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Visual and acoustic sensors for early detection of biological invasions: Current uses and future potential

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ABSTRACT

Development of tools for early detection of invasive species is critically important as the threat of global invasions increase. Early detection as applied to invasive species is a system of active and passive surveillance to find and verify the identity of new invaders as quickly and efficiently as possible. The earlier such species can be detected the more feasible their control and potential eradication will be. A sensor is a device that detects or measures a physical or biological property (here an invasive species), and records, indicates or responds to it. Here, I summarize what features of visual and acoustic sensors make effective tools for early detection of invasives, and suggest future potential for their use. Visual sensors are by far the dominant mode of detection, particularly in terrestrial habitats. At small scales they include photography and video technology along with the advent of advanced image acquisition and automatic identification. At larger scales remote sensing by use of drones, satellites and video technology are being developed to map invasive species habitats in both terrestrial and aquatic environments. Future use will depend in part on further development of automatic detection methodology. There is also large potential in the use of acoustic methods for early detection of invasives, especially cryptic ones, but such technology is still in its infancy due to technological and analytic limitations. In conclusion, the use of visual and acoustic sensors holds much promise for detecting and monitoring invasive species, particularly in remote settings.

1. Introduction

As the threat of global invasions continues to increase (Early et al., 2016) it is critically important to develop tools for early detection of invasive species (Holcombe & Stohlgren, 2009). The earlier such species can be detected the more feasible their control and potential eradication will be (Wittenberg, 2001; Waugh, 2009). Unfortunately most new invasive species are detected by accident when making general surveys often when it is too late for rapid response or in a location where capacity for response is limited (Lui, Cudmore, & Bouvier, 2007). Standard visual surveys provide longterm systematic and regular documentation of species present in a given habitat; species are identified and vouchered to provide inventories for future research (Wittenberg, 2001). Surveys involve the use of sensors to find, and then verify the identity of new invaders as quickly and efficiently as possible. A sensor is a device that detects or measures a physical or biological property (here an invasive species), permitting subsequent responses such as recording, alerts or control. Desirable characteristics of sensors may include dependability, accuracy, flexibility, target-specificity, automation and being 'low cost'. Clearly all of these traits will not be possible or desirable in every sensor; their importance will be context-specific.

A variety of tools can provide early detection of invasive species, via active or passive means. Traditional methods for invasive-species detection include human-conducted visual and acoustic surveys to identify and voucher the species present in a given habitat, simultaneously providing reference inventories for the future (Wittenberg, 2001). However, camera traps, passive acoustic devices and other remote sensing technologies have expanded the utility of simple surveys at different scales so that data can be recorded, digitized, saved, scanned, compared to known libraries and then easily mapped.

In this paper, I summarize the primary methods used for early detection of invasive species and highlight challenges for future sensor development and use. I do not include chemical methods, such as the use of environmental DNA (e-DNA), as they are covered elsewhere in this issue.

2. Camera traps

Camera traps have long been used to detect and count wildlife species, particularly terrestrial vertebrates. The use of camera traps has recently experienced a dramatic increase (Burton et al., 2015; O'Connell, Nichols, & Karanth, 2011). In addition to surveying and

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monitoring wildlife (Saito & Koike, 2013), camera trap networks may be an efficient method with which to monitor biodiversity at landscape (McShea, Forrester, Costello, He, & Kays, 2016) and global scales (Steenweg et al., 2017). Their strength lies in the ability to capture images of often elusive wildlife in remote environments. They provide a relatively inexpensive and minimally invasive approach to assess wildlife distribution, abundance, behaviour and community structure. As camera traps are static, their weaknesses include relatively small detection areas, a bias towards mobile target species, and limited ability to provide accurate population estimates especially given large species ranges, low densities or inaccessible habitat. These challenges can be addressed with improved statistical modeling, remote access and automated image identification (Burton et al., 2015; González et al., 2016).

However, to date camera traps are rarely used for early detection of invasives. Their effectiveness as early detection sensors will increase as remote access and automated identification improve (Yu et al., 2013). For example, invasive rodents are remotely monitored using traps (Engeman et al., 2006), and more recently monitoring has been automated using images of their footprints. Rodent 'motels' attract invasive ship rats (Russell, Towns, & Clout, 2008). Once in the trap their footprints are captured on ink tracking cards. These images can then be scanned and species identified using image analysis methodologies with high recognition rates (Yuan, Russell, Klette, Rosenhahn, & Stones-Havas, 2006). A similar methodology is being developed to automate standard camera trap images (He et al., 2016) by developing automatic identification algorithms (Yu et al., 2013). Perhaps the best recent example of the use of such technology are web-based traps for early detection of alien wood-boring beetles. The baited traps attract the insects, images are taken, transmitted by a cellular phone network and automatically identified by image analysis (Rassati et al., 2016). Camera traps for larger invasive wildlife are now beginning to develop with the advent of remote access to and automated identification of collected images. For example, invasive wild boar (*Sus scrofa*) presence and activity levels have recently been documented using camera traps in western Canada (Stolle, van Beest, Wall, & Brook, 2015).

The lack of mobility of standard camera traps has been circumvented by developing networks of citizen scientists carrying mobile phones used to document the presence and location of invasive species. This information is rapidly transmitted and, if the web of users is extensive enough, such a method can produce accurate and wide-ranging maps. An example is the iMapInvasives effort (www.imapinvasives.org), an online GIS-based data management system to assist citizen scientists to report, document and map invasive species. The webpage contains a user manual, mobile tools, identification guides and a decisions analysis tool to help managers make decisions about invasive species control.

Similar image acquisition technology is being developed for use of early detection and identification of invasive species from aquatic samples. In aquatic habitats traditional monitoring protocols have included collection plates, SCUBA surveys, underwater video, wharf, dock and boat hull surveys to detect invasive invertebrate species (McKenzie et al., 2016). In addition, plankton tows are often taken to survey larval pelagic invertebrates, followed by detection using light microscopy, scanning electron microscopy (SEM), flow cell cytometry or genetic methods (Hosler, 2011). However much effort is needed to detect rare species with high probability using these methods (Counihan & Bollens, 2017). Dreissenid mussel species are major biofouling pests as they can quickly colonize hard surfaces (e.g., docks, buoys, boats) and clog water intake structures. In North America there are two related species, zebra (*Dreissena polymorpha*) and quagga mussels (*D. rostriformis*). Early detection of these species while they're still in their larval (veliger) stages, and not large enough to restrict water flow, is critical (Hosler, 2011). However this is challenging as they are small (80–400 um) and it is visually difficult to distinguish them from other species. New technology, using automated image particle analysis, has been developed to detect, identify and enumerate invasive quagga and zebra mussels (dreissenids) (Nelson et al., 2015). These methods can process more data faster, but morphologically similar species can still be distinguished more readily with light traditional microscopy (Stanislawczyk, 2016).

The use of camera traps and other visual sensors for detection of invasives will continue to increase especially as image acquisition technology improves. Further development will be facilitated by the incorporation of new technologies into existing methods, for example the recent integration of sound playback into standard wildlife camera traps (Suraci et al., 2017).

3. Remote sensing

On a broader geographic scale remote sensing by use of drones, satellites and video technology is rapidly being developed to map invasive species habitats in both terrestrial and aquatic environments. The use of remote sensing and GIS applications to map invasive species, particularly plants, has increased exponentially in the last few decades (Joshi, de Leeuw, & van Duren, 2004), but until recently has been used to map current distributions and predict their spread (Rocchini et al., 2015) rather than as early detection tools. Remote identification of plants is typically based on spectral signatures (He, Rocchini, Neteler, & Nagendra, 2011), but textural and phenological differences can also be used (Bradley, 2014).

Although remote sensing can be used for early detection and response, accurately detecting small, sometimes cryptic, populations is challenging (Bradley, 2014; Young, Schrader, Boykin, Caldwell, & Roemer, 2007). However, recent work has shown that small inconspicuous species such as bryophytes can be accurately mapped using remotely sensed data. Although its use for early detection depends on many factors, this approach would reduce searching efforts in large areas (Skowronek et al., 2017). Asner and Vitousek (2005) combined remote sensing with photon transport modeling to measure canopy cover visually, and canopy water content and leaf Nitrogen concentrations chemically. This technique allowed them to map the distribution and biogeochemical effects of the invasion of *Morella* (=*Myrica) faya*, a nitrogen-fixing tree from the Canary Islands that is replacing the dominant native overstory tree species, *Metrosideros polymorpha*, at Hawaii Volcanoes National Park. They also made a surprising finding in some understories that showed low foliar N but high canopy water due to the invasion of *Hedychium gardnerianum* (Kahili ginger), a herb that is invisible to conventional remote sensing because it colonizes the forest understory.

Remote sensing technology is also beginning to be used in aquatic systems for the identification and mapping of invasive plants (Meinesz, 2007) and has been especially useful for the detection of harmful algal blooms (Shen, Xu, & Guo, 2012). However, its use is limited in freshwater ecosystems because of their optical complexity and variability (Palmer et al., 2015). Recent applications have included detection of submerged aquatic vegetation (Purkis & Roelfsema, 2015), wetlands (Tiner, Lang, & Klemas, 2015), coral reefs (Goodman, Purkis, & Phinn, 2013) including mapping of coral bleaching (Hedley et al., 2016, Hedley, Roelfsema, Koetz, & Phinn, 2012), mangroves (Klemas, 2015), marsh (Bustamante et al., 2016), and seagrass (Roelfsema et al., 2013) habitats. Mangrove forests can also be mapped and threats identified using shoreline video assessments. This technique collects and analyzes georeferenced hyperlapsed imagery (camera moving through space rather than fixed images over time) which can then be combined with satellite image remote sensing of the same areas (Mackenzie, Duke, & Wood, 2016). To date remote sensing technology has been used primarily for mapping invasive plant species (Huang & Asner, 2009; Johnston, 2015); early detection is more of a challenge because the graminoid structure of many invasive species makes it difficult to distinguish them from other species using remote sensing and thus is most efficient when the invader has colonized and formed large monotypic stands (Johnston, 2015).

On relatively smaller spatial scales, the use of unmanned aerial vehicles (UAVs), commonly known as drones, is emerging as a valuable conservation tool (see ConservationDrones.org) as they are inexpensive, widely available, easy to use, can provide high resolution images closer to the targets, and survey hard-to-access areas (Chabot & Bird, 2015; Koh & Wich, 2012). In particular, drones provide an aerial sensor platform for wildlife monitoring and habitat classification over both terrestrial and aquatic environments (Wich, 2015; Wich, Scott, & Koh, 2017). Such sensors include standard video/still, hyperspectral (measure the frequency of reflected light) and thermal (infrared) cameras. As examples, drones have been used to detect or track sea turtles (Bevan et al., 2015), black bears (Ditmer et al., 2015), salmon (Whitehead et al., 2014), chimpanzees (Van Andel et al., 2015), elephants (Vermeulen, Lejeune, Lisein, Sawadogo, & Bouché, 2013), rhinos (Mulero-Pázmány, Stolper, van Essen, Negro, & Sassen, 2014), marine mammals (dugongs: Hodgson, Kelly, & Peel, 2013; killer whales: Durban, Fearnbach, Barrett-Lennard, Perryman, & Leroi, 2015), and birds (Chabot & Bird, 2012). Bioacoustic monitoring with drones to count soniferous species, such as songbirds, also holds promise, but excessive noise produced by the drone motor is still a major hurdle (Wilson, Barr, & Zagorski, 2017).

The use of drones for early detection of invasive species remains limited. A variety of studies have explored the use of drones for mapping invasive plant species (Hill et al., 2017; Michez, Piégay, Jonathan, Claessens, & Lejeune, 2016; Peña, Torres-Sánchez, De Castro, Kelly, & López-Granados, 2013; Wan et al., 2014), but to my knowledge none so far for invasive animals or for early detection. I suspect such use will increase as the technology becomes more widespread and available. Recent developments in drones, artificial intelligence and miniaturized thermal imaging systems are making such systems more flexible, affordable, and accurate (González et al., 2016). But, as with other forms of remote sensing, drone technology is restricted by the need for accurate automated image detection to facilitate the rapid processing of images. The use of automatic detection and classification algorithms to process such images is promising but still developing (Christiansen, Steen, Jørgensen, & Karstoft, 2014; Dvořák, Müllerová, Bartaloš, & Brůna, 2015; Van Gemert et al., 2014). Rapid development of such algorithms along with more widespread availability of remote sensing technology will likely increase its use for early detection of invasive species.

4. Passive acoustics

There is large potential in the use of acoustic monitoring for early detection of invasives, especially cryptic invasions (Morais & Reichard, 2018), but such technology is still in its infancy. Soniferous species, such as cetaceans (Zimmer, 2011), primates (Kalan et al., 2015; Spillmann et al., 2015), wolves (Suter, Giordano, Nietlispach, Apollonio, & Passilongo, 2017), birds (Towsey, Wimmer, Williamson, & Roe, 2014; Wilson et al., 2017; Joshi, Mulder, & Rowe, 2017), fish (Rountree et al., 2006), insects (Potamitis, 2014), and bats (Andreassen, Surlykke, & Hallam, 2014; O'Donnell, 2000) are monitored using passive acoustics. In addition to monitoring, this non-invasive technology allows researchers to localize and track individuals using recorder arrays, describe the soundscape and measure anthropogenic noise, and discriminate among species, sexes or age groups via detection algorithms (see review by Blumstein et al., 2011). Recent results suggest that automatic detection algorithms show similar accuracy to results obtained by manual identification for a fraction of the cost (Kalan et al., 2015). For example, the Government of Alberta, Canada, has developed a program to monitor the diversity of rare and elusive species using automated recording units that can be deployed in remote locations (Monk & Kohler, 2014).

However, there are very few examples of the use of passive acoustics, including automated identification of the collected sound files to species, for invasive species detection. Passive acoustics is routinely used to detect and map the location of invasive cane toads (*Bufo marinus*) in Australia using a wireless acoustic sensor network (Hu et al., 2009). Sounds are collected in the field using remote microphones, spectrograms generated and frog species identified, with high accuracy, using a classification algorithm. In western Australia, starling (*Sturnus vulgaris*) calls are automatically detected to assist in the location and tracking of their invasions (Campbell, Roberts, Craemer, Pacioni, Rollins & Woolnough, 2017 , Campbell, Barnard, Karjalainen, Obolonkin, & Parsons, 2017). Similarly, the acoustic patterns of an invasive bird, the red-billed leiothrix (*Leiothrix lutea*) have been explored using passive acoustics as a way to measure their impact on invaded soundscapes (Farina, Pieretti, & Morganti, 2013). Their results showed that the red-billed leiothrix is a new acoustically dominant species; its song production amounting to 37% of the total bird community sound production. Such a dominance is likely to be an important modifier of the indigenous bird community soundscape leading to increased competition and contributing to the decline of co-occurring native species (Shigeho, 2006). Finally, passive acoustics tools have also been used in freshwater ecosystems to detect the presence and the potential introduction pathway of an invasive fish species, the freshwater drum (*Aplodinotus grunniens*), in the Hudson River (Rountree & Juanes, 2017).

Although promising, the use of passive acoustics monitoring has not reached full potential due to limitations in observation technologies, data processing capacity and acoustics software development (Rountree, 2008). In aquatic systems very few species have been auditioned out of the many potential soniferous species (see for example for the NE Pacific Ocean, Wall, Rountree, Pomerleau, & Juanes, 2014) and thus automatic detection is not feasible severely increasing processing times. Software hurdles include the ability to filter out noise which can mask fish sound production (Slabbekoorn et al., 2010) as they both peak at low sound frequencies. In addition, localization at small scales remains a challenge (Rountree, 2008). However, recent efforts to combine simultaneous video and audio recordings should go a long way in identifying the source of unknown sounds, including invasive species. The use of underwater observatories in which to develop such technology is particularly promising (Wall, Rountree, & Juanes, 2016), as they can store large amounts of data and make them available to citizen scientists for detection and processing (Matabos et al., 2017). Such observatories, as well as mobile recorders, will be particularly valuable to monitor remote locations such as the deep sea (Rountree, Juanes, Goudey, & Ekstrom, 2012), or the Arctic as it becomes more accessible due to shrinking sea ice (see example of Cambridge Bay observatory; http://www.oceannetworks.ca/cambridge-bay-observatory-monitors-arctic-ocean-health-and-safety), leading to increased shipping, tourism and likely invasion of non-indigenous species (Ware et al., 2016).

Once an invasive species is detected, active acoustics (e.g., playback) can also be used to modulate behaviour to prevent range expansion or to facilitate trapping for biocontrol. Invasive silver carp (*Hypophthalmichthys molitrix*) in the Mississippi River catchment exhibit negative phonotaxis to complex sounds (underwater recordings of outboard motors) that could be used to control their movement (Vetter, Cupp, Fredricks, Gaikowski, & Mensinger, 2015). Adding a male cane toad advertisement call attracts toads by phonotaxis. If the acoustic attractant is placed inside the trap, trapping efficiency of females increases suggesting that such modifications could be an effective method of biocontrol (Yeager, Commito, Wilson, Bower, & Schwarzkopf, 2014). Similarly, invasive Palla's squirrels (*Callosciurus erythraeus*) can be attracted for eradication using mobbing or mating sounds (Tamura et al., 2013) and starlings are trapped using playbacks of their feeding and nestling alarm songs (Campbell et al., 2012).

5. Conclusion

In conclusion the use of visual and acoustic sensors hold much promise for detecting and monitoring invasive species in both

terrestrial and aquatic environments, particularly in remote settings. Their efficiency will increase with the growth of observatories, especially in marine systems (see for example, www. oceannetworks.ca). It is likely that use will increase and cost decrease as technology improves and automation becomes more feasible. More research is needed to facilitate the incorporation of new technologies into existing methods as they become available. Ultimately, growth of the use of sensors for early detection of invasives will be driven primarily by the development of automatic detection and identification procedures, allowing the efficient processing of large amounts of data at time scales where rapid responses are still possible, and before such species colonize and naturalize in their new habitats.

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