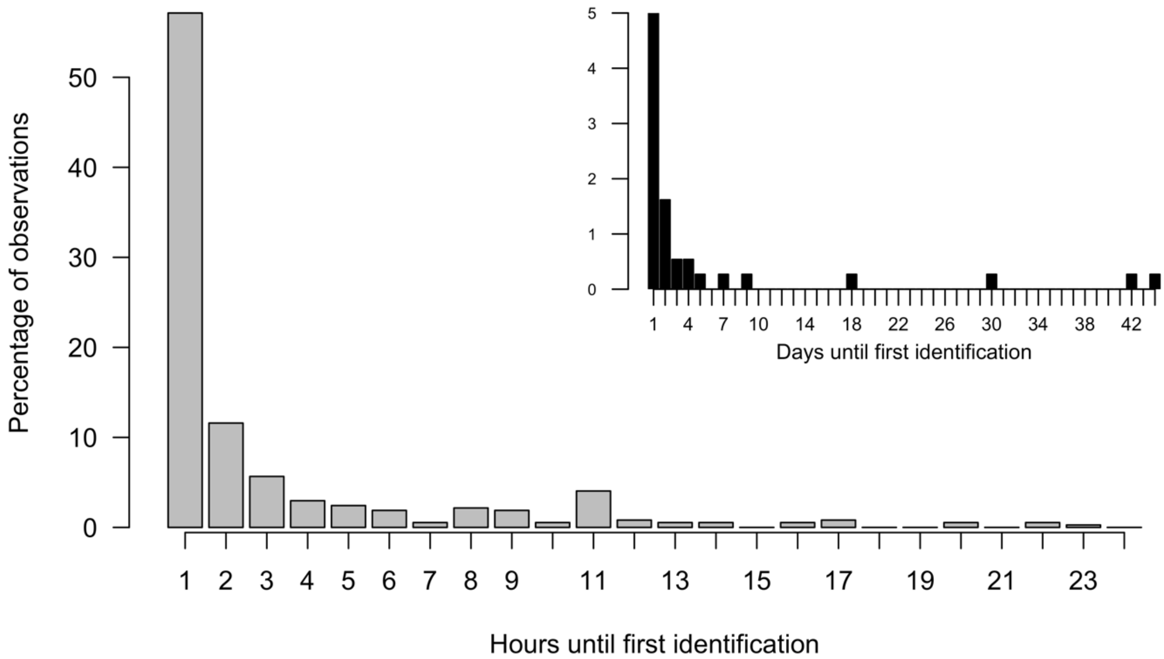

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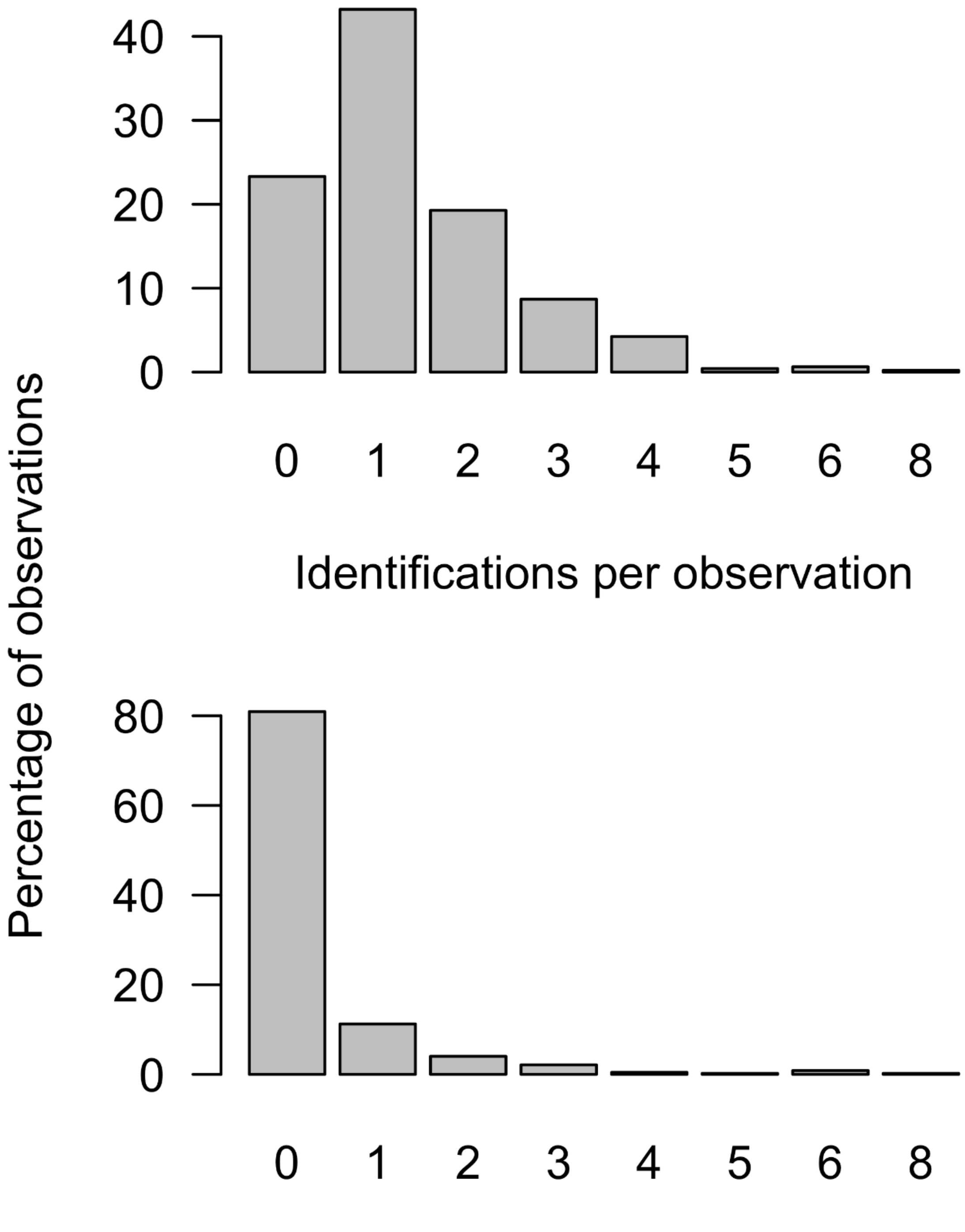
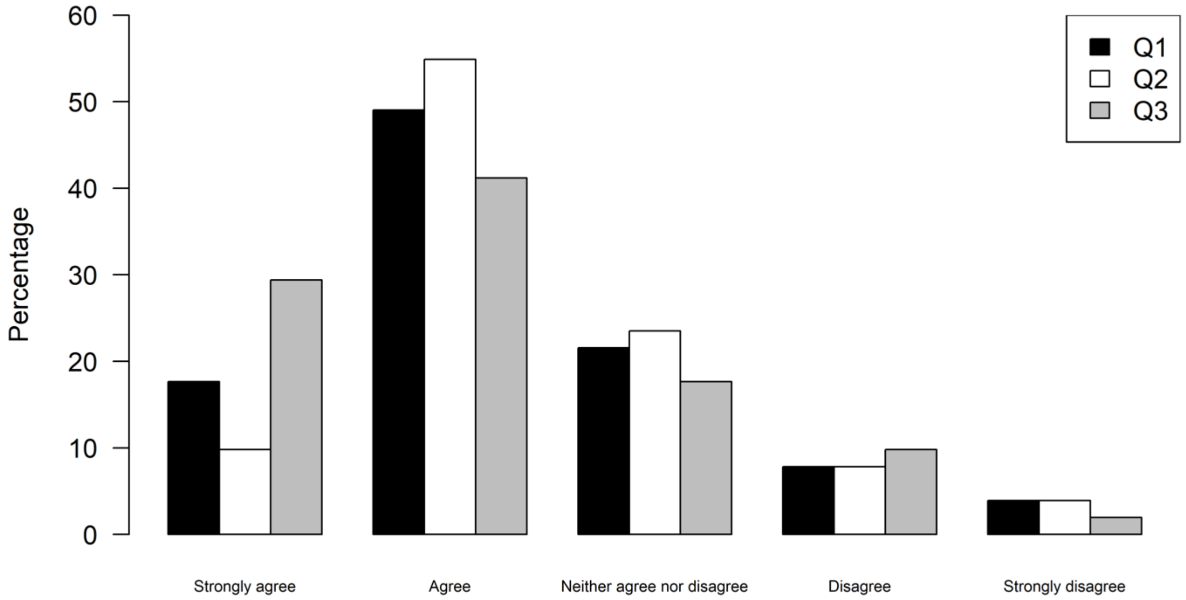

Percentage of observations
40
30
20
10
0
0
1
2
3
4
5
6
8
Identifications per observation
80
60
40
20
0
0
1
2
3
4
5
6
8
Comments per observation

Figure 5.



Percentage
0
10
20
30
40
50
60
Q1
Q2
Q3
Strongly agree
Agree
Neither agree nor disagree
Disagree
Strongly disagree

Figure 6.

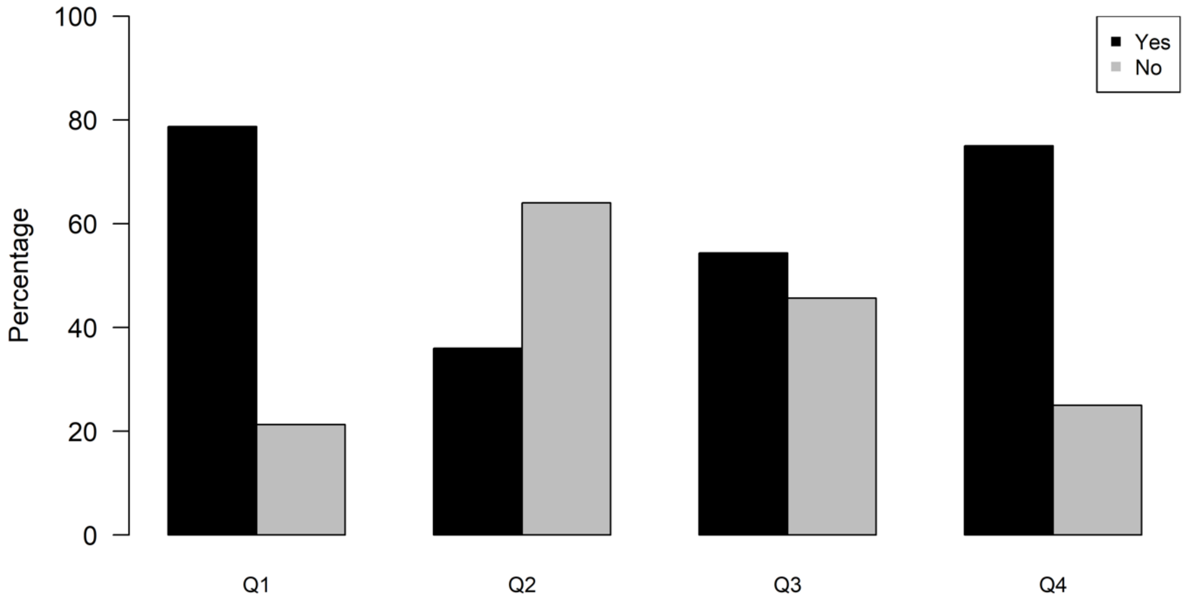
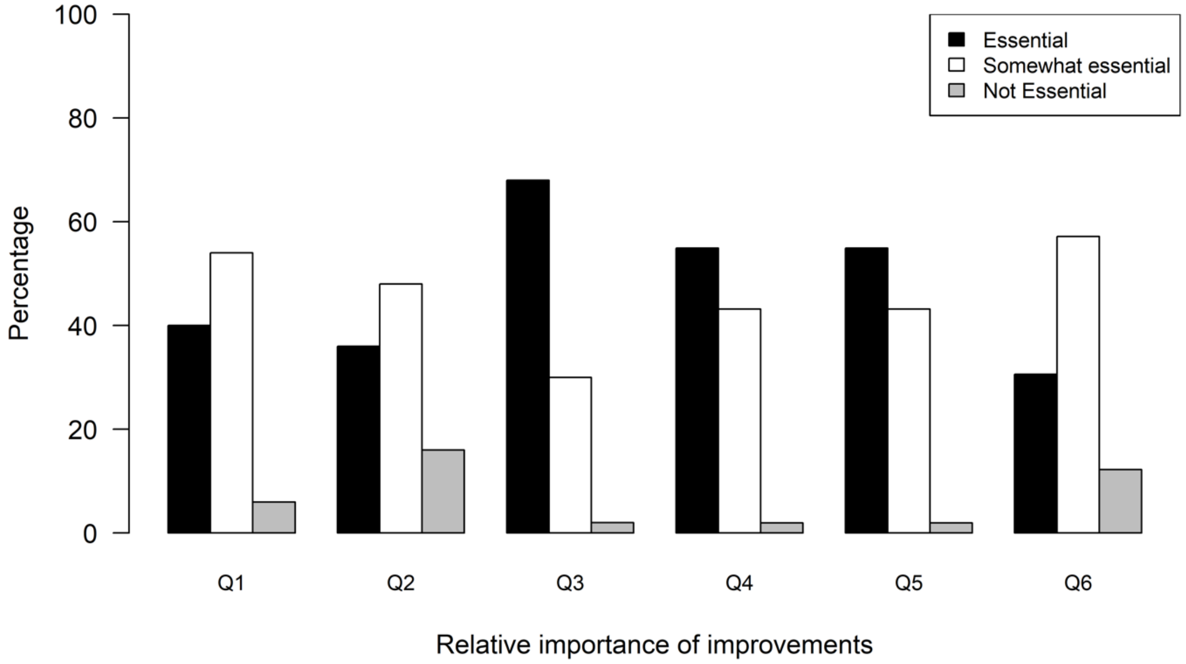


Figure 7.



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766 Figure 8.

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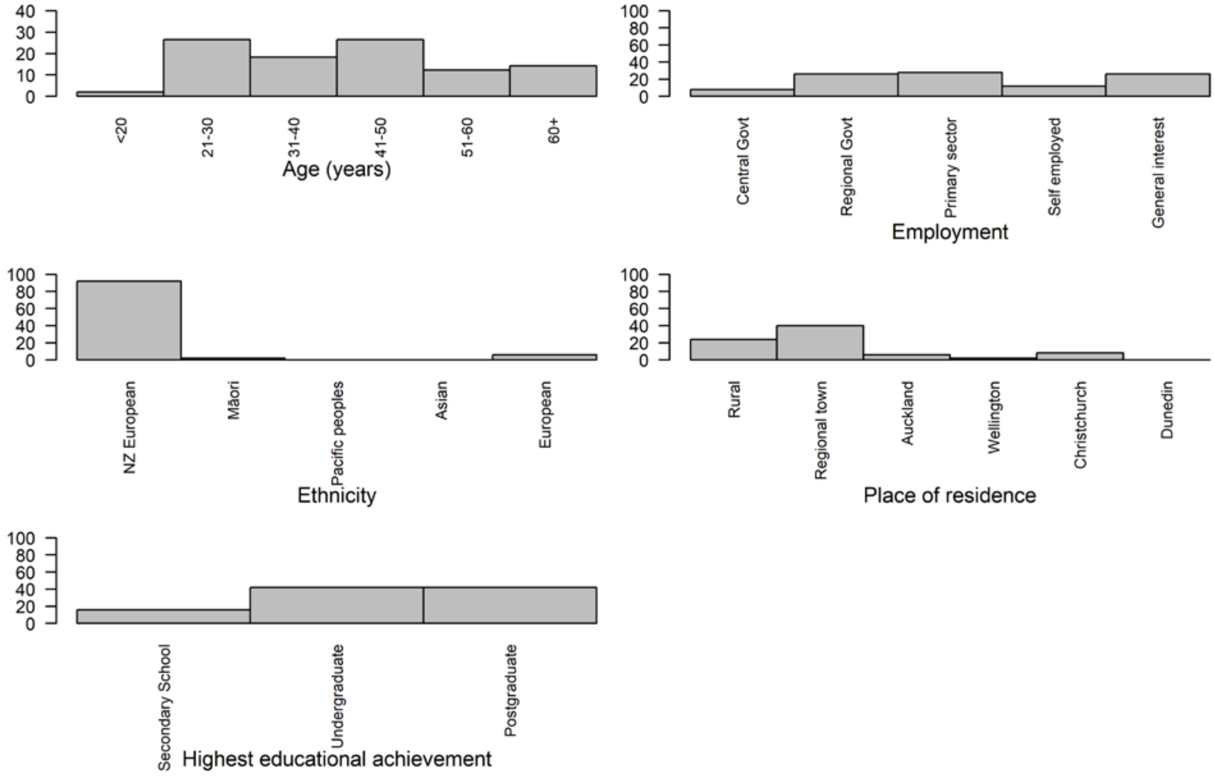

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769 Figure 9.

Supplementary material

Appendix A: Case studies

A series of five case-studies of varying intensity was undertaken with different user groups between 12 February and 30 May. These were:

Forestry

Forestry case studies included communications targeted at range of different participants within the industry. All members of the New Zealand Forest Biosecurity Committee (FBC) received an email with accompanying Find-A-Pest 'how to guide'. A Find-A-Pest tutorial that explained the tool and provided an identification workshop with example pests and pathogens was delivered to the FBC annual workshop. All coordinators of the PineNet, forest biosecurity network was emailed an introductory letter and the 'how to guide' to pass on to their members. These emails were then followed up by an in-person phone call to answer questions. All branch secretaries of the New Zealand Farm Forestry Association received a postal letter with the 'how to guide'. Half of the branches were selected at random for follow up phone calls with a in person visit to a weekend field day of the North Canterbury branch of the society to discuss Find-A-Pest. The app was also profiled in the February newsletter of the NZ Farm Forestry Association. Finally, all forestry offices receiving the NZ Farm Owners Association (NZFOA, corporate forestry companies) received two copies of the 'how to guide' as part of the March NZFOA newsletter mail out.

Kiwifruit

The case study was run by Kiwifruit Vine Health (KVH) that is an industry body responsible for biosecurity for the kiwifruit industry in New Zealand. As part of the case study KVH undertook the following activities. An article highlighting Find-A-Pest was emailed to 2500 growers in February. Find-A-Pest was highlighted in the kiwifruit industry magazine in the April issue. A 9-

minute podcast promoted Find-A-Pest to KVH members. The ‘how to guide’ was emailed to the Zespri Orchard Productivity staff that provide advice to growers. Find-A-Pest information was emailed to KiwiNet members that are biosecurity champions within the industry. Lastly the ‘how to guide’ with Find-A-Pest information was emailed to post harvest growers services staff that provide advice to parts of the kiwifruit industry.

Northland Regional Council

Northland Regional Council biosecurity staff were involved in the co-design of Find-A-Pest and invited to test out the app during the case study period. Unanticipated staff changes at the council during this time reduced the level of council involvement in Find-A-Pest testing. Northland Regional Council connected us with Reconnecting Northland, a community group focused connecting the land, the people, and their wellbeing. Reconnecting Northland works with nature-focused community groups throughout Northland to facilitate nature restoration. Two emails about Find-A-Pest were sent out by Reconnecting Northland ecologist Gary Bramley to all participating community groups, one before and one after their West Coast Hui (meeting) on 1 April. One of us (JJS) also presented Find-A-Pest at the West Coast Hui, generously hosted by the Omanaia Marae in Hokianga Harbor. There were 35 people in attendance, plus additional members of the marae that joined throughout the day. This included staff and governance from Reconnecting Northland, staff from Northland Regional Council and Department of Conservation, local community members, staff from Unitec (an Auckland-based university), and various iwi representatives. Gary was also provided with Find-A-Pest pamphlets to distribute to community groups.

Auckland Council

A small-scale case study was run in Auckland where the ‘how to guide’ was distributed to staff from the biodiversity and parks groups that evaluated Find-A-Pest. It was also demonstrated at the councils February Pest Liaison Group meeting where the ‘how to guide’ was distributed to participants that included, council staff, council contractors and consultants that work in the areas of biodiversity and biosecurity, and representatives from a wide range of community groups.

Southland Regional Council

The case study run in collaboration with Environment Southland (the Southland Regional Council) was focused on a community group on Stewart Island (Rakiura), the Stewart Island Rakiura Community Environment Trust (SIRCET). This trust has for many years led indigenous vegetation restoration and pest and weed control in and around Oban, the only town on Stewart Island. The SIRCET and the wider Oban community were suggested by Environment Southland as a suitable small community in which to trial Find-A-Pest. We worked with SIRCET pest manager Willie Gamble to engage with SIRCET members and the wider Oban community. This included two visits by Find-A-Pest project members to demonstrate the Find-A-Pest app and identifier web tool to Willie and SIRCET members, and regular video conferences and emails between with Willie to coordinate activities and respond to feedback. Willie thoroughly tested the app and encouraged SIRCET volunteers to use the app. This was done in person at SIRCET's community events, in hard copy with our printed pamphlets, and via their Facebook page and email list. We also posted a story on Find-A-Pest in the Stewart Island News (community newspaper), introducing Find-A-Pest and advertising a Find-A-Pest community event and BBQ (held on 27 April). Willie also tested out Find-A-Pest with approximately 20 students of Oban's Halfmoon Bay School.

Feedback survey

Every user of Find-A-Pest that submitted one or more observations during the study period was sent an email asking them to participate in a post case study feedback questionnaire. Participants used survey monkey to participate in the questionnaire (see below) with a follow-up email to all participants thanking those that had already participated and reminding others that the survey was closing soon. Data was processed by the authors, individual responses were anonymous unless the participant chose to disclose their email address to receive additional feedback.

Questionnaire

1. Do you find it useful that the app focuses on just the pests relevant to your region and area(s) of interest?
2. The Find-A-Pest app a useful way to learn about the most important pests to look for in your area and interests?
3. The Find-A-Pest app easy to use?
4. Did you find the blue camera icon a useful and quick way to take a photo for anything you didn't know? (yes/no)
5. New features are planned for Find-A-Pest. We're interested in which you think are most important.
    a. Instant identification suggestions using computer vision machine learning
    b. Ability to reply to comments made by identifiers directly from the Find-A-Pest app
    c. Alerts of new biosecurity incursions as notifications on your phone
    d. News of biosecurity discoveries and events relevant to your area and interests
    e. See a map of all observations of pests made near you
    f. Automatic suggests of what to look for based on the current location of your phone.
6. Did you encounter any bugs in the app (crashes, malfunctioning features)? If so please describe the issue and please include as much information about your phone and its operating system as you can (e.g., iPhone SE with iOS 12).
7. If Find-A-Pest wasn't available, do you think you would have reported your observations via the Biosecurity New Zealand 0800 pest hot line? (yes/no).

8. Did the feedback you received via Find-A-Pest encourage you to make multiple reports? (yes/no)
9. Were you invited to be a Find-A-Pest identifier (Yes/No)
    a. If ‘yes’, was the Find-A-Pest Identifier website suitable for you to process and identify the observations submitted from your sector?
    b. How could the Find-A-Pest Identifier website be improved to make it more efficient to process observations?
10. Demographic questions
    a. Age
    b. Ethnicity
    c. Highest level of education
    d. Where do you live.
    e. What area of employment describes your job.

Notes:

- Participants were asked to assess questions 1 to 3 on a scale from strongly agree, agree, neutral, disagree, or strongly disagree
- Participants were asked to assess each item in question 5 as essential, somewhat essential, or not at all essential.
- Two survey responses were removed as they were clearly malicious in intent with 100% negative assessments, no specific comments that might have indicated a genuine desire to provide feedback, and demographic responses that were illogical and designed to obfuscate the survey.