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Locating species range frontiers: a cost and efficiency comparison of citizen science and hair-tube survey methods for use in tracking an invasive squirrel

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Abstract

Context. Improved knowledge of changing species distributions is critically important for conservation managers in the face of increasing species invasions, habitat disturbance and climate change. Efficient monitoring of the location of advancing species invasion frontiers is especially crucial for effective species community and habitat management.

Aims. To compare the cost-effectiveness and efficiency of two survey methods, a citizen science survey and a traditional hair-tube survey, in their abilities to locate the current southern invasion frontier of grey squirrels (*Sciurus carolinensis*) in Ireland.

Methods. In the citizen science survey, we collected sighting reports of the grey squirrel and its native congener, the red squirrel (*S. vulgaris*), from the geographic region of the invasion frontier from untrained members of the public over a 2-year period. Hair-tube surveys were carried out in 14 woodlands ($\geq$30 ha) in the same geographic area to test the ability of this indirect field method to identify colonising grey squirrel populations. The costs, efficiency and cost-effectiveness of each method were compared.

Key results. The citizen science sighting reports resulted in the clear delineation of the southern frontier of the zone invaded by the grey squirrel. The hair-tube survey ascertained the presence of grey squirrels in 4 of 14 sites, but did not detect this species close to the invasion frontier defined by the citizen science survey. Even though the total cost of the citizen science survey was higher, it was more cost-effective and efficient on a per detection basis for the purposes of detecting the presence of grey and red squirrels.

Conclusions. The citizen science survey detected invasive squirrels in sites where the hair-tube survey did not. As such, the citizen science survey provided a more comprehensive snapshot of the location of the grey squirrel invasion frontier more efficiently and cost-effectively than did traditional field techniques.

Implications. In the face of increasing ecological and economic costs of biological invasions, we recommend straightforward citizen science surveys, over indirect field surveys, to managers and researchers seeking to efficiently track progressing invasions of readily observable animals cost-effectively.

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Introduction

The ecology of invasive species and invaded ecosystems is a well published and sometimes controversial topic in the larger fields of ecology research (Mack *et al*. 2000; Davis *et al*. 2001), applied landscape management and public policy (Lodge and Shrader-Frechette 2003). When invasive species advance through exclusion barriers and control measures are unsuccessful, longer-term monitoring and management becomes necessary (Bertolino and Genovesi 2003; Courchamp *et al*. 2003; Simberloff 2003). It is difficult for landscape managers with limited resources to maintain surveillance on occupied areas while also tracking the advancing or evolving frontier and managing damage caused by the invader. As such, decisions on invasive species monitoring techniques should be taken transparently, with careful consideration given to the most effective use of available budgetary and time resources without unnecessary sacrifice of scientific rigor (Gaidet-Drapier *et al*. 2006; Tulloch *et al*. 2011). Authors have argued the need for more research into choosing efficient and effective methods for monitoring species distribution, richness, and the change in these metrics over time (Barea-Azcón *et al*. 2007; Lyra-Jorge *et al*. 2008). A cost-effective survey method is one that provides the highest rate of return or greatest benefit (e.g. in terms of species detectability or number of species detected) for a given level of investment. Previous studies have compared the efficiency and cost-effectiveness of numerous direct and indirect field-survey methods in determining species presence and/or abundance (Gurnell *et al*. 2004*a*; Gaidet-Drapier *et al*. 2006; Garden *et al*. 2007; Lyra-Jorge *et al*. 2008; Roberts 2011; Tulloch *et al*. 2011; Paull *et al*. 2012). However, invasive-species tracking is a particularly challenging case because of the potentially rapid spread of a species through the landscape. As a result, there is an urgent need in the invasive species management and research fields for novel methods to keep up with the frontier of spread. Here, we compare the efficiency and efficacy of a field survey method with an alternative citizen science approach for locating the invasion frontier of a spreading introduced species.

Citizen science is an increasingly well utilised tool in species richness and distribution studies. It has been suggested that ecological studies that span large national and international areas require an element of citizen science (Cooper *et al*. 2007; Cohn 2008; Silvertown 2009; Devictor *et al*. 2010). Although the employment of species-sightings reports from the public in scientific endeavours is not novel, the utilisation of lay people for more complex and involved surveys has greatly increased in the past decade as have the project-design strategies and statistical methods involved in obtaining optimal, least-biased results (Tulloch and Szabo 2012; Tulloch *et al*. 2013*a*, 2013*b*). Publicly collected datasets, which have the capacity to monitor biodiversity over space and time or from sometimes inaccessible privately owned lands (Dickinson *et al*. 2010), are a boon to species distribution science. Dickinson *et al*. (2010) noted that the public can be particularly effective at recording the presence of species that are rarely seen or have low population densities and are therefore an asset in tracking the expanding ranges of invading species or wildlife disease (Eraud *et al*. 2007; Koenig *et al*. 2007; Peacock *et al*. 2007; Delaney *et al*. 2008; Fujisaki *et al*. 2010).

Indirect field surveys for the presence of animal species have the benefit of being cost-effective, time-efficient, requiring little need for the licencing or training of operators, and causing little stress to the animal being surveyed in comparison to direct capture trapping surveys. Evidence of species presence in an indirect survey is gathered through the collection of a visual sighting or physical sign left behind by the species, which may be subject to identification uncertainty. Examples of indirect species-presence surveys include sighting transects, point observations, feeding transects, scent stations, scat surveys, drey counts, footprint tunnels and the use of remote wildlife camera traps (Brown *et al*. 1996; Barea-Azcón *et al*. 2007; Gurnell *et al*. 2009). A further method, the hair-tube or hair-snare survey, is a widely used type of indirect survey that allows for the methodical collection of small mammal hair to establish presence in a site (Scotts and Craig 1988; Catling *et al*. 1997; Pocock and Jennings 2006; Harris and Nicol 2010; Schwingel and Norment 2010; Reiners *et al*. 2011). Although less intensive than direct capture surveys, the downside of hair-tube surveys is that they can still be expensive in personnel time and equipment costs, and therefore there are trade-offs in the area that can be covered compared with the ability to detect a species.

The eastern grey squirrel (*Sciurus carolinensis*), native to eastern North America, has been frequently introduced to locations worldwide (Bertolino 2009) where it often easily establishes (Wood *et al*. 2007) to the detriment of native sciurid populations (Kenward and Holm 1993; Gurnell *et al*. 2004*b*; Sainsbury *et al*. 2008). The grey squirrel was introduced to one site in the Republic of Ireland in 1911 (Watt 1923; O'Teangana *et al*. 2000*a*), via populations in Great Britain (Fig. 1). Since then, the range of the grey squirrel has expanded to the north, east and south of the island of Ireland, resulting in a corresponding decline in the population and range of its native congener, the Eurasian red squirrel (*S. vulgaris*) (Wauters *et al*. 2000; Carey *et al*. 2007; Lawton *et al*. 2010). The landscape in Ireland is primarily agricultural, although forest cover has recently exceeded 10% and, although patchy, is increasing. Approximately 62% of Ireland's human population is concentrated in urban areas and the remaining 38% is well distributed throughout the rural landscape, which covers 97.6% of the total Irish land area (CSO 2011).

We chose the two squirrel species present in Ireland to test the cost-effectiveness and efficiency of citizen science and indirect field surveys in determining invaded range because both species are charismatic, relatively easy to distinguish from one another and rare in certain areas. The grey squirrel invasion and the 'plight of the Irish red squirrel' are well and emotively covered in national news media and nature television programming, resulting in public being reasonably aware of the situation of these species. Hair-tube surveys have proved a reliable technique in Ireland to record the presence of both red and grey squirrels (Finnegan *et al*. 2007; Waters and Lawton 2011; O'Meara *et al*. 2012) and were utilised in detecting the presence of these species elsewhere in Europe and North America (Gurnell *et al*. 2004*a*; Fimbel and Freed 2008; Bertolino *et al*. 2009, 2014). In the present study, we apply both methods, (1) a citizen science survey for squirrel sightings and (2) a hair-tube survey for squirrel presence, along the southward invasion frontier of the grey squirrel. We compare the strengths and weaknesses as well as the overall costs, cost-effectiveness and efficiency of both methods in acquiring species detection records and characterising the advancing edge of the invasive squirrel population. We discuss the fitness of each method for the stated purpose and make recommendations for their use in future research or management projects.

Materials and methods

Citizen science survey

We collected records of red and grey squirrel sightings from the public in Munster Province, Republic of Ireland (2011 human population: 1 246 088; CSO 2011), which includes the previously determined southern invasion frontier of the grey squirrel (Carey *et al*. 2007; Fig. 1). To reduce the possible bias of the urban–rural divide of the human population on sighting distribution, we employed diverse methods to publicise the survey over the course of the study in an attempt to reach all potential groups of volunteers. Sightings were solicited between November 2010 and October 2012 and publicity was sustained throughout that period through a dedicated website, colour posters distributed to notice boards in local population centres, presentations to the public, articles in local and national newspapers, as well as continuing local and national radio and television coverage. Background information pertaining to both species of squirrel was provided with each public mention of the survey project. We did not request volunteers to report sightings from specified areas or seek reports of species absence. Volunteers reported

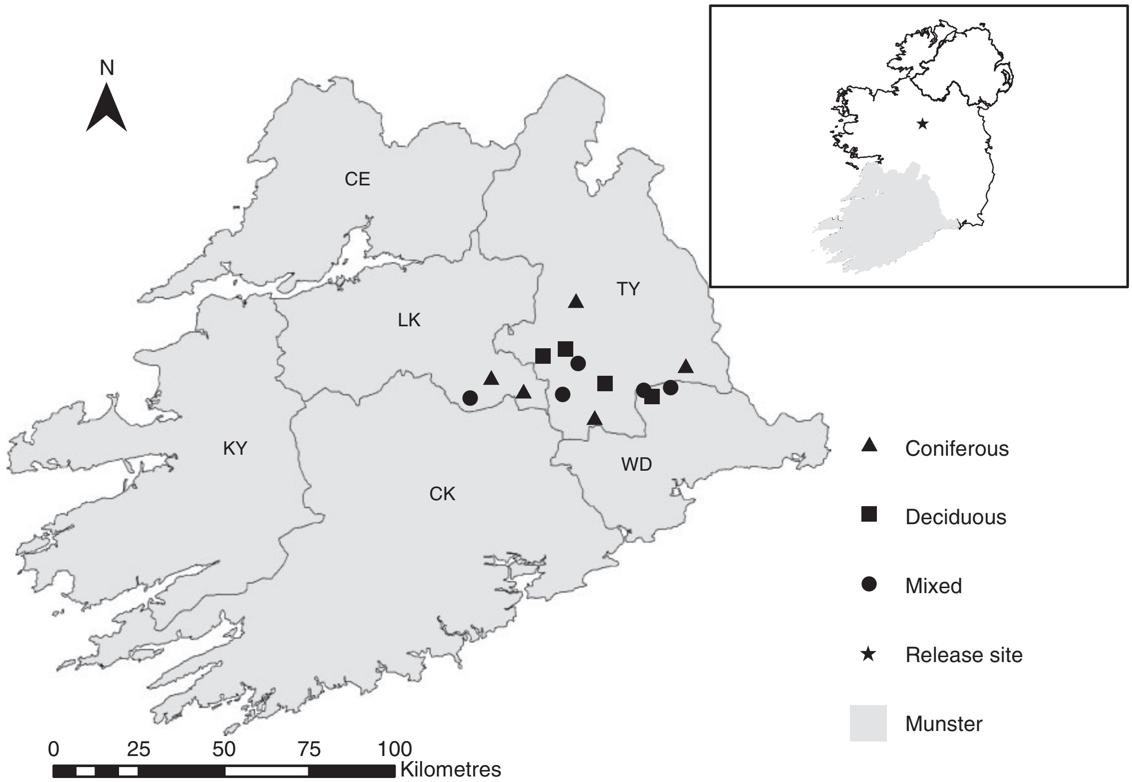

Fig. 1. Map of Munster Province, showing the location and habitat types of the 14 hair-tube surveys for the presence of *Sciurus carolinensis* and *S. vulgaris*. Habitat types of the survey sites are indicated as follows: coniferous habitat (▲), deciduous habitat (■), mixed habitat (●). Inset map of the island of Ireland displays the extent of Munster Province and the initial release location of *S. carolinensis* (★). CE, Clare; CK, Cork; KY, Kerry; LK, Limerick; TY, Tipperary; and WD, Waterford.

their sightings either through the website facility, by telephone or post. Respondents provided the species, date and location of the sighting, habitat type, condition of the animal (e.g. live or road kill) and contact information. Sighting reports were accepted when the respondent indicated the sighting was of a deceased specimen, provided photographic evidence, or if the respondent, on interview, was able to adequately describe the species sighted. Sighting reports that did not fulfil the above criteria or did not include sufficient contact information to allow for follow-up were not incorporated into the analysis or results. The survey responses from the six Munster counties of Clare, Cork, Kerry, Limerick, Tipperary and Waterford were mapped in ArcMAP 10 (ESRI, Redlands, CA, USA). Sighting reports within 1 km of each other, the maximum distance a squirrel will normally travel within its range (Gurnell 1987), were grouped to avoid duplication and over-sampling.

Hair-tube survey

Indirect field surveys using hair tubes to record the presence of squirrel species were initiated in 14 woodlands in Munster between March and August 2011 (Fig. 1). All sites were ≥30 ha and were classified as one of the following three forest types: coniferous (≥80% conifer coverage; $n = 5$), deciduous (≤25% conifer coverage; $n = 4$) or mixed woodland ($n = 5$). Survey sites were chosen *a priori* on the basis of available and accessible forested habitat and proximity to the previously published southern extent of grey squirrel range (Carey *et al*. 2007).

The hair tubes consisted of 300-mm lengths of 65-mm × 65-mm square PVC pipe (Gurnell *et al*. 2004*a*; Finnegan *et al*. 2007). The tubes were tied to trees at a height of ~1.8 m and baited with whole hazelnuts and a 4 : 1 whole maize and shelled peanut mixture. Two removable wooden blocks, each with three 10-mm × 10-mm squares of paper-backed adhesive, were positioned with metal clips on the inside upper surface at either end of each tube to collect mammalian dorsal hairs. Thirty hair tubes were set out in each site, at a density of 1 tube ha^{-1} for a period of 14 days (Finnegan *et al*. 2007; Bertolino *et al*. 2009; Gurnell *et al*. 2009), after which they were retrieved, cleaned and redeployed with fresh glue blocks in a new site.

Collected mammal hairs were removed from the glue block with forceps and cleaned with distilled water and a histological clearing agent (Histo-Clear, National Diagnostics, Hessle, Hull, UK) to remove oil. Hairs (≤10) from each positive tube were arranged on separate gelatin-coated microscope slides following the techniques described in Teerink (1991), to create impressions of the cuticle scales. The distinctive scale patterns on the hair shield, viewed with ×100 magnification under a light microscope, allowed for identification of hair collected in each tube to the species or genus level. We viewed cross-sections of *Sciurus* hair shields under ×100 magnification by cutting each perpendicularly with a razor blade and fixing it to the side edge of a microscope slide to distinguish grey squirrel hair (oval) from red squirrel hair (concavo-convex) (Teerink 1991).

Cost-effectiveness analysis

Accurate calculation of the cost-effectiveness and efficiency of a survey method requires an estimation of the research or conservation value of the data collected by each survey method and a calculation of the costs. We utilised multiple metrics in our analysis, including number of locations where squirrels were detected (unique detections) and how quickly these reports were obtained, detection efficiency (detections day^{-1}) and spatial detection efficiency (detections ha^{-1}), as well as the cost-effectiveness metric of cost per detection (cost $detection^{-1}$). Cost-effectiveness metrics divide the realised scientific benefit by the cost required to achieve it. The cost of each survey method was calculated on the basis of the cost output required to detect the presence of squirrel species at each location and the total cost to complete each survey. We divided costs into the following four main areas of expenditure for each survey method: equipment and/or one-off costs, bait and/or consumables costs, personnel costs and travel costs (Garden *et al*. 2007). A summary of prices and costs is given in 2012 € (Table 1; for details of expenditure, see Supplementary Material available for this paper).

Equipment and/or one-off costs encompassed expenses related to acquiring the materials necessary to complete the survey but were not consumed completely during the course of the study. Hidden costs not taken into account in the equipment-cost calculations were the light microscope used to identify mammal hairs and the ArcGIS10 licence fee. Bait and/or consumables costs covered expenditures on bait for the hair tubes and materials that were consumed during laboratory and citizen science publicity work. Personnel costs were calculated at three rates depending on the hourly wage of the person(s) required to complete each task. The majority of the tasks could have been assigned to a basic-level research assistant employed at the rate of €12.50 h^{-1}, but others required the expertise of a technical officer (€25.00 h^{-1}) or an IT professional (€30.00 h^{-1}). Travel costs were calculated on the basis of the mileage cost of €0.39 km^{-1} charged for the hire of institutional vehicles.

A comparison of the detection or non-detection of squirrels within the 14 hair-tube sites with detection in the entire region encompassed by the citizen science survey is not sufficient on its own for the objectives of this research. For the direct and standardised comparison of survey methods, the set of sighting reports from the citizen science survey was limited to include only those originating from locations within the hair-tube study sites during the 5-month period over which hair-tube surveys were performed. We calculated the overall and standardised cost-effectiveness (detections $cost^{-1}$) and spatial cost-effectiveness (detections $cost^{-1}$ ha^{-1}) of both survey methods. A higher cost-effectiveness value is indicative of a wiser resource investment.

Statistical analysis

The number of hair tubes containing red squirrel hair, the number containing grey squirrel hair, and the aggregate number of tubes with hair of either species were expressed as a proportion of the total number of tubes collected in each site. These data were arcsine square-root transformed and the assumption of normality was tested using Levene's test of homogeneity before analysis. We performed ANOVA tests on transformed data to examine differences in the proportion of hair tubes positive for squirrel hair among site habitat types, and the difference in the proportion of tubes positive for red or grey squirrel hair among habitat types in the four sites where both species were known to be present (Carey's Castle, Bansha, Gortarush and Kilnamack). A 2×3 Fisher's exact test of independence was used to investigate the association of the three habitat types and number of hair tubes used by each of the two squirrel species (Kirkman 1996). Seasonal effects on the proportion of positive tubes were examined with separate ANOVA tests for each squirrel species, using the month collected as a fixed effect. Normality and ANOVA tests were performed using SPSS v. 20.0 (IBM, Armonk, NY, USA).

Results

Citizen science survey

During the survey period, 665 public reports of squirrel sightings were accepted, relating to 424 unique locations in Munster Province from 529 individual members of the public. There

Table 1. Costs by category of the hair-tube survey, both total and per survey, and the citizen science survey, total and per week, to detect squirrel presence

Where appropriate, costs are separated by initial outlay or cost per survey or per week. Personnel time for the hair-tube survey included fieldwork and laboratory analysis but refers to publicity, website and data management for the citizen science survey. Additional detail on costs is provided in Supplementary Material available for this paper

Survey	Category	Initial outlay (€)	Price per survey or per week (€)	Total (€)
Hair-tube survey	Personnel	425.00	525.00	7775.00
	Travel		143.52	2009.28
	Equipment	300.55		300.55
	Bait and/or consumables	108.82	3.78	161.74
Total		834.37	672.30	10 246.57
Citizen science survey	Personnel	1459.92	108.04	12 279.92
	Travel	448.50		448.50
	Equipment		1.37	142.00
	Bait and/or consumables	60.00		60.00
Total		1968.42	109.40	12 930.42

was an initial peak in responses following the launch of the survey, although reports were consistently returned throughout the study period for both squirrel species. An accumulation curve showed that reports from over half of the unique grey squirrel sighting locations were received within the first 6 months of the citizen science survey (Fig. 2), after which the speed of report collection slowed at a different pace for each species. We observed that multiple sightings per unique location were generally associated with areas of higher human population density or designated outdoor recreation areas and were not meaningfully linked to the frontier of grey squirrel invasion. The majority of locations related to sightings of red squirrels only ($n = 310$), whereas locations with grey squirrel sightings only ($n = 62$) or sightings of both species in a single location ($n = 52$) were less common (Fig. 3). We report a conservative estimate for the zone invaded by grey squirrels, which incorporates all accepted sightings of grey squirrels in Munster (Fig. 3). The frontier line is composed of 18 locations of grey squirrel sightings. Approximately 90% of these sightings ($n = 16$) had been received by August 2011, 10 months after the beginning of the citizen science survey. The general shape and location of the frontier was established by sighting locations collected by May 2011, only 7 months after the commencement of the survey, by which time 14 of the frontier sightings had been received.

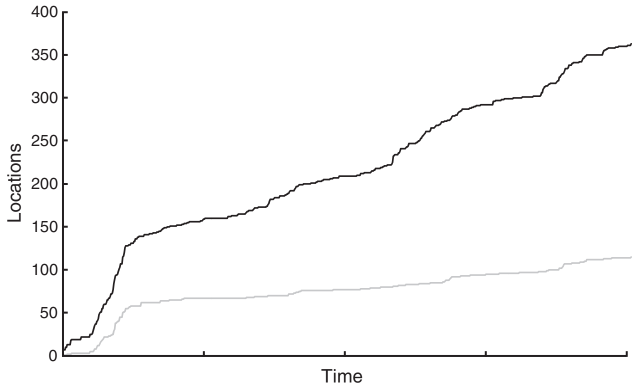

Fig. 2. Accumulation curve of unique sighting locations for *Sciurus carolinensis* (grey line) and *S. vulgaris* (black line) during the citizen science survey. Tick marks on the horizontal axis delineate 6-month intervals. The initial peak in number of responses accounted for over 50% of grey squirrel and over 40% of red squirrel locations.

Hair-tube survey

In total, 420 hair tubes were set out during the course of the 14 surveys, of which 184 (43.8%) contained mammal hair, 89

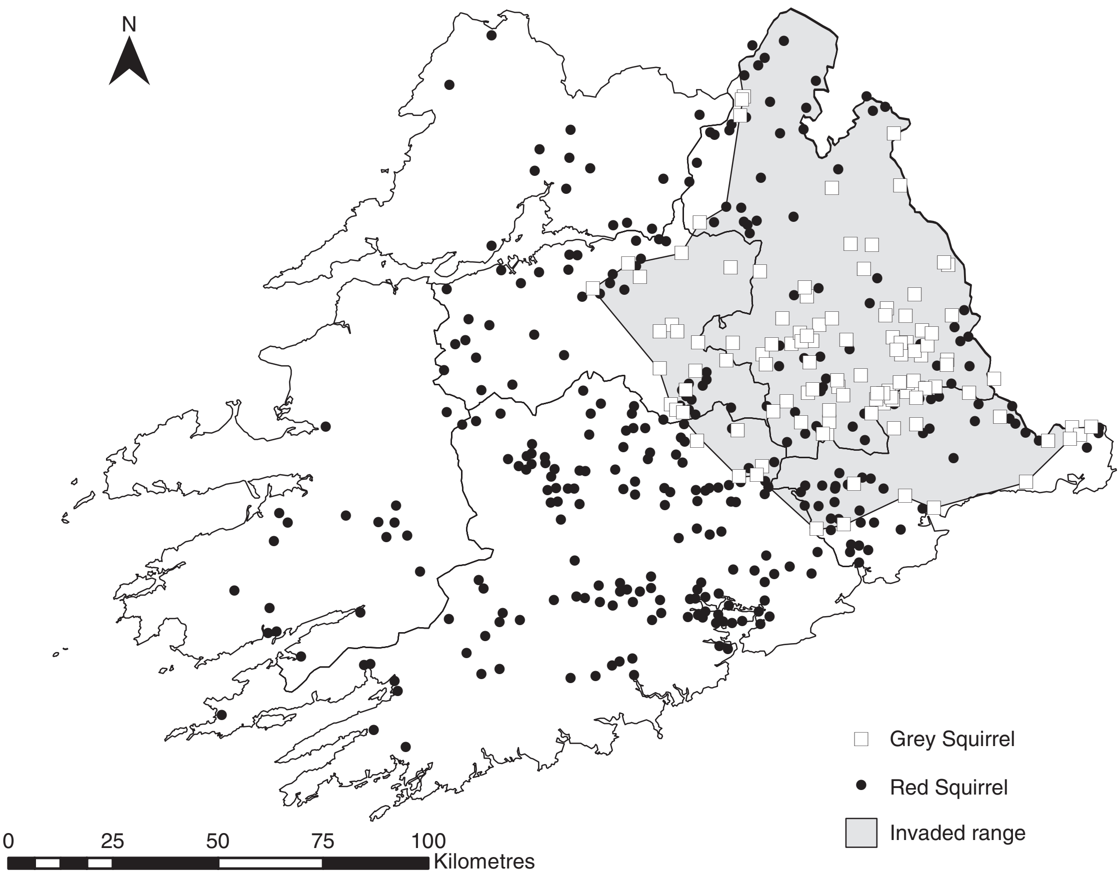

Fig. 3. Map of Munster Province, displaying the locations of public sightings of *Sciurus carolinensis* (□) and *S. vulgaris* (●) collected between November 2010 and October 2012 in the citizen science survey. The grey squirrel-invaded zone, as determined by the citizen science survey, is shown in shaded grey.

(21.2%) contained bird feathers and three (0.7%) were vandalised or stolen and not included in the analysis. The hairs of seven non-target mammal species were collected in the hair tubes, in addition to the hairs of the two target squirrel species (Table 2). Red squirrel presence was detected in 12 of the 14 sites surveyed, whereas grey squirrel presence was detected in four field sites only. Grey squirrels were observed during fieldwork in two sites (Carey's Castle and Tikincor) where the presence of this species was unrecorded by the hair tubes. No collected hair-tubes contained the hair of more than one mammal species.

Habitat type did not have a significant effect on the aggregated proportion of all hair tubes visited by squirrels, both red and grey, in each site ($F_{2,11} = 1.059$, $P = 0.380$). Fisher's exact test of independence also found no significant difference in the frequency of hair tubes positive for either red or grey squirrels among the three habitat types ($P = 0.094$). Grey squirrel hair was detected in three of the four sites where the presence of both squirrel species was confirmed (Table 3); however, there was no significant difference between the proportion of hair-tubes positive for red squirrel hair or for grey squirrel hair ($F_{1,6} = 5.188$, $P = 0.063$) in these sites. Neither was habitat type a significant influence on the proportion of tubes visited by either squirrel species (habitat × species: $F_{1,4} = 2.649$, $P = 0.202$) in the four both-species sites. There were no significant time-of-year effects on the proportion of positive hair tubes for either species (grey squirrel: $F_{5,8} = 1.448$, $P = 0.305$; red squirrel: $F_{5,8} = 2.407$, $P = 0.129$).

Table 2. Number of sites and hair tubes within which mammal species were detected at 14 hair-tube study sites in Munster Province, Republic of Ireland

Additional tubes recorded the presence of birds or were vandalised or stolen. In total, 14 sites were surveyed with 420 hair tubes

Species	Number of sites	Number of hair tubes
Sciurus carolinensis	4	4
Sciurus vulgaris	12	63
Apodemus sylvaticus	14	75
Crocidura russula	1	1
Mustela erminea	2	7
Martes martes	2	3
Mus musculus	2	2
Myodes glareolus	7	8
Rattus norvegicus	10	21
Bird	12	89
Vandalised or stolen	1	3

Cost-effectiveness and efficiency of survey methods

The total cost of surveying the 14 sites with hair tubes was €10 246.57, whereas the cost of the citizen science survey was €12 930.42 over 2 years in Munster Province (Table 1). Personnel time was the most expensive cost category of both survey methods. The initial outlay for the hair-tube study (construction and purchase of field equipment, purchase of bulk materials) made up €834.37 of the total budget and the cost to survey and analyse each of the 14 sites (personnel time, travel, bait) totalled €672.30. The cost of the initial outlay (website design and creation, publicity, travel) for the citizen science survey was €1968.42 and there was a further cost of €109.40 per week to maintain and host the website as well as manage sighting reports. The cost of the citizen science survey, when standardised to a time period comparable to the duration of the hair-tube survey, was €2850.77.

The restricted set of citizen science sighting reports, used in the calculation of standardised cost-effectiveness metrics, consisted of 10 squirrel sighting locations within the hair-tube study sites. This group of sightings recorded the presence of grey squirrels in eight of the hair-tube field sites, whereas red squirrels were recorded in nine sites. The standardised citizen science survey detected the presence of grey squirrels at five sites where they were not detected by hair-tube surveys (Table 3). Conversely, the

Table 3. Results of the hair-tube and citizen science surveys to detect presence of the invading grey squirrel in 14 Munster woodland sites

Hair-tube results are given as the proportion of tubes used by each squirrel species in each site. C = conifer, M = mixed conifer and deciduous, D = deciduous. The asterisk indicates that grey squirrels were observed in the site but not detected by the hair-tube equipment. Red and grey squirrel citizen science sighting reports at the site are indicated by R and G, respectively; – indicates that no reports were received from the defined area. The citizen science survey return from Gortarush was received outside of the standardised time period, in which the two survey methods were directly compared, and is shown in parentheses

Site	Habitat	Month collected	Proportion tubes used		Citizen science survey returns at site
			Red	Grey	
Anglesborough	C	May	0.30	0	–
Kildanoge	C	Mar.	0.17	0	–
Killeen	C	May	0.13	0	–
Killurney	C	July	0.10	0	R
Gortarush	C	July	0.21	0.03	(R, G)
Ballydavid	M	June	0.50	0	R, G
Ballyhoura	M	June	0.33	0	R, G
Glengarra	M	Mar.	0.13	0	R, G
Tikincor	M	July	0	0*	R, G
Kilnamack	M	Aug.	0.03	0.03	R, G
Bansha	D	July	0.07	0.03	R, G
Carey's Castle	D	June	0.11	0*	R
Cahir Park	D	Apr.	0	0.03	G
Gortavoher	D	Apr.	0.03	0	R, G

standardised citizen science survey did not detect red squirrels at three sites where hair tubes recorded the presence of this species.

We used the standardised cost of the citizen science survey to compare the cost of each detection of squirrel presence recorded at the hair-tube sites by both survey methods. Comparisons of scientific benefits, efficiency and cost-effectiveness are summarised in Table 4. The cost of each detection was considerably lower in the standardised citizen science survey than in the hair-tube study. The cost to detect the presence of grey squirrels at a site using hair tubes was also considerably higher than the cost to detect the presence of red squirrels using the same method. The detection efficiency of the total citizen science program was higher than the efficiency of the hair-tube survey, although results from the standardised citizen science survey were more comparable within each species. We found that both the total and standardised citizen science surveys were more cost-effective than was the hair-tube survey program. The standardised spatial cost-effectiveness of the citizen science survey was also higher than that of the hair-tube survey. Furthermore, even though the area covered by the total citizen science survey program was more than 3600 times larger than the area encompassed by the hair-tube survey, its spatial cost-effectiveness was lower by only two orders of magnitude.

Discussion

A 2-year public survey confirmed the widespread distribution of red squirrels in Munster and characterised the advancing invasion of grey squirrels in this region. It is now clear from the results that the southern frontier of the grey squirrel range has progressed in a south-westerly direction since the most recent Irish squirrel-distribution survey (Fig. 4; Carey *et al.* 2007), at a rate comparable to mean rates of spread for this species previously estimated in Ireland, namely, 1.94 km $year^{-1}$ (O'Teangana *et al.* 2000*a*) and 1.75 km $year^{-1}$ (McGoldrick 2011). The favourable comparison between these mean rates of expansion and the current citizen science survey lends credence to the ability of this survey method to accurately track the presence of grey squirrels as the species continues to invade new areas.

As with other volunteer-based citizen science surveys, there was an opportunity for biases to affect the quality and evenness of the squirrel-sighting data received. Dickinson *et al.* (2010) noted that citizen science surveys that do not seek to standardise spatial sampling effort can find an over-sampling of residential, amenity and accessible landscapes and an under-sampling of roadless or inaccessible areas. It is unlikely that this bias would affect the results of the standardised comparison between the two survey methods within the hair-tube sites, and we attempted to control for it within the overall citizen science survey by including only unique sighting locations in the analysis. The hair-tube sites were accessible by road and open to the public. On a national scale, Ireland possesses a dense road network for a primarily rural landscape and inaccessible areas are limited. Although we did not find that habitat affected detection of squirrel presence in the hair-tube survey, red and grey squirrels are known to exhibit differing habitat preferences and this may have led to a difference in the capability of the citizen science survey to detect each species. For instance, grey squirrel detection in the citizen science survey may have been enhanced because of the well documented preference for deciduous woodland of this species and its ability to thrive in urban or suburban landscapes (Koprowski 1994; Bowers and Breland 1996; O'Teangana *et al.* 2000*b*), whereas capacity to perceive the red squirrel could have been reduced. The red squirrel is known to avoid settling in areas of high human disturbance and is more common in coniferous woodlands (O'Teangana *et al.* 2000*b*; Bryce *et al.* 2002; Lurz *et al.* 2005), which mostly occur as large plantations away from large settlements in Ireland. A tendency of survey volunteers to preferentially report rarely sighted or unusual species (Galloway *et al.* 2006; Dickinson *et al.* 2010) may have also improved the ability of this survey to detect both species of squirrel because of differing habitat preferences, the recent arrival of grey squirrels, and the more favourable cultural perception of the native red squirrel.

Table 4. Summary table of efficiency metrics from citizen science and hair-tube surveys for grey and red squirrels in Munster

Total program results relate to the entirety of both surveys. The standardised results were calculated using citizen science records collected over an area and time comparable to those of the hair-tube survey

Scale	Efficiency metric	Citizen science survey		Hair-tube survey	
		Grey squirrel	Red squirrel	Grey squirrel	Red squirrel
Total program	Total area covered by program (km^2)	15 166	15 166	4.2	4.2
	Total time covered by program (days)	730	730	196	196
	Total unique detections	114	362	4	12
	Total cost (€)	12 930.42	12 930.42	10 246.57	10 246.57
	Cost-effectiveness of entire program (detections/cost (€))	8.8×10^{-3}	2.8×10^{-2}	3.9×10^{-4}	1.2×10^{-3}
	Spatial cost-effectiveness (detections/(cost (€) × ha))	5.8×10^{-9}	1.8×10^{-8}	9.3×10^{-7}	2.8×10^{-6}
	Detection efficiency (detections/day)	0.16	0.50	0.02	0.06
Standardised to field-survey area and duration	Total unique detections within area	8	9	4	12
	Standardised cost (€)	2850.77	2850.77	10 246.57	10 246.57
	Cost per detection (cost (€)/detections)	356.34	316.75	2561.64	853.88
	Relative cost-effectiveness (detections/cost (€))	2.8×10^{-3}	3.2×10^{-3}	3.9×10^{-4}	1.2×10^{-3}
	Relative spatial cost-effectiveness (detections/(cost (€) × ha))	6.7×10^{-6}	7.5×10^{-6}	9.3×10^{-7}	2.8×10^{-6}
	Relative detection efficiency (detections/(day × ha))	9.9×10^{-5}	1.1×10^{-4}	4.8×10^{-5}	1.5×10^{-4}
	Spatial detection efficiency (detections/ha)	2.1×10^{-2}	2.3×10^{-2}	9.5×10^{-3}	2.9×10^{-2}

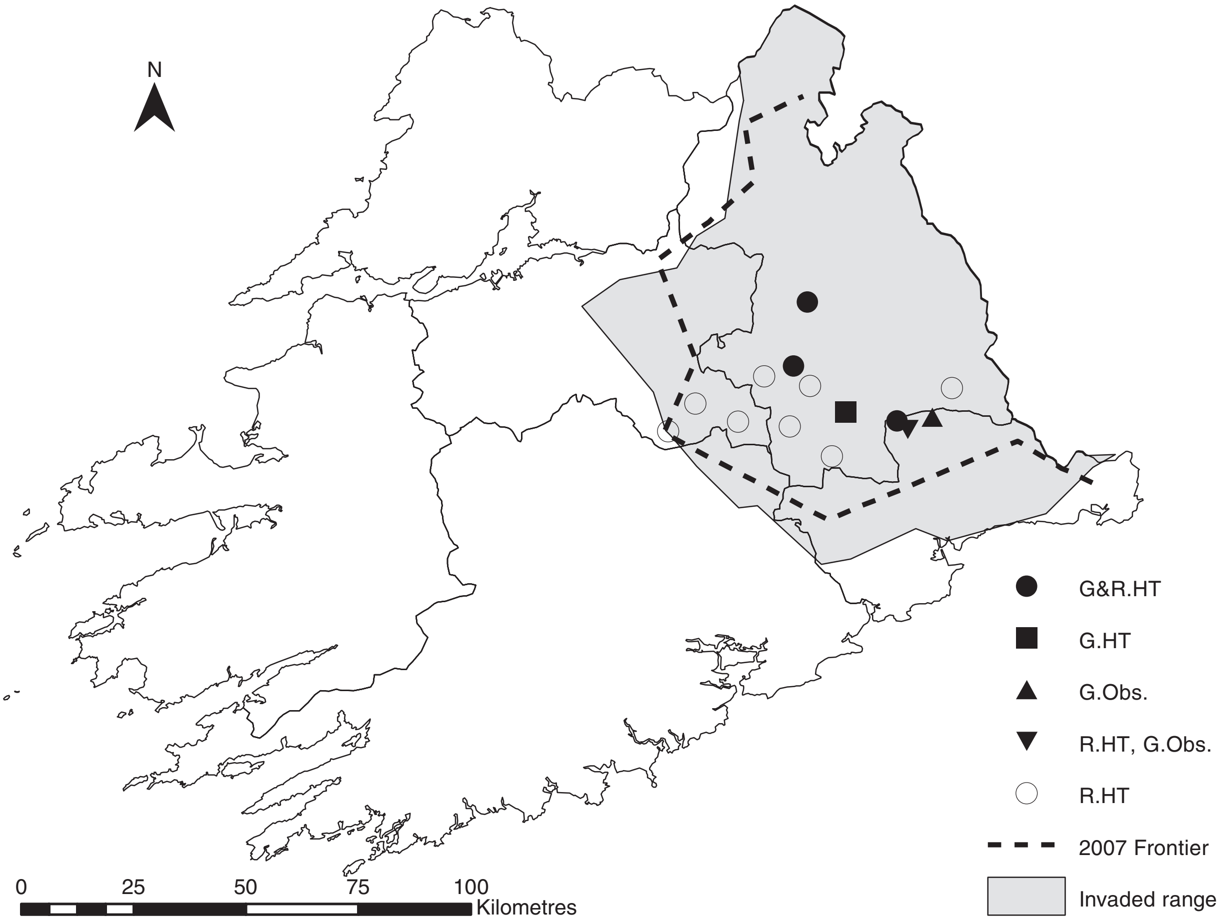

Fig. 4. Squirrel presence detected in Munster Province by the hair-tube survey, overlaid on the grey squirrel-invaded zone, as determined by the citizen science survey (shaded grey). The dashed line indicates the identified frontier of the invasive grey squirrel in 2007. The symbols indicate the squirrel presence ascertained at each site, as follows: positive for red and grey (G&R.HT; ●), positive for grey only (G.HT; ■), observation of grey (G.Obs.; ▲), positive for red with observation of grey (R.HT, G.Obs.; ▼) and positive for red only (R.HT; ○).

The sighting-report acceptance regime was instituted to address a common criticism of previous citizen science projects, namely their reliance on data of unknown quality. The strict sighting-acceptance criteria were established to provide a means to distinguish credible sightings from those of uncertain validity. Relevant supplementary information and colour pictures of each species were prominently displayed on the website, posters and in public presentations, to aid identification. We believe that the greatest potential for misidentification in the present survey was in confusion between red and grey squirrels, rather than misidentification of other mammals as squirrels. Seasonal and age-related pelage-colour changes in both red and grey squirrels could deceive inexperienced observers (Shorten 1954; Gurnell *et al*. 2008), although there are noticeable and easily recognisable differences in the body size and profile of the two species year-round. The high number of responses ($n = 665$) from the small geographic area examined should act to reduce the background noise of erroneously accepted sighting reports. Correct species identification and accuracy in location reporting are key issues that researchers overseeing citizen science projects are seeking to address with new tools (Newman *et al*. 2012). For example, research groups are beginning to take advantage of the wide availability of smartphones with GPS technology and state-of-the-art cameras as well as reasonable smartphone application-development costs to enhance the spatial accuracy and species or individual recognition capabilities of public sightings (Bolger *et al*. 2012; Teacher *et al*. 2013).

Probability of detection of target species by the survey method is a central consideration when determining species presence with direct or indirect surveys (MacKenzie 2005; Stanley and Royle 2005). False absences, or the non-detection of species that are actually present, are likely to be recorded if the detection probability of members of a population is less than 1 (MacKenzie *et al*. 2002). Numerical estimations of detection probability require repeated sampling occasions at several sites. Non-detection of species that are present by the hair-tube surveys may be caused by avoidance of unfamiliar equipment, removal of bait by non-target species or equipment failure. Red squirrel detection probability with hair-tube surveys has previously been estimated to be relatively high (Mortelliti and Boitani 2008), but can be affected by habitat type (Amori *et al*. 2012) and detection of non-target species (Mortelliti *et al*. 2010). The detection probability of grey squirrels by hair tubes has not been similarly examined in the literature and is an area where further study is needed. Because each study site was sampled once, it was not possible in the present study to estimate detection probability of the hair-tube surveys directly for red and grey squirrels. However, a comparison of species-presence recordings at the 10 sites where citizen science sighting reports spatially co-occurred with the hair-tube surveys illustrated a clear trend (Table 3). We have little evidence to suggest that the detection probability of red and grey squirrels by the citizen science survey in the current study was close to 100% (owing to citizen scientists not being asked to record absences). However, we have clear evidence that the detection efficiency of the overall citizen science program is greater than the red squirrel detection efficiency of hair tubes, which in turn is greater than the grey squirrel detection efficiency of our hair-tube protocol.

Finnegan *et al*. (2007) asserted that hair-tube surveys are an effective method to detect grey squirrel presence at low population densities, such as while the species is colonising new areas. The present study detected grey squirrel presence at distances between 24 and 31 km behind the invasion front defined by the citizen survey (Fig. 4), which is farther behind the invasion edge than might reasonably be expected if standard 14-day hair-tube surveys were indeed well suited to detecting colonising populations. Although we did not record squirrel density in the hair-tube survey sites to determine whether populations were well established, it must be assumed that these sites were not the most recently colonised because of the measured distance to the edge of the recorded invasion. A limitation of indirect field techniques is that such methods can detect species presence only where deployed and where animals interact with the equipment. Dispersing squirrels may be more difficult to detect with baited equipment because they are transient rather than exploring or foraging and do not remain in the area to become familiar with experimental devices. A recent hair-tube study in an Irish woodland with an established grey squirrel population recorded 20% of hair tubes positive for grey squirrel (Sheehy and Lawton 2014), which is considerably higher than any proportion of grey squirrel-positive tubes found in the current study. Squirrels in low-density populations may also be less likely to interact with baited equipment because of incomplete exploitation of natural food resources. Habitat type has been shown to influence probability of red squirrel detection by hair tubes rather than species presence (Amori *et al*. 2012), although in the present study, we found no significant effect of habitat on proportion of tubes visited by either squirrel species. Grey squirrels are notably more difficult to live trap in the summer and autumn than are red squirrels, during which time they are more attracted to natural food sources than to bait (Perry *et al*. 1977; Gurnell 1996). There were no significant effects of survey month (March–August) on the proportion of hair tubes visited by either species, although the season ranged from early spring to late summer.

The effective recognition of changes in species distribution, abundance and health is critical in all ecosystems in the face of accelerating species invasions, climate change and increasing anthropogenic disturbance. Often species research or management goals can be convincingly addressed through a combination of complementary survey methods. Long-term and high-quality citizen-science datasets such as the Christmas Bird Count and the Breeding Bird Survey in North America allow for the monitoring of trends in population size and distribution (Tulloch *et al*. 2013*a*). Careful examination of these datasets, along with results from other volunteer-dependent surveys such as dead-bird reports, has enabled researchers to track the evolving range and influence of the West Nile virus (LaDeau *et al*. 2007) and compare observed trends with roost surveys or seroprevalence data (Crosbie *et al*. 2008; Wheeler *et al*. 2009). Not all projects need be so far reaching. Indeed, shorter-term localised citizen science projects have provided enhanced insight into species habitat use, alongside indirect surveys (van der Merwe *et al*. 2005) and insect-biodiversity data in poorly documented habitats (Braschler 2009).

Resource constraints in the conservation-management sector dictate that survey methods that are efficient and cost-effective should be the most utilised. Although it is difficult to directly compare the results of a citizen science sighting survey carried out over a period of years with a discrete series of field surveys, we have assessed each method on its cost-effectiveness, efficiency and ability to detect target species in the geographic area of an invasion frontier. We have shown that more expense was required for each squirrel detection using hair-tube survey techniques than when our basic volunteer citizen science sighting survey was used. Indeed, through the overall citizen science program, we were able to collect squirrel species-presence information over an area more than 3600 times larger than the total hair-tube survey area at similar levels of spatial cost-effectiveness. The collection of squirrel-presence data over a similar spatial scale using hair-tube survey methods would have been economically unviable. To make the most efficient use of scarce time and monetary resources, we propose that the monitoring and tracking of biological invasions of recognisable terrestrial animal species can be carried out through straightforward citizen surveys, given an amenable and appropriately distributed human population, as opposed to hair-tube field surveys. Close monitoring of an accumulation curve of survey responses could indicate to researchers or managers when the majority of the benefit, in terms of numbers of reports or unique locations, has been achieved, so that they may avoid unnecessary input of time and resources. Indeed, the stated objectives of this citizen science survey were largely fulfilled within the first 6–12 months of the program, although the time period of highest productivity will likely vary with each project. Hair-tube surveying is efficient and cost-effective when compared with live-trapping methods for detecting mammal-species presence (Garden *et al*. 2007) and is a valuable technique when employed to assess species presence in sites or habitats of specific interest. Fundamental volunteer sighting surveys, of the variety utilised in the current study, are better suited to acquiring the broad landscape-level species-presence information needed to conservatively locate and track an invasion front than are targeted field surveys. Basic citizen science surveys can be attuned to the early detection of new arrivals to an area because rare and different species are preferentially reported (Dickinson *et al*. 2010); however, these techniques may be less appropriate when the species of interest is less charismatic or noticeable to the general public. In such cases, survey organisers may find that more elaborate volunteer reporting protocols, such as repeated records from defined transects or the requirement of certain survey methodologies (Gaidet-Drapier *et al*. 2006; Tulloch *et al*. 2013*a*), are necessary to acquire the desired detection data, which may in turn increase monetary and time expenditure.

Ideally, decisions regarding management and exclusion of an alien species are formulated before its arrival (Leung *et al*. 2002), although a quick response to a recent arrival can improve outcome (Myers *et al*. 2000). Management response to an invading species should be informed by up-to-date knowledge of the current location of the species and movement trends. Basic citizen science projects can provide information on range expansion in a timely and cost-efficient manner, which should improve the efficiency and efficacy of management response to species invasions.

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