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PERSPECTIVES AND PARADIGMS

The contribution of passive surveillance to invasive species management

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Abstract It has been recognised for some time that the community has an important role to play in invasive-species management. Reports from the community about new incursions can lead to significant cost savings when this early detection results in shorter management programs. Unfortunately there is little to guide invasive-species managers on cost-effective ways to elicit and incorporate information from the public in their pest-management programs. Not all community surveillance is equal: some information from the public about the presence of pests and diseases may arise from chance encounters, other data may be reported by stakeholders from a particular industry or by groups of volunteers organised on the basis of citizen science activities. While the resources, activities and effort required to encourage each type of community surveillance are known to differ, very little is known of the relationships that determine effectiveness, and thus the appropriate level of investment that would be required to encourage a particular level of reporting. In this research we focus on passive surveillance—the most fortuitous type of community surveillance—and review the current knowledge base on measuring its cost and effectiveness. We aim to stimulate the research required to improve our understanding of passive surveillance, and we provide guidance on the type of data that should be collected by agencies to enable this research. This information could then provide us with the ability to design optimal surveillance portfolios that integrate the surveillance opportunities provided by the public to best advantage.

Keywords Passive surveillance · General surveillance · Citizen science · Community engagement · Biosecurity · Cost-effectiveness

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Introduction

Biological invasions cause significant damage worldwide through their effects on human health, the environment and the economy (Aukema et al. 2011; Pimentel et al. 2005). As a result, considerable amounts of public and private funds are spent across the globe managing invasions (Sinden et al. 2004).

Surveillance is an essential part of invasive species management programs. The surveillance literature is extensive but its focus has been on decision-making in the *active surveillance* context, where targeted searching is conducted by trained personnel (Baxter and Possingham 2011; Bogich and Shea 2008; Cacho et al. 2006; Epanchin-Niell et al. 2014; Yemshanov et al. 2014; Spring and Kompas 2015) with little coverage of how to incorporate surveillance undertaken by members of the public into decision-making (Cacho et al. 2010; Cacho and Hester 2011; Cacho et al. 2007; Keith and Spring 2013). This is despite long-standing recognition within biosecurity agencies of the usefulness of reports from members of the community of their encounters with invasive species (Beale et al. 2008; MAFBNZ 2008). This recognition stems from important detections of new incursions, or new foci of existing incursions, as a result of reports by members of the public. For example, in Australia, reports from the public led to the initial discovery of the European wasp (Davis and Wilson 1991) and Khapra beetle (*Trogoderma granarium*) (Beale et al. 2008) in Western Australia, and red imported fire ant (RIFA) (*Solenopsis invicta*) in Queensland (Jennings 2004). In New Zealand members of the public were responsible for initial discovery of RIFA, crazy ant (*Paratrechina longicornis*), carpenter ants (*Camponotus* sp.) and fall web worm (*Hyphantria cunea*) (Froud et al. 2008), painted apple moth (*Teia anartoides*) (Harris 1988) and white-spotted tussock moth (*Orgyia thyellina*) (Hosking 2003).

Recognition of the usefulness of community surveillance for detecting new incursions, or new foci of incursions, has resulted in pest and disease management programs routinely including some level of investment in community engagement activities to encourage reporting. Such activities might include pest displays, newspaper or magazine articles, identification cards, posters or even rewards. The reporting mechanism is often through a telephone 'hotline' where calls are screened and subsequently directed to the relevant government agency for further action, which might include a site visit to confirm a detection followed by treatment and targeted surveillance by the agency.

Despite the routine nature of investment in community engagement activities in pest and disease management programs, little is known about the effectiveness of these activities. This means the level of community reporting that could be expected for a given level of investment cannot be estimated with information currently available. The most pressing knowledge gaps include: the types of activities that induce the most reporting; the likelihood that particular types of people will report pests; the reliability of these reports; and how characteristics of pests and diseases affect the level of reporting. Pest and disease management programs would greatly benefit from improved knowledge about passive surveillance, both in terms of detection of outlier infestations and early detection of new invasions.

In this paper we propose a typology for community surveillance but focus on the least studied type of community surveillance: *passive* surveillance. We provide a conceptual model for incorporating passive surveillance into incursion management programs, suggest the type of research needed to estimate optimal investment in passive surveillance, and propose a framework for gathering data.

The surveillance continuum

The use of reports from the community of their encounters with invasive species has been variously termed passive surveillance (Cacho et al. 2010; Froud et al. 2008; MAFBNZ 2008), general surveillance (Hammond 2010) and citizen science (Silvertown 2009), each term indicating a surveillance process that is different to the organised, deliberate searching undertaken by pest management agencies. Passive surveillance, general surveillance and citizen science are often used interchangeably but there are important differences between them that need to be understood when planning types and amounts of investment in surveillance programs.

Describing and defining surveillance undertaken by the general public is not easy because sometimes their detections of invasive species occur completely by chance, while at other times they occur as the result of organised community or industry activities—there are different degrees to which detections can be considered accidental or fortuitous. This is illustrated using a 'surveillance continuum' (Fig. 1). At one extreme is the *active*, targeted surveillance carried out by pest-management agencies, involving deliberate, coordinated search for new or managed pests and diseases. At the other extreme is *passive* surveillance where members of the community report chance sightings of pests and diseases at their discretion. Their reports are particularly valuable if they lead to detections of new pests and diseases or information about new outbreaks of known incursions. Intermediate forms of detection include citizen science, where scientists and volunteers collaborate on specific pest and disease surveillance projects (see for example: Devictor et al. 2010; Dickinson et al. 2010; Silvertown 2009) and general

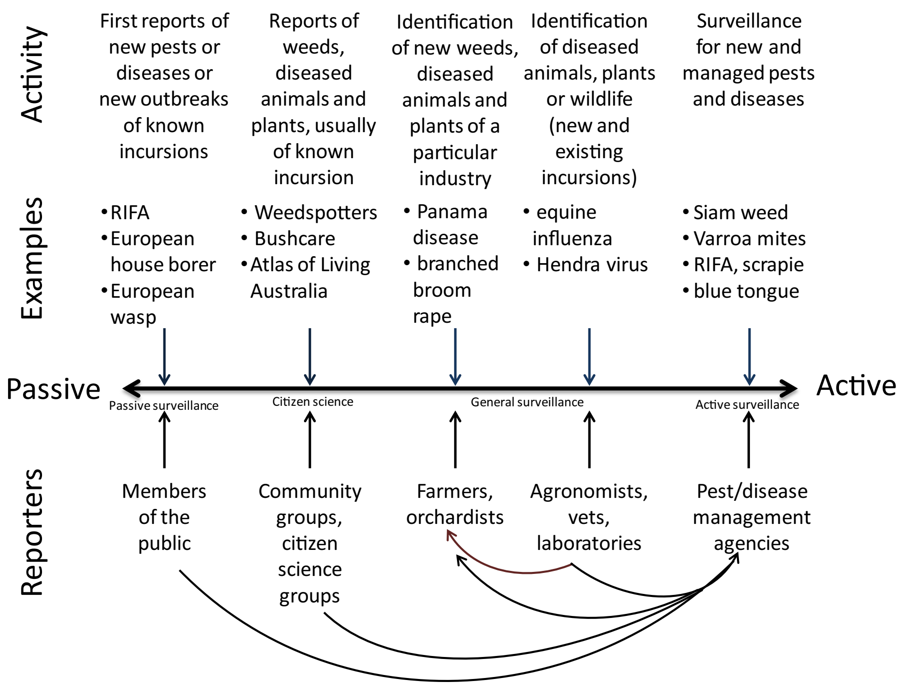


Fig. 1 Illustration of the surveillance continuum with selected Australian examples

surveillance where stakeholders of agricultural industries detect and report incursions that affect their particular industry (see for example: del Rocio Amezcua et al. 2010; Hammond 2010; Hernández-Jover et al. 2011; Rautureau et al. 2012).

Passive surveillance

Passive surveillance can be defined as any encounter with a pest by members of the public that is reported to the relevant authority. As discussed earlier, passive surveillance is the most fortuitous and accidental of all types of community surveillance (Fig. 1). It is activated and maintained through public awareness campaigns and their associated community engagement activities.[1] Community engagement activities about invasive species are known to raise awareness of that issue (Marchante et al. 2010; Martin 2007; Reis et al. 2011), result in increased passive surveillance (Brooks and Galway 2008; Witmer et al. 2007), reduce reporting times following detection (Hawley 2007), and increase cost-effectiveness of public engagement events over time (Cacho et al. 2012).

The action of detecting a pest by a member of the public is known as a *passive detection* (Cacho et al. 2010). Understanding the factors that drive the *probability of passive detection*—the likelihood that a pest or disease will be detected and reported—is key to understanding the level of investment required to achieve a given level of passive surveillance. The probability of passive detection depends on (1) the probability that a species is present in the landscape × (2) the probability of a person detecting it × (3) the probability that it is reported (given it is detected). In this paper we describe a framework for data collection that would allow us to understand how to increase (2) and (3), with (1) given. Keith and Spring (2013) used data collected during the RIFA Eradication Program in Queensland to report the only known published estimates of the probability of passive detection: 0.02 and 0.01 per month for urban and rural areas respectively. The difference in the values reflects the lower population density in rural areas. These are considered to be 'background' estimates because they do not distinguish between passive detections made before community engagement and after community engagement, but are nevertheless valuable.

[1] We acknowledge the importance of community reporting that is not in response to any pest-specific community engagement activity—often these reports are responsible for the first known incursions of a pest. The level of biosecurity awareness that drives those completely passive detections is not explored in this paper.

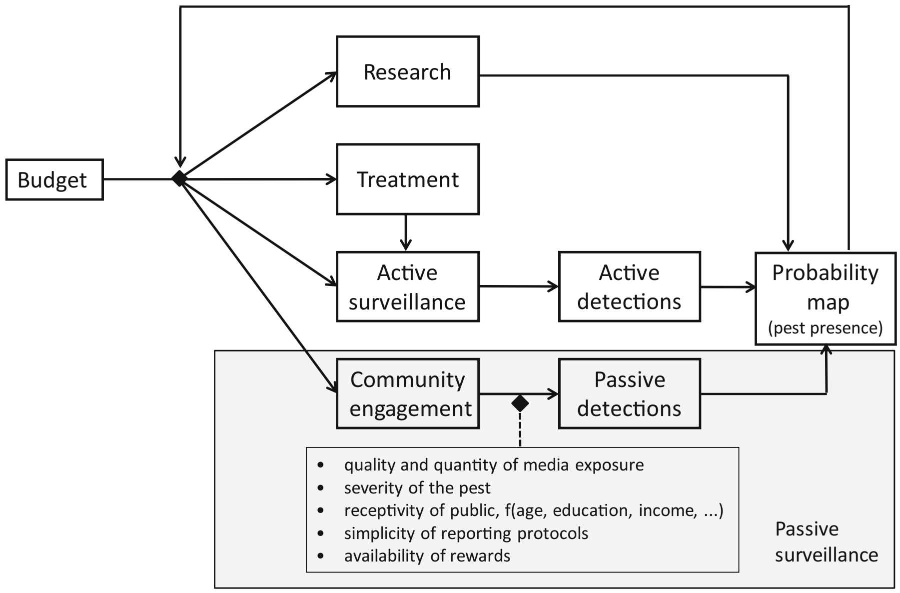


Fig. 2 Conceptual model of a pest-management protocol featuring passive surveillance and community engagement

Incorporating passive surveillance into pest and disease management programs

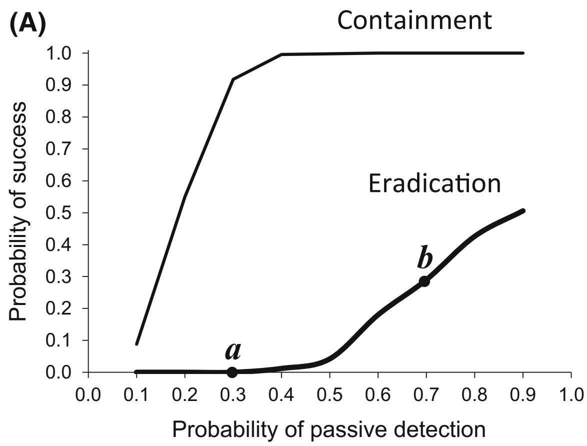
Agencies involved in the management of invasive species must allocate a limited budget across a range of activities. Their decision problem is illustrated in Fig. 2. The budget constrains the options available to design and implement a management strategy, but the goal should be to use the budget as efficiently as possible. The management strategy regulates the allocation of resources based on the best information available, often represented as a probability map. This might be a detailed map containing actual probabilities, or a priority list of sites to be monitored and treated as necessary.

There are usually four key activities that are funded as part of pest-management programs: treatment of known infestations; research to improve future management decisions; active surveillance; and community engagement to encourage the public to keep an eye out for the pest and report infestations—passive surveillance. The optimal allocation of resources between these activities will depend on their relative effectiveness and cost, with the allocation changing as management actions evolve in response to an incursion. The relationship between the effort put into passive surveillance and its outcomes is difficult to measure compared with the other activities in Fig. 2 whose effectiveness can be measured in more direct ways (Baxter and Possingham 2011; Cacho et al. 2006; Leary et al. 2013; Moore et al. 2011; Reed et al. 2015).

Ideally, pest management authorities would know the probability of passive detection and how this value relates to the probability of successfully achieving particular management goals. This is illustrated in Fig. 3. Increases in the probability of passive detection improve the probability of achieving eradication and containment (Panel A). The key is to understand the level of investment in passive surveillance required to induce particular values of the probability of passive detection and how this affects the management program. For example, increasing the probability of passive detection from ***a*** to ***b*** in Panel (A) (0.3–0.7 in this example) results in the probability of successfully eradicating a pest rising from 0 to 0.3, total eradication program costs fall from $4.8 to 3M (Panel B)—the pest is eradicated more quickly. Without information on the level of investment in community engagement activities required to induce the increase in probability of passive detection, we can only conclude that a pest management agency should be willing to spend up to $1.8M on these activities.

Research needs and data requirements

Unfortunately current knowledge and data collection practices by pest-management agencies do not provide enough evidence to quantify the relationship between



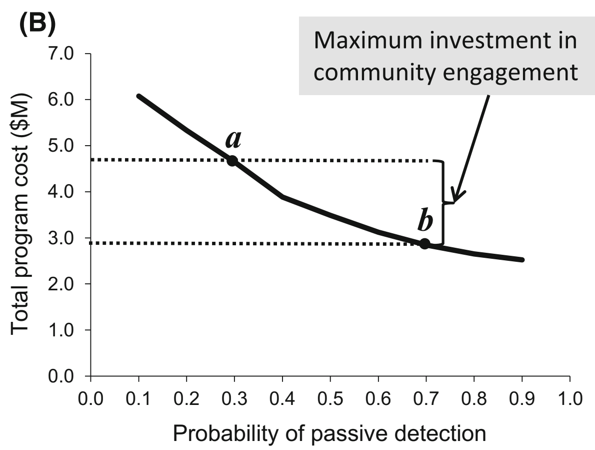


Fig. 3 An illustration of the effect of passive surveillance (as probability of passive detection) on the probability of successful eradication and containment of a pest (**a**) and on the cost of achieving this success (**b**). Improving the probability of passive detection improves success and reduces total program costs. In this example the maximum investment in community engagement to increase the probability of passive detection from ***a*** to ***b*** in (**a**) would be the vertical difference between ***a*** to ***b*** in (**b**). *Source* redrawn from simulation data reported in Cacho et al. (2012) and Cacho and Hester (2011)

investment in community engagement and the subsequent changes to reporting by the public. There are many dimensions to this problem and understanding the intricacies is crucial to designing efficient community engagement strategies.

Undertaking community engagement activities in invasive species management has similarities with public policy initiatives such as encouraging natural disaster preparedness, providing a hotline to encourage the reporting of neighbourhood crime to police, or persuading people to wear a face mask during an influenza epidemic. Such behaviours generally require some effort on the part of the individual, and while they may or not may not have individual benefits they all have substantial public benefit. There is evidence that the propensity of members of the public to undertake these behaviours is influenced by demographic factors, including age, socio-economic status and ethnicity. Studies demonstrating these relationships have been in areas that include weed management (McCluggage 2004), influenza communication campaigns (Bish and Michie 2010; Eastwood et al. 2009; Gray et al. 2012), law enforcement (Huq et al. 2011), and natural hazard preparedness (Paton et al. 2006).

The literature on community engagement and public attitudes to invasive species (Bremner and Park 2007; DEFRA 2008; Kruger et al. 2012) suggests that the response of the public to awareness activities surrounding invasive species is likely to depend on[2]:

1. Attributes of the community engagement activities, such as message content, media channels, additional media reporting, provision of feedback, ease of reporting, frequency and location of activities;
2. Demographic factors within a community, such as age, gender, knowledge, altruistic or materialistic tendencies and concern for the environment.
3. Attributes of the pest, such as its potential to cause physical harm or financial costs, and its detectability within the local environment;

We now explain how each of these might be measured.

Attributes of community engagement activities

To understand whether attributes of different activities make them more or less effective in terms of the probability of passive detection, information should be collected on the type of activity undertaken, the timing and location of any reports made, and the number of

[2] It may also be the case that active surveillance activities in an area—visibility of traps and pest-management officers—could in turn increase the probability of passive detection, although this remains to be tested.

detections resulting from these reports, including the number of false positives. There are several ways to measure effectiveness of a given activity, for example: the total number of detections; the number of detections per time period; or the number of reports (positive and negative) per time period. These values could simply be monitored for each activity over time or formal statistical measures could be designed to determine the relationship between effectiveness and explanatory factors such as pest characteristics, event duration, location and reporter characteristics. To test hypotheses regarding these relationships, data with enough variation in all factors are required so that statistical tests can be applied.

Demographic factors

People respond in different ways to information campaigns, advertisements, rewards and other activities designed to stimulate passive surveillance. Assuming that reporting procedures are available and are not onerous, people's responses, in combination with the presence of the pest in a particular area, will determine the probability of passive detection.

Community engagement activities will raise community awareness temporarily and have limited spatial influence (Cacho et al. 2012). This means it is important to understand the spatial reach of a particular event and the length of time that the event will remain in the memory of the public. This would allow pest-management agencies to choose the appropriate timing and location of community engagement events. The spatial influence of events is difficult to ascertain as events vary in size, duration and population catchment and hence would vary in their spatial influence. There are also likely to be spatio-temporal correlations between events and passive detections that must be disentangled using statistical techniques.

Cacho et al. (2012) reported frequency distributions of distances between events and subsequent passive detections in the RIFA Eradication Program in Queensland (Fig. 4). For a single year the authors found a 'distance threshold' at approximately 4.2 km, at which the average event starts losing its effect on public awareness (Fig. 4a), but high variability of the data means that statistical tests are not significant. A similar relationship was found when all previous years of events were used, with the distance threshold at just above 1 km (Fig. 4b), suggesting that the effect of events depreciates over time.

Attributes of the pest and invaded environment

An important aspect of passive surveillance programs is the ability of the reporter to accurately identify the target species being reported. This is likely to be related to the characteristics of the pest and whether it is easily identifiable in the landscape. Of particular concern is the rate of false positives, where the target pest is reported as present when it is in fact absent. The false positive rate is important because, in order to eradicate an invasion, all detections reported by the public must be followed up and the pest treated if present. A rate of false positives that is too high will result in wasted program resources by leading to unnecessary active surveillance (Spring and Cacho 2015) and may negate the benefits of passive detections.

False positives may also occur because the pest is hard to identify or because the community engagement activities have been badly designed or targeted but this remains to be tested. False positives may also decrease over time as knowledge about a pest improves. The widespread use of smartphones in the community has allowed the development of applications that may result in a reduction in false positives. Some applications send photos of a suspected pest or disease to pest-control agencies for identification and verification, while others contain photos of invasive species that should be reported.

Reliability of reports about a pest, either in response to a particular activity or bundle of activities, may be measured from data on the number of reports and the number of false positives over time. Froud et al. (2008) used positive predictive value (PPV)—the proportion of the total number of reports that are confirmed as positive—to measure the reliability of the general public's calls to New Zealand's Exotic disease and pest emergency hotline. Over a 3-year period, although the PPV was only 2%, reports from the public were responsible for 49% of all the new exotic organism detections (355 detections in total). Cacho et al. (2012) used PPV in their analysis of data from the RIFA Eradication Program in Queensland to suggest the program's community engagement activities had become more effective over time—PPV increased from 1.1 to 6.1% during the first 10 years of the

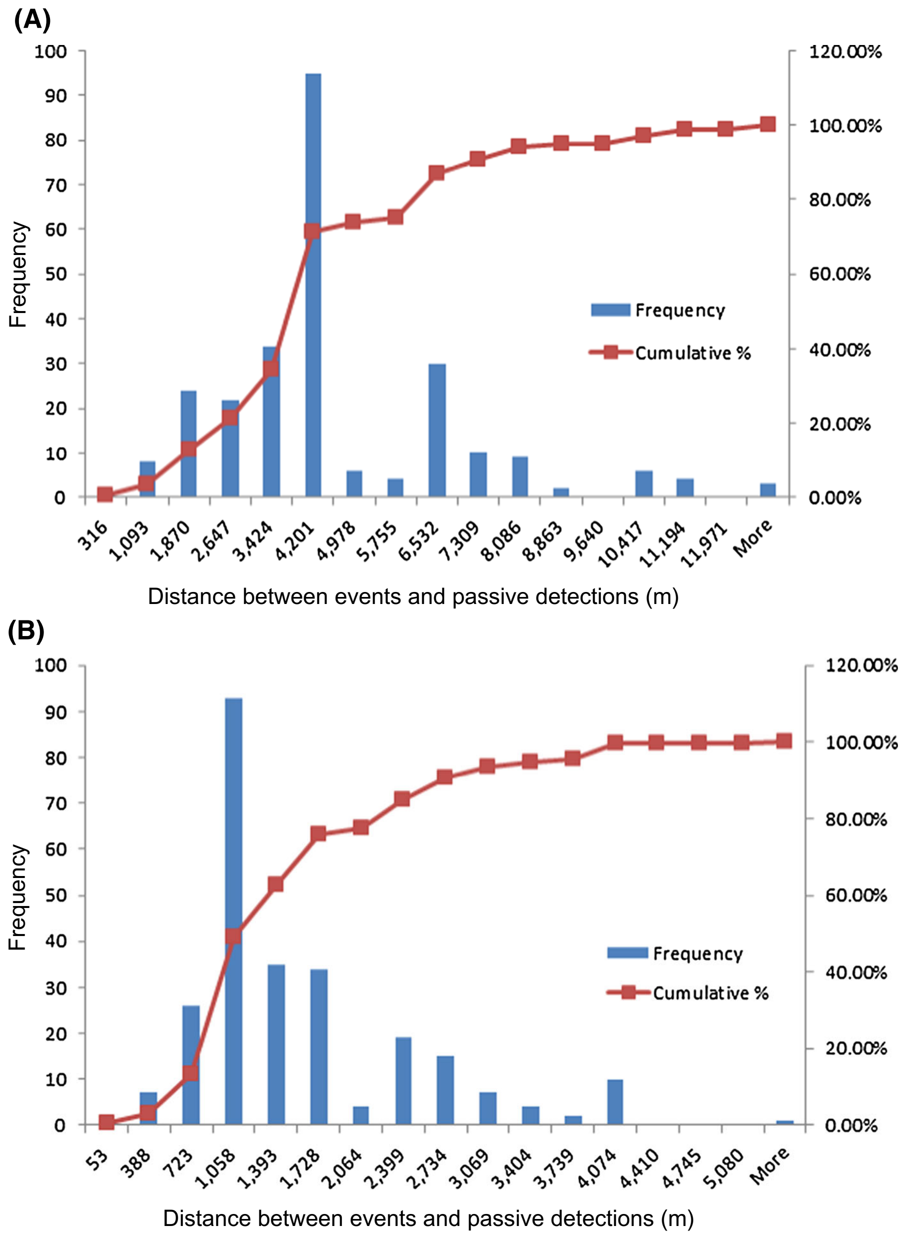


Fig. 4 (**a**) histogram of distances from each passive detection in 2008 to the nearest event in 2007; there appears to be a distance threshold at ~4.2 km at which the average event loses its effect on public awareness. (**b**) histogram of distance from each passive detection in 2008 and the nearest event for all years prior to 2008; again there is a clear threshold, but this time at just over 1 km. *Source* Cacho et al. (2012)

program. The question is then whether the damage that was avoided through passive detections outweighs the cost of following up on all public reports.

If enough published results were available, a meta-analysis (Dodd et al. 2015; Gurevitch and Hedges 1999) of community engagement activities could be used to test hypothesis regarding pest characteristics that make them amenable to detection and reporting by the public. Anecdotal evidence suggests pest characteristics that make them amenable to reporting include: whether they bite or sting; whether they are easily observable and identifiable in the landscape;

and whether a pest is easily distinguishable from similar species in the landscape.

Unfortunately not enough published data are available for any meaningful meta-analysis to be undertaken currently. Additional data collection from current and past programs will be required. New data collection could also involve expert consultations and detection experiments with volunteers (Hauser et al. 2012; Moore et al. 2011).

Investment in community engagement

The key reason for collecting and analysing data on community engagement activities is to efficiently allocate limited pest-control budgets to passive surveillance. As discussed earlier, the optimal allocation of resources to community engagement activities, and thus to passive surveillance, depends on their relative cost-effectiveness compared to the other activities that are usually funded as part of pest-management programs (Fig. 2). Measuring the cost-effectiveness of passive surveillance would require analysis of community awareness activities, relating expenditure on the activities to particular outcomes, such as the number of reports or detections by members of the public. Data on the spatial and temporal aspects of the awareness activities and subsequent reports, including characteristics of the individuals making the reports, would also provide useful information to allow better targeting of activities and events. This type of data is seldom recorded or reported by pest-management agencies.

Although this has not been proven empirically, one would expect passive detections to exhibit diminishing returns with respect to exposure to community engagement activities. This may be related to the timing, intensity and location of activities, but may also be related to the diverse range of attitudes in human populations.

(Cacho et al. 2012) calculated the change in the frequency of passive detections per $1000 spent on community engagement for the RIFA Eradication Program in Queensland (Fig. 5). Although a significant increase in detections per dollar is evident between 2003 and 2010, this cannot be used as a measure of cost-effectiveness of community-engagement. The increase in passive detections could have been caused by a combination of factors, including an increase in the number of nests available to be detected, combined with human population growth in the area infested leading to more people being available to detect nests.

In the current context the costs of community engagement depend on the types and scale of activities undertaken, the benefits are improved detections of invasive species, leading to reduced future damages. The only known attempt to estimate the monetary value of community engagement to enhance passive surveillance is that of Cacho et al. (2012), who estimated the savings in active surveillance that were achieved through reports from the public in the RIFA

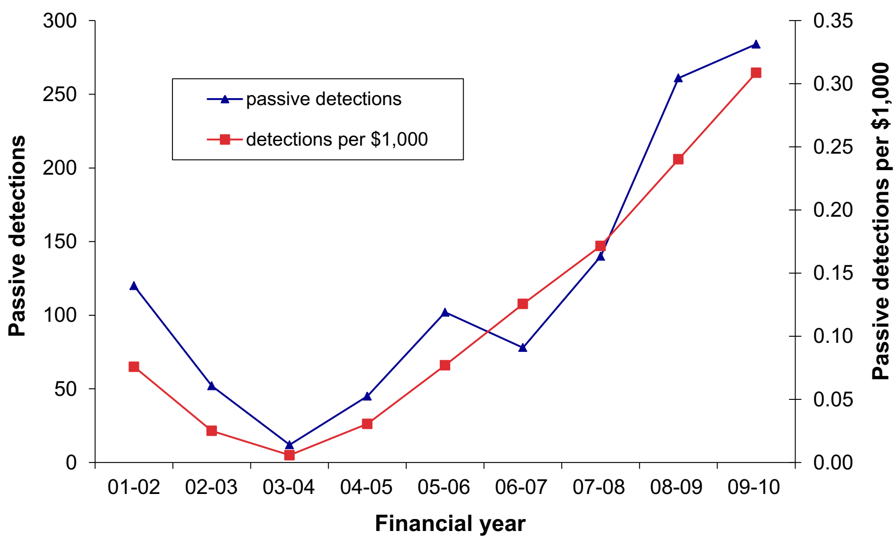


Fig. 5 The number of passive detections and passive detections per $1000 per financial year for the RIFA Eradication Program in Queensland. *Source* Cacho et al. (2012)

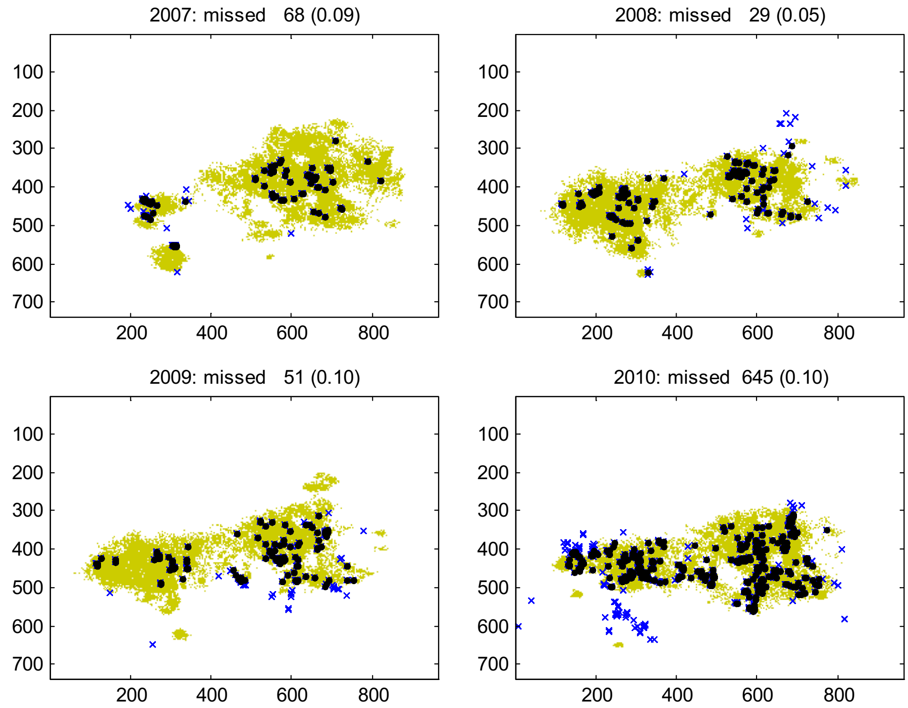


Fig. 6 Detection maps for fire ants (*Solenopsis invicta*) invasion in Brisbane, Australia for 2007 to 2010. Actual detections are indicated with *x markers*, *green dots* represent the area that would be covered with active surveillance when a large budget (enough to cover 80,000 ha) is available. Search points were allocated based on probability maps generated using the model of Schmidt et al. (2010), which calculates probability of pest presence spatially at annual intervals based on known ant colony locations using a Bayesian approach. *Blue x markers* indicate actual passive detections that would not have been detected if only passive surveillance were available. These missed detections for different budgets were used to construct a counterfactual to calculate the value of community engagement in the RIFA program

Eradication Program in Queensland. They estimated that $1m invested in public engagement activities had resulted in $60m saved in active surveillance costs between 2006 and 2010. To calculate this figure it was necessary to construct a counterfactual—the likely outcome in the absence of community engagement activities—and this involved some modelling. The amount of active search that would have been required to detect all the known ant colonies in the period 2006–2010 if passive surveillance had not been available was estimated from the data. In the counterfactual, all nests had to be detected using active surveillance, with the search area allocated based on a probability map (Fig. 6) generated using a modified version of the model of Schmidt et al. (2010). Combining this information with an active search cost of $400/ha, resulted in an annual return of $52 million in avoided active surveillance costs. Comparing this figure to an average community engagement budget over the same period of $860,000 results in a return on investment of $60 per $1 invested in community engagement.

As can be seen in this example, to generate credible estimates of the benefits and costs of passive surveillance we require a counterfactual, which is unobservable. This means we need to combine empirical evidence with modelling of the managed spread process. The data required to generate solid estimates of the counterfactual is not available for most invasions, hence our emphasis on the need to collect the right data.

The optimal level of passive surveillance

Economic principles prescribe that resource allocation should be based on marginal quantities (rates of change) rather than absolute quantities. The optimal operating point is where the marginal benefit of an action equals its marginal cost. In many practical situations, however, it is not possible to calculate the cost and benefit functions required to derive marginal values through differentiation. This is one reason benefit-cost analysis (BCA) is popular. In BCA total benefits are compared to total costs (in present-value terms) for different scenarios, and the alternative with the highest benefit-cost ratio is selected (Hester et al. 2013).

In the current context, the optimal level of passive surveillance would be where the marginal cost of increasing passive detection by one unit equals the marginal benefit of doing so. That is the point at which the resources employed to activate and maintain passive surveillance are used most efficiently. The actual optimisation problem is more complex than this because of its dynamic nature—pests available to be detected today depend on previous control actions that have been taken, and the marginal benefit and marginal cost functions may change through time.

To estimate the marginal cost of passive surveillance we need to derive a function relating expenditure on community engagement activities to the probability of passive detection. The derivative of this function could then be used to calculate the marginal cost of increasing passive detection probability. On the benefit side, the ideal approach would be to measure the additional benefit as the avoided damage achieved by increasing passive detection probability plus the reduction in eradication costs from savings in eradication-program duration (Kompas et al. 2016). In practice, measuring this relationship would require experiments where the treatment can be compared to a control. Alternatively, the benefit function could be inferred through modelling (as in Cacho et al. 2012).

Concluding comments

There is no doubt that the community has an important role to play in the management of invasive species. This could occur through involvement of organised groups of volunteers in citizen science activities, using information supplied by stakeholders of a particular industry, or through individuals who are motivated to report chance sightings of pests as they go about their everyday life. The typology we present is aimed at improving the way we manage biological invasions by understanding how different types of community surveillance operate within a continuum.

We focus on passive surveillance, the extreme in the surveillance continuum for which very little is known. Despite expenditure on community engagement activities becoming a routine aspect of pest-management programs across the globe, only a small amount of published research on aspects of community engagement effectiveness exists. Our aim is to suggest a course of action for research on passive surveillance and to identify data needs. Our ultimate aim is to guide collection of quantitative information that will enhance our understanding of passive surveillance in a meaningful way, as a component in a surveillance continuum. Much of the data required for the analysis is relatively easy to collect.

Research linking the effectiveness of different types of community engagement activities to passive surveillance is needed not only to improve efficiency in the use of public funds, but also to reduce the damage caused by invasions through early detection with assistance of the public. This research must consider spatial and temporal variation in the invasion process as well as its interactions with human populations. Filling the research gaps identified in this paper should enable the development of cost-effective strategies to get the most out of members of the community in managing invasive species.

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