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Advancing federal capacities for the early detection of and rapid response to invasive species through technology innovation

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Abstract

Invasive species early detection and rapid response (EDRR) actions could integrate technologies, innovation, and other outside expertise into invasive species management. From early detection by forecasting the next invasion and improved surveillance through automation, to tools to improve rapid response, the next generation of management tools for a national EDRR program could integrate advances in technologies including the small size and ubiquity of sensors, satellites, drones, and bundles of sensors (like smartphones); advances in synthetic, molecular, and micro-biology; improved algorithms for artificial intelligence, machine vision and machine learning; and open innovation and citizen science. This paper reviews current and emerging technologies that the federal government and resource managers could utilize as part of a national EDRR program, and makes a number of recommendations for integrating technological solutions and innovation into the overall Federal Government response.

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Early detection and rapid response (EDRR); invasive species; technology; synthetic biology; machine learning; citizen science.

INTRODUCTION

In the United States (U.S.), invasive species are a major economic (Bradshaw et al. 2016), biosecurity (Meyerson and Reaser 2003), and environmental threat to natural resources (Simberloff et al. 2013), infrastructure (Connelly et al. 2007), agricultural production (Bradshaw et al. 2016), human health (Bradshaw et al. 2016, World Bank 2016, Young et al. 2017) and wildlife health (Drake et al. 2016, Young et al. 2017). The total economic damages of invasive species are estimated at almost $120 billion per year (Pimentel 2005), and a result of increasing international travel and trade. Invasions are expected to continue to increase into the future unless we are able to scale better and more effective solutions (Seebens et al. 2017).

Early detection and rapid response (EDRR) are critical processes to prevent the spread and establishment of invasive species. To coordinate EDRR on a national scale, in 2016 the U.S. Department of the Interior published "Safeguarding America's Lands and Waters from Invasive Species: A National Framework for Early Detection and Rapid Response" (hereafter "EDRR Framework"). It defines early detection as, "the process of surveying for, reporting, and verifying the presence of a non-native species, before the founding population becomes established or spreads so widely that eradication is no longer feasible" and rapid response as "the process that is employed to eradicate the founding population of a non-native species from a specific location" (U.S. Department of the Interior 2016).

There is a narrow window of time when EDRR efforts can effectively eradicate or control invasive species before populations become too big and eradication or control efforts become too expensive (U.S. Department of the Interior 2016). Emerging technologies may expand the window of opportunity for an effective response, reduce the costs (in dollars and other resources) associated with response efforts, and achieve eradication ambitions. The democratization of science and technology and greater interconnectivity, coupled with new approaches to collaboration and open innovation can dramatically improve the efficacy, speed, cost, and scale of preventing, detecting, responding to, and eradicating or controlling invasive species. All of these advances create an opportunity for the Federal Government to enhance the technology and tools utilized in a national EDRR program to address invasive species challenges at the pace, scale, and level of precision necessary to keep up with, and even get ahead of, the problem.

Following the EDRR Framework (U.S. Department of Interior 2016), this paper considers emerging technologies and their applications that, if scaled, could enhance a national EDRR program. Further, as the invasive species challenges and technologies are constantly evolving, it is equally important to build platforms that unlock innovation, data, and new technologies and continue to develop new solutions that can adapt to new threats and opportunities. This paper reviews the potential for open innovation and open data to assist the Federal Government and partners with adaptation and keeping pace with the scale and dynamics of the threat. We conclude the paper with a discussion of what is needed and recommendations so that the Federal Government can realistically apply, scale, and implement many of these technologies in support of a national EDRR program.

1. Automating Early Detection

The most cost-effective defense against biological invasion is preventing invasive organisms from ever arriving (U.S. Department of Interior 2016, Lodge et al. 2016). Forecasting potential invasions through "horizon scanning" can help prioritize among different threats (Gallardo et al. 2015), predict and assess the most likely pathways (Essl et al. 2015), and predict the species most likely to invade (Roy et al. 2014). Conventional horizon scanning involves extensive literature reviews and expert meetings (Sutherland et al. 2011, 2013), but this is increasingly difficult given the growing size of published scientific literature (Ware and Mabe 2012) and new sources of data such as Data.gov; experts are also subject to cognitive biases (World Bank 2015).

Federal agencies could use data analytics and machine learning to improve horizon scanning (Qiu et al. 2016). In the biomedical field, the program Meta scans all of PubMed and online technical publications to make predictions about scientific discoveries and assists users with literature reviews. Using AI-assisted horizon scanning could accelerate the identification of potential invasive species and prioritization of responses. However, AI systems still need human intelligence and capacity to train and verify algorithms (U.S. Senate Committee on Commerce Science and Transportation 2016).

2. Early Detection: Surveillance, Identification, and Verification of Invasive Species

International trade and travel are major pathways for invasive species (Lodge et al. 2016, Essl et al. 2015) (see Box 1). Pathways include crates and luggage, shipments of food and other commodities, ballast water, wood products and packaging, and humans. Currently, without sophisticated identification and detection tools, inspectors and practitioners rely on vigilance and personal taxonomic knowledge to identify a potential invasive species. Multiple federal agencies are responsible for monitoring ports of entry for invasive species (see National Invasive Species Information Center), so coordination is important. Moreover, agencies are inspecting cargo for hazardous materials, security threats, or contraband, not necessarily invasive species. For instance, the Department of Homeland Security's (DHS) U.S. Coast Guard screens shipping containers at ports of entry, and Customs and Border Protection (CBP) utilizes X-ray systems and detector dogs to inspect cargo and travelers (U.S. Customs and Border Protection 2016). There is an opportunity to leverage and improve these technology and resources that these agencies already employ for reviewing cargo to automate early detection at border entry points.

Box 1: Invasions from Wood Packaging

Wood packaging is a repeated source of introductions of wood-boring larval insects, including the Asian longhorned beetle (Haack et al. 2014, Flø et al. 2014, Wu et al. 2017), despite international standards requiring treatment of all wood packaging used in trade (IPPC 2009). Replacing packaging with plastics and other composites that are inhospitable to insects is one solution, but the Defense Advanced Research Project Agency's (DARPA) Engineered Living Materials program may offer additional options. DARPA's research program aims to create a new class of "living" or "smart" *materials that combines the structural properties of traditional building materials with attributes of living systems. This allows the materials to better adapt to the physical and biological environment. Hybrid materials will be made of nonliving scaffolds that give structure to and support the long-term viability of engineered living cells. Such "smart" or "living" materials could change its color to indicate that the presence of an invasive species or pathogen, or even "consume" potential invasive species.*

Once an invasive species makes it across a border, the challenge is to identify and verify the species, understand the extent and distribution of its presence; predict where it will may establish next, stop its spread, and control or eradicate it. There is distributed and insufficient knowledge on the locations of emerging populations of invasive species, and it is very expensive and time-consuming for invasive species specialists to survey for and determine the locations and distributions for all emerging and growing invasive species populations. Technology can be extremely helpful in increasing the capability and reducing the cost to conduct such assessments at scale, and in accelerating the reporting and analysis of the data for managers.

A. Detecting Presence of Invasive Species at Local Scales

Species may be difficult to detect for a number of reasons: they occur at low densities, live cryptic lifestyles, are difficult to separate from endemic species, or are difficult to see without additional equipment, like spores and microorganisms. The following technologies, if scaled, offer less labor- and time-intensive solutions for the early detection in the field. For any of the following detection technologies, one needs to consider lessons-learned from years of utilizing camera traps to monitor wildlife – an assessment of the distribution and abundance of species still requires human capacity to design data collection protocols that consider, for example, the range detected by the technology and the behavior of the targeted species, as well as the application of capture-recapture statistics (Burton et al. 2015).

1. Visual Monitoring

Camera traps utilize motion sensors to remotely capture photo and/or video footage (Swann et al. 2010, Burton et al. 2015). Camera traps work well for detecting the presence of large-bodied, mobile, and cryptic species that are challenging to detect through traditional field survey methods in rough terrain (Linkie et al. 2013, Sollmann et al. 2014). Despite the ability to detect cryptic species, camera traps are time consuming because of the need to analyze images, which limits their use for detecting invasive species over large geographic ranges. However, camera trap technology is emerging, with additional "smart" capabilities such as 360 image capture, computer vision algorithms for species recognition, sensors that facilitate automatic object tracking once a species is recognized, creating interconnected grids of camera traps, and the ability to report species in real-time. Some of these functions already exist in consumer drones and camera traps (Ramsey 2012). Crowdsourcing through platforms like eMammal and

Zooniverse can also accelerate the identification and classification of large numbers of complex images (Swanson et al. 2016) that may contain invasive species, and serve to train algorithms.

2. Acoustic Monitoring

Acoustic monitoring already allows for the identification of individual species through environmental audio recordings (Servick 2014). The Stevens Institute of Technology, working with CBP, sought to use acoustic sensors (piezoelectric sensors, lasers Doppler vibrometers – also applicable to wood, ultrasound microphones) to monitor rodents and insect pests in grain shipments (Flynn et al. 2016). In laboratory settings, off-the-shelf laser vibrometers detected Asian longhorned beetle larvae (*Anoplophora glabripennis*) in wood samples (Zorović and Čokl 2014) and both adults and larvae of Dermestid beetles (*Trogoderma inclusum*) and Mealworms (*Tenebrio molitor*) in rice samples (Flynn et al. 2016). Smartphones, which contain microphones and sufficient computational power (Lane et al. 2010) for acoustic monitoring, may also allow for democratization of such monitoring in the future.

Such acoustic sensing technologies will be deployed in the near future, including at monitored ports of entry; DHS is developing methods for CBP that include both microwave and acoustic sensors (Flynn et al. 2016). Mosquito detection is an emerging application – a program called HumBug is creating a system that utilizes portable devices for real-time detection and alerts combined with high resolution imagery to notify users about the presence of mosquito vector species in users' proximity. Such programs could be an effective early detection and warning system as part of a national EDRR program to detect mosquito vectors of invasive pathogens like Zika virus, as well as other audible invasive species.

3. Chemical Monitoring

Advances in nanofabrication have permitted the manufacture of highly sensitive nanobiosensors in high volumes at relatively low cost. With more development, these sensors may offer a solution for monitoring large areas or ports of entry. Nanobiosensors have been developed for the agricultural and veterinary sectors to detect pathogens (fungal, viral, and bacterial) in crops and animals (Lambe et al. 2016, Handford et al. 2014, Chen and Yada 2011), and they could be developed for invasive species. Nanosensors can act as accurate chemical sensors (Chikkadi et al. 2012), and if networked and scaled, they could potentially signal the presence of invasive species by detecting volatile organic compounds (VOCs) emitted by invasive plants, insects, and pathogens over a large area (Afsharinejad et al. 2016).

Detection dogs can serve highly sensitive chemical sensors for detecting invasive species (Box 2). E-nose devices, engineered biomimics of a dog's nose, are currently used in laboratory settings within the agricultural industry to detect, for example, the presence of hazardous microbes on crops (Wilson et al. 2004, Wilson 2013), plant diseases (Jansen et al. 2011, Wilson 2013), and wood rot caused by pathogenic fungi (Baietto et al. 2015). There is at least one portable e-nose device on the market (Sensigent's Cyranose e-nose), but low-cost sensor components and microcontrollers are making it possible to construct and experiment with inexpensive portable e-nose devices (Macías Macías et al. 2013). Portable e-nose devices could be deployed in the field (e.g. attached to drones, or at a port of entry) to detect the volatile organic compounds emitted by plants when vegetative tissues are damaged by invasive species (Unsicker at al. 2009).

Box 2: Detector Dogs
One sensor that has proven effective over the past 15 years in wildlife and ecological sciences is the use of detector dogs. Initially used to detect the scat and other signs of cryptic endangered species (Reindl-Thompson et al. 2006), detector dogs have been repurposed to accomplish other tasks including detection of bird carcasses resulting from impacts with anthropogenic structures (Homan et al. 2001), identification of animal parts in illegal wildlife trafficking, and detection of invasive species. Not surprisingly, dogs have been used most frequently and successfully to rapidly detect the sign of small to large invasive mammals, including feral cats, nutria, and mongooses (Fukuhara et al. 2010, Kendrot 2011, Glen et al. 2016). However, detector dogs have also successfully located of a variety of other invasive taxa, including Dreissenid mussels (see MussellDogs.info), brown tree snakes and Burmese pythons (Savidge et al. 2011; Avery et al. 2014), insects (Lin et al. 2011; Lee et al. 2014), and even invasive weeds (Goodwin et al. 2010). In addition to their use in the field, detector dogs are used to inspect both outgoing and incoming cargo at ports (Vice and Vice 2004).

4. Portable DNA Sequencing, Environmental DNA, & Biological Assays

The use of DNA for species identification is well-established; for example, lab-based DNA barcoding identified invasive wood-boring beetles in solid wood packaging (Wu et al. 2017). However, this generally requires expensive equipment, time, and specialized expertise. Portable, field-ready DNA sequencing systems could reduce costs, training and equipment required, and shorten detection times. These systems are becoming increasing feasible, enabled in part by the International DNA Barcode of Life Library database and new devices such as the Oxford Nanopore MinION (and nextGen Smidgion) (Jain et al. 2015). A collaborative effort among Conservation X Labs, the Smithsonian Institution, and the University of Washington is pursuing the development of a low-cost, modular, battery-powered, field-ready device to extract, amplify, and identify DNA barcodes from biological samples (John 2016).

Environmental DNA (eDNA), is the DNA of organisms secreted into the environment in their feces, mucus, and gametes, as well as through shed skin, hair, and decomposing carcasses (Thomsen and Willerslev 2015). eDNA is readily detectable in soil and water samples and solves many of the issues with respect to assessing the presence and distribution of cryptic species (Foote et al. 2012, Jerde et al. 2011). Federal and non-federal researchers use eDNA methods to detect and track many invasive species around the world (Table 2 and Kamenova et al. 2017). Advances in high-throughput sequencing of eDNA could radically reduce labor costs by processing hundreds of samples simultaneously (Taberlet et al. 2012, Reuter et al. 2015). One of the shortcomings of eDNA analysis is that it detects the presence of the target DNA, but the analysis does not distinguish the source of the DNA (Roussel et al. 2015). Also, the assay's high sensitivity is both a benefit and a limitation, as eDNA can be detected from fish removed from an ecosystem up to 35 days after elimination (Dunker et al. 2016). Thus, currently this method is best used in conjunction with traditional sampling methods, using eDNA analysis to better focus sampling in areas with positive tests (Kamenova et al. 2017).

Field-based biological assays designed to identify species in a short period of time based on genetic material is another potentially scalable technology. For example, USGS is creating an assay to detect invasive carp based on eDNA via loop-mediated isothermal amplification (LAMP) (Merkes et al. 2017). Microsoft's Project Premonition, an IARPA-funded (Intelligence Advanced Research Projects Activity) effort, is developing AI insect traps that will selectively capture mosquitoes based on machine vision, and remotely detect disease threats (like Zika virus) via assays based on genetic material from the captured mosquitoes.

5. Early Detection Tool Development and Sharing: Risk Assessments

Detection of potential invasive species must be coupled with risk assessment and decision support tools. There are a number of data sources to complete risk assessments (Lodge et al. 2016, see Online Resource 1) and various types and methodologies of risk assessments (Kumschick and Richardson 2013, Faulkner et al. 2014, USFWS 2016). Of note, Howeth et al. (2016) describes a comprehensive, trait-based risk assessment for non-native freshwater fish becoming invasive species in the Great Lakes. Automating this process, for example through algorithms trained by experts complemented by targeted collection of data, could be a highly valuable tool coordinated by a national EDRR program.

B. Connected Ecosystems: Detecting Species at Landscape Scale

New technologies, such as drones and nanosatellites, allow for the surveillance, detection, and reporting of an invasive species on a landscape scale as it spreads and expands its range, especially in areas where it might not be feasible to monitor with traditional sampling. The democratization of mobile platforms, dramatic increases in connectivity, and the ability to harness the power of nonprofessional scientists has created opportunities for distributed early detection and rapid response of invasive species. The technologies described in this section, if scaled, offer the possibility to better detect and monitor invasive species over large geographic ranges.

1. Connected Ecosystems

There are more than 7.5 billion mobile subscriptions around the world, including 3.9 billion smartphone subscriptions (Ericsson 2016). Smartphones today contain multiple sensors (Lane et al. 2010), including microphones, cameras, altimeters, accelerometers, barometers, gyroscopes, proximity sensors, compasses, Bluetooth network devices, and GPS sensors. Furthermore, the current popularity of open source hardware provides an opportunity for a global community of engineers and scientists to perform the development, maintenance, and modification of these systems.

The Internet of Things (IoT) phenomenon is based around the use of internet-connected sensors (visual, chemical, acoustic, and biological) to make decisions or increase efficiency within our homes and cities based on near-real-time data collection. The adaptation of this hardware and software into environmental protection is being explored in projects globally (Guo et al. 2015, Hart and Martinez 2015). Readily available low-cost sensor components and microcontrollers (e.g. Arduino, Adafruit, and Raspberry Pi) are improving and expanding data collection capabilities. For example, the winning entry in the US State Department's 2016 Fishhackathon (a digital technology coding competition focused on marine issues) was "Great Lakes Savior," a solution that leveraged basic scientific sensors, an IoT infrastructure, and spawning models to attempt to predict the hatching period of invasive carp in the Great Lakes based on water temperature.

2. Citizen Science

With greater connectivity through smart mobile platforms, there are greater opportunities to expand the pool of data collectors and analyzers to increase the reach and scale of monitoring invasive species (Pimm et al. 2015). Citizen scientists can increase the on-the-ground capacity for EDRR efforts, allowing scientists to leverage, for instance, the eight billion recreational visits that are made annually to terrestrial protected areas (Balmford et al. 2015). A number of recent studies provide strong evidence that volunteer-collected data are just as accurate as that collected by professionally trained scientists (Lewandowski and Specht 2015), and there are robust analytical methods to sort through the noise of volunteer datasets to reveal critical data and trends (Wiggins et al. 2011, Hochachka et al. 2012, Kelling et al. 2015, Swanson et al. 2016).

Box 3: The BugWood Apps

The Center for Invasive Species and Ecosystem Health at the University of Georgia has been especially prolific in harnessing citizen scientists in addressing invasive species. The Center's suite of Bugwood mobile apps has capitalized on the ubiquity of smartphones plus the public's interest in pest and invasive species. Many of the apps are dedicated to both early detection and rapid response. For example, the Squeal on Pigs app provides services to both landowners and state officials to effectively work together to report and eradicate feral pig populations. In Florida, users can report real-time sightings of live invasive species, like Burmese python and melaleuca trees, through the IveGot1 app. The app collects the GPS locations of users when they submit images, and the images are e-mailed to local and state verifiers for review.

Existing citizen science and crowdsourcing-based programs are specifically designed to report and monitor invasive species by submitting observation data through websites, mobile phone applications, or even through paper forms (Table 1). Citizen science biodiversity observations submitted to iNaturalist, which collects observations of native and non-native species from people all over the world, is integrated into the Global Biodiversity Information Facility (GBIF). The Bugwood suite (Box 3) includes multiple near-real-time early detection and distribution map apps (*e.g.,* EDDMapS) that are already supported by federal entities, including U.S. Forest Service (USFS), National Park Service (NPS), U.S. Army Corps of Engineers (USACE), U.S. Department of Agriculture (USDA), and USFWS. Participants in the invasive species citizen science programs are providing much-needed spatial and temporal granularity, and these efforts are critical for a national EDRR program.

3. Unmanned Aerial Vehicles & Remotely Operated Vehicles

A challenge for any sensor-based monitoring method for invasive species is gaining physical access to an area under study. Drones (unmanned aerial vehicles, UAVs), underwater remotely operated vehicles (ROVs), and Do-it-Yourself (DIY) kite or balloon mapping can achieve access and carry sensors that could help detect invasive species through remote imaging at scale and, as demonstrated by UAVs and ROVs, control invasive species (Table 3). UAVs and ROVs can efficiently and cheaply cover a large geographic range: they can reach places that are physically difficult for humans to access, are less expensive than aircraft, cover substantially more territory and topography, can carry a variety of cameras and sensors, and can even collect biological specimens or target and eliminate individual organisms through ballistic application of herbicides. For instance, drones have successfully mapped the distribution of the common reed *Phragmites australis* in Trasimeno Lake in Italy (Venturi et al. 2016); although this species is not invasive in Italy, some *Phragmites* species are invasive in the U.S.

Drones can also replace aircraft and other vehicles in carrying advanced sensor packages like LiDAR, which effectively detects the distribution of invasive plant species (Asner et al. 2008, Barbosa et al. 2016). Similar three-dimensional data can be collected by drones using cameras and multi-view stereopsis technology (Harwin and Lucieer 2012) and lightweight LiDAR sensors for drones are already on the market (e.g. LeddarTech). Despite the regulatory and licensing barriers to deploying drones in the U.S. (Werden et al. 2015), with the combination of infrared cameras, pre-programmed night flights, the ability to deliver baits, and advances in Artificial Intelligence (AI), Campbell et al. (2015) predict that drones will be widely adopted for invasive rodent eradication programs in the next five years.

Citizen scientists and active communities are creating inexpensive DIY aerial platforms to collect high-resolution imagery of various environmental features. Public Lab pioneered the use of kite and balloon mapping, where people image the earth remotely using digital cameras (or other sensors) attached to kites or helium-filled balloons (Delord et al. 2015). Public Lab also created free and open source software, MapKnitter, to combine aerial images into a georeferenced mosaic. This inexpensive alternative makes aerial mapping accessible to a much larger community and should be seen as an opportunity for a national EDRR program to encourage communities to self-monitor for invasive species that are visible in high-resolution images, and as a frugal tool for land managers to map the spread of invasive species.

4. Nanosatellites

Small, low-cost nanosatellite constellations offer an alternative method for collecting remote-sensing data where drones may be limited by battery power, payload, and social acceptance, and where larger satellites are limited by cost, resolution, cadence, and coverage to effectively detect invasive species (Selva and Krejci 2012, Table 4). One company, Planet, operates a constellation of 149 nanosatellites, enabling 3-meter-resolution imagery of the Earth every day, compared to Landsat 8, which provides 30-meter resolution (15 meters panchromatic) of the entire planet every two weeks. Nanosatellites also have the capacity to harness the rapid evolution of consumer electronics. Traditional earth observation satellites are costly (Landsat 8 costs approximately $900 million), purpose-built technology that is frozen at the beginning of the design and manufacturing process, and require a decades-long development time. By comparison, nanosatellite constellations can leverage the low costs of the satellites and low launch costs coupled with a rapid launch cycle, to allow for rapid development of the constellation capacity, as new instruments can be flown much more quickly than with conventional satellites.

There are some drawbacks. Sensors for nanosatellite platforms must generally be smaller and operate with lower power, and there are larger data analysis challenges, such as calibrating sensors across many individual satellites, groundtruthing, and data integration (Dash and Ogutu 2016). Well-calibrated instruments like Landsat can complement nanosatellites to overcome some of these issues. Even given these limitations, the potential for landscape-scale monitoring based on frequent, high-spatial-resolution data would be a powerful tool for detecting significant population changes of invasive species across very large regions. A national EDRR program should have access to up-to-date and frequently available remotely sensed data, as high-resolution distribution maps of invasive species are critical to target management of early infestations and to model future invasion risk (Bradley 2014).

C. Automating Data Analysis for Identification and Verification

Advances in "data science," including predictive analytics, machine learning, and microwork, can automate the mining of data sets, including images, audio files, and chemical signatures, to reveal patterns, trends, and associations that would otherwise be unclear or difficult to identify. There are a number of global, regional, and local databases that catalogue large amounts of information on invasive species (Online Resource 1) and related databases tied to taxon such as the International Barcode of Life database, GenBank, Fishbase, as well as vast troves of historical data from collections in Natural History Museums (Thiers et al. 2016) and government agencies (e.g. Data.gov) that could be mined with such advances.

Machine learning and vision, coupled with artificial intelligence, can help verify species observations and create comprehensive intelligent decision support systems when applied to data collected by humans and sensor networks. In order for a machine to learn, humans need to train the machines with deep learning recognition algorithms, which are created using libraries and large datasets of labeled images (or other types of labeled files). Datasets must be labeled manually, which occurs in some citizen science datasets, or can be accomplished using crowdsourced microwork platforms like Mechanical Turk. Moreover, there are online communities and open innovation sites dedicated to facilitating the merger of AI and big data analytics (e.g. Kaggle, Zooniverse, Banerji et al. 2010, Beaumont et al. 2014).
EDRR applications could combine data collected from sensors, drones, citizen scientists, and satellites with machine learning algorithms for near-real-time on-board data analysis for detection and verification of invasive species. Machine vision techniques have been developed to automate genus or species identification for multiple plants and animals (Table 5). For example, the U.S. Geological Survey (USGS) is working with Conservation Metrics, Inc. to develop machine vision algorithms from existing camera trap images of the invasive brown tree snake (*Boiga irregularis*) to automate detection of the snake in the wild on Guam, where it has devastated the islands' native bird fauna (Klein et al. 2015).

The invasive species EDRR community can also harness social media hypertargeting to improve the ability to detect invasive species outbreaks. For example, Daume (2016) found that an analysis of Twitter posts about a few specific invasive species was a strong indicator for important life cycle activities (e.g. adult emergence for Emerald Ash Borer), as well as a landscape of public communications and perceptions of invasive species and their management. Researchers have used online geotagged photo sharing sites, like Flickr and Panoramio, to mine for data on ecosystem services (Figueroa-Alfaro et al. 2017), and these datasets could also provide additional geographic granularity for some invasive species.

Automation will expedite the identification of species, yet the EDRR Framework states that authorized representatives (taxonomic experts) are needed to confirm species' identity before rapid response actions are implemented (U.S. Department of Interior 2016). Data submitted to EDDMapS and iMapInvasives, for example, are verified by experts. Yet, for a national EDRR response, both the recognition that there is a new and invasive species in a new location and verification of that new species by experts are potential bottlenecks when timing is critical between early detection and rapid response to prevent the geographic spread of invasive species. We may address these bottlenecks and expand leverage and scale not only through the automation of species identification, but also through national efforts that formally train and entrust citizen scientists as experts.

3. Rapid Response: The Development of Scalable Programs and Technologies to Prevent Populations from Spreading

The failure to sufficiently target eradication efforts may lead to negative side effects such as the unintended consequences of indiscriminate pesticide application (Pimentel 2005) or introduction of non-native natural enemies of invasive species (Messing and Wright 2006). New technologies can provide more targeted approaches at different scales and timeframes. Managers may deploy autonomous robots to address both new and established invasive populations on local scales while new molecular tools may be more feasible for longer-term control due to regulatory and social constraints. Advances in communications, mapping, and data processing could help to scale national rapid response actions.

Rapid response actions require leadership and coordination across networks to create, implement, and communicate plans for quarantine and emergency containment; treatment procedures; and, monitoring, evaluation, and reporting (U.S. Department of the Interior 2016). Advances in communications, mapping, and data processing could help to scale national rapid response actions.

A. Coordination, Implementation, and Efficiency of Rapid Response

The Federal Emergency Management Administration's (FEMA) National Incident Management System (NIMS) provides a template for a national-scale training and response system, while CDC's protocols for disease outbreak management may be also similarly instructive. USDA's Animal Plant and Health Inspection Service, Plant Protection Quarantine (APHIS-PPQ) created a framework for emergency management of invasive and pest species (USDA APHIS PPQ 2014) that potentially can be adapted for all invasive taxa. To increase boots-on-the-ground for rapid response incidents, the relevant networks might include well-trained citizen scientists as well as invasives species practitioners. A national EDRR program could leverage the existing emergency response organizational frameworks plus mass communication network technology to deliver information to the smartphones of responders.

B. Automating Rapid Response

1. Robotics

With advances in sensors, robotics, drones and AI, there is an opportunity to automate response efforts and minimize human effort (Cantrell et al. 2017). For example, robots provide added capacity and can work longer hours, in adverse conditions for humans, such as underwater, in inclement weather, or at night. Researchers at the Queensland University of Technology created the COTSbot, an autonomous robot equipped with machine vision, stereoscopic cameras, and a pneumatic injection arm to identify and kill invasive crown-of-thorns starfish in the Great

Barrier Reef. The COTSbot also demonstrates that robotics and/or drones combined with machine learning could serve as a powerful rapid response tool for both newly introduced species, and species that are well-established where human-led eradication efforts have failed.

2. Genetic Engineering

Current advances in genetic engineering are rivaling—and in some cases overtaking—the rate of change that we have seen in computing and information technology. Further, such genetic modification is cheaper, easier, more precise, and more rapid than ever before, and is thus widely accessible. A modern synthesis of biology and technology has created the entirely new field of synthetic biology, a sub discipline of molecular biology that merges biology with engineering, where scientists are able to design (or redesign) species' genomes and fabricate novel biological functions and systems that do not exist in the natural world. CRISPR/Cas9 endonuclease and other biological tools have made such precise genomic editing possible by allowing scientists to delete a target gene and/or insert a synthetic one at multiple positions within a genome (Cong et al. 2013, Barrangou and Doudna 2016), with the potential to create targeted and highly efficient responses to invasive species. In contrast to traditional, non-targeted response efforts (e.g. blanketing areas with pesticides or introducing predators), modern molecular biology research aims to confer new traits to organisms by rapidly and purposefully modifying their genomes, which can then be introduced in a targeted fashion to specific geographic areas.

Researchers have created techniques to control mosquito vectors to reduce the transmission of non-native diseases. In Brazil, the Oxitec company successfully released genetically modified male *Aedes aegypti* mosquitoes, the vector of dengue fever, Zika virus, and chikungunya, where the modified mosquitos can mate with wild females, but the resultant offspring die before they reach maturity (Winskill et al. 2015). This is a variation of an earlier approach in which the DNA of the male mosquitoes is damaged through irradiation and the mass release of these sterile males suppresses the population (Piaggio et al. 2017). Some conservationists believe that this may be beneficial to managing avian malaria which has devastated Hawaii's endemic avifauna (Piaggio et al. 2017). Risks from using this approach include potential disruption of acquisition of natural immunity to Plasmodium infection by endemic avifauna.

3. Gene Drives

Gene drives enable genetic modifications to be transferred into a population without introducing large numbers of modified organisms. Researchers have proposed using gene drives to ameliorate insect-borne pathogens (Sinkins and Gould 2006; Esvelt et al. 2014). This strategy is based on natural "selfish genes," which permeate the population faster than what would be expected by the conventional shuffling of genetic information during sexual reproduction (Burt 2003).

Gene drives could be used to push deleterious traits into an invasive population, thereby reducing the population's overall fitness (Esvelt et al. 2014). One example of conferring a trait to invasive species is a "sex ratio distortion" drive (Galizi et al. 2014, Hammond et al. 2016), which results in fertile offspring of only one sex. The release of a limited number of these modified individuals into a natural population would have the potential "to eventually breed that population out of existence" (Piaggo et al. 2017). A related strategy was used to crash the malaria vector mosquito species, *Anopheles gambiae*, in a closed, experimental setting (Galizi et al. 2014). Modeling studies show that full replacement occurs between approximately 5 and 20 generations, and varies greatly depending on the competitive burden the transgenic elements place on the organism (Burt 2003, Deredec et al. 2008).

Gene drives may pose risks because once introduced, they intentionally drive through populations with no further human control. Other risks include potential gene transfer between modified individuals and endemic species; public opposition; and unanticipated ecosystem effects following successful eradication (National Academies of Sciences, Engineering 2016, Piaggio et al. 2017). However, there are several experimental mitigation strategies to reduce the risk of the uncontrolled genetic modification of wild populations (Esvelt et al. 2014), like "reversal" gene drives, or "immunization" gene drives to protect against deleterious ones. Also, fine-tuning of the genetic burden of the gene drive, or "daisy-chaining" multiple gene drive elements into distinct portions of the genome, could allow implementers to create constructs that will reach local but not global fixation (Esvelt et al. 2014). DARPA's Safe Genes program aims to support these advances in synthetic biology and the tools and methodologies to mitigate the risk of unintentional consequences or intentional misuse of these technologies.

4. Signaling Disruption

Many invasive species and parasites use chemical signaling for mating, communication, and to identify resources. Disruption of those processes by chemical spraying has significantly reduced the burden of those pests on their target populations. For example, spraying multiple different pheromones achieved nearly complete disruptions of populations of the light brown apple moth, an invasive pest targeting multiple fruit crops (Brockerhoff et al. 2012). Investigators recently identified at least five volatile compounds emitted by *Plasmodium chaubaudi*-infected mice (a model of human malarial infection) that attract mosquitoes, and another that repels them (De Moraes et al. 2014). Further development of high-throughput assays to determine potent and specific signaling disruptors of critical invasives could enable safe and effective chemical agents against their invasion.

Signal disruption and gene drives could be combined to engineer organisms affected by invasive species to conditionally express biosynthetic pathways for disruptive signaling molecules of the invasive species. Researchers genetically engineered the bioaccumulation of an aphid alarm signaling molecule in wheat, but it did not affect parasitism in initial field trials (Bruce et al.

2015). Cutting edge research in signaling disruption and genetic engineering is a field that would greatly benefit from continued federal support to ensure that applications are effective, low-risk, and socially acceptable.

5. Engineering Microbiomes
Another possible solution to combatting invasive mosquito disease vectors is to change the microbiome on the mosquito itself to prevent the passage of the disease. *Wolbachia pipientis* is a bacterium that plagues some 60% of insect species worldwide (Hilgenboecker et al. 2008) — but doesn't naturally infect *Aedes aegypti* mosquitoes. Infecting *Aedes aegypti* with *Wolbachia* hinders the mosquito's ability to transmit Zika, dengue, and chikungunya to humans; hinders the fertility of the mosquito hosts; and influences the sex of the offspring (Aliota et al. 2016, Molloy et al. 2016). Moreover, *Aedes aegypti* pass the bacteria to their offspring (Ye et al. 2015, Walker et al. 2011). The U.S. Agency for International Development (USAID), through its Zika Grand Challenge, recently funded research groups to use *Wolbachia* to combat Zika (USAID 2016).

4. Reimagining Innovation
Open innovation through mass collaboration, and prizes and challenges, can transform how problems are solved by sourcing solutions from various disciplines around the world (McKinsey 2009). Researchers found, in general, that the more distant a solver was from the industry, the more novel the solution (Franke et al. 2014). Through the America COMPETES Act, federal agencies can conduct prizes and competitions to encourage innovation, seek solutions to tough problems, and advance an agency's core mission. Since the COMPETES Act was signed, the U.S. Government has utilized a number of open innovation tools to incentivize people who might not be the usual subject matter experts to assist with data analysis, the creation of decision support systems, solutions to grand challenges, and data visualizations. The Federal Government can use innovation tools to improve the discovery, speed, and scale of EDRR technologies as part of a national EDRR program.

A. Open source mass collaboration
Open source mass collaboration is a technique that could be used to generate new solutions to the invasive species challenges. One example of a successful open mass collaboration was Open Source Drug Discovery (OSDD), which used open mass collaboration to develop new drugs for neglected tropical diseases, and the resulting drug formulations were readily available for anyone to license. OSDD collaboratively aggregates the biological, genetic, and chemical information available to scientists to hasten the discovery of drugs among bioinformaticians, wet lab scientists, contract research organizations, clinicians, hospitals, and others who are willing to adhere to the affordable healthcare philosophy and agree to the OSDD license.

B. Hackathons and Crisis Mapping

Hackathons and Crisis Mapping are collaborative techniques to encourage interdisciplinary collaboration and innovation. Crisis mappers have pioneered new approaches to harness mobile and web-based applications, participatory maps and crowd sourced event data, aerial and satellite imagery, geospatial platforms, advanced visualization, live simulation, and computational and statistical models (Avvenuti et al. 2016). Similar to invasive species, crisis mappers use these approaches to create effective early warning systems for rapid response to complex humanitarian emergencies. For example, crisis mapping in response to the 2015 Nepal earthquake helped responders locate survivors and roads after people all over the world digitized street maps (Parker 2015). Similarly, data software hackathons or codefests are events where computer programmers, design experts, and subject-matter experts collaborate within a specific amount of time to sort through and "hack" data to produce more solutions. In the invasive species field, hackathons can help engineer solutions to problems where, for example, there are large data sets or the need to create decision support systems.

C. Prizes and Challenges

Prizes and challenges are competitive performance based mechanisms that can draw upon novel disciplines, harness innovations from adjacent sectors, and attract new solutions and new solvers. Prizes and challenges focus on defining the problem and its constraints, rather than imagining a specific solution. Accordingly, such open innovation mechanisms can be much more efficient than traditional grants as they are pay-for-performance mechanisms that only reward the achievement of the goal, rather than a promise (grant) or commitment (contract) to achieve the goal. A prize can be a useful tool to focus solvers on a specific breakthrough. The best known recent prize was Ansari XPrize, which awarded $10 million dollars to the first team to launch a reliable, reusable, privately financed, manned spaceship capable of carrying three people to 100 kilometers above the Earth's surface twice within two weeks. The prize was awarded in 2004 and it helped launch a private space industry. In contrast to a prize, a challenge awards grants or equity investments to multiple winners that meet the terms of the challenge USAID pioneered and launched numerous non-research focused challenges, through its Grand Challenges for Development initiative, resulting in hundreds of new innovations, some from previously unknown solvers, that redefined what was possible within different fields of development.

RECOMMENDATIONS

Creating an Innovation Ecosystem for Invasive Species

The 2016-2018 National Invasive Species Council (NISC) Management Plan (National Invasive Species Council 2016) outlines a set of priority goals, needs, and actions to carry out the requirements of E.O. 13112, including the need to establish a national EDRR Task Force and program. The challenges faced by the Federal Government and their partners dealing with EDRR on a national scale are similar to the ambiguous and dispersed challenges faced by federal agencies in defense, intelligence, and disease surveillance and response sectors. A national

EDRR program can learn from advances in intelligence collection, analysis, and data sharing, as well as prevention and response to national security threats through improved interagency collaboration and coordination. For example, after the 9/11 Commission Report, the Federal Government recognized the need to coordinate data access across multiple agencies and offices so that necessary information is made available to maintain national security. Similar efforts were made in previous preparations for pandemic diseases, like avian influenza. A national EDRR program needs similar up-to-date information sharing across agencies and partner organizations in order to effectively plan, leverage resources for, and execute programs, including early warning systems. Much like reactions to national security threats, EDRR actions need to occur on a faster timeline than current practice.
Federal institutions are pioneering research, investment, collaboration, and application of a number of innovative EDRR technologies and programs, including investment in external private industry and academic programs that have the potential to address some of the greatest challenges regarding invasive species EDRR. Moreover, DARPA, IARPA, National Science Foundation's (NSF) National Robotics Initiative, and Small Business Innovation Research (SBIR) programs at various agencies have provided underlying funding for the research and development (R&D) of remote sensing tools, drones, improved sensors, nanosatellites, and robotics, that can have substantial impact on EDRR of invasive species, but there is a need for translational research and implementation science to make such tools available to the EDRR community. To encourage the uptake, implementation, scaling of these technologies, there needs to be a larger enabling innovation ecosystem that not only coordinates and catalogues federally-funded EDRR R&D, but also attracts new technologies, new approaches, new solvers, and new disciplines for how the Federal Government addresses invasive species as a national EDRR program.

Finally, regulations for the implementation and social acceptance of specific interventions will differ by geographic region and by technology, and pose additional barriers to developing new solutions. There may be regulatory barriers to implementing technological EDRR solutions, including where multiple agencies have regulatory authority over a specific technology. As for social acceptance, the public might not even recognize the problems caused by invasive species (Courchamp et al. 2017, Russell and Blackburn 2017), but be more fearful of the potential technological solution, reducing the acceptance of some EDRR technologies. For example, there are issues of privacy and private property rights around the use of drones, sensors, monitoring, and citizen science projects. Likewise, genetic engineering, synthetic biology, and artificial intelligence are complicated scientific technologies that are not well-understood by non-practitioners.

Below are some specific recommendations for the U.S. Federal Government to harness technology and innovation to increase the scale and impact of innovative technologies for a national EDRR program.

1. Preparedness: Harnessing Artificial Intelligence and New Tools to Predict Future Threats and Focus Activities

To guide national priorities for EDRR, the federal government should support the creation of a publically available and open source AI platform, similar to the IARPA-funded Meta project, that regularly scans the literature to predict and assess the common pathways for introductions of invasives, the non-native species likely to impact native ecosystems, and the identification and prioritization of existing and future invasive species. There should be an annual horizon scanning exercise that utilizes the AI platform that would allow agencies at the federal, tribal, and state levels to better target and prioritize their actions. Government officials at every port of entry should have access to intelligent and accurate detection systems, which utilize innovative sensing devices based on machine learning technology, to automate potential and known invasive species identification.

2. Early Detection: Augment Expert Verification Bottleneck with Decentralized Methods

For a national EDRR response, both the recognition that there is a new invasive species in a new location and verification of that new species by experts are potential bottlenecks when timing is critical between early detection and rapid response to prevent the geographic spread of invasive species. Networks of citizen scientists can be leveraged to scale "expertise" through national voluntary training and certification programs (like the Master Naturalist program), and observations by volunteer "experts" can be integrated with curated mobile platforms like iNaturalist and EDDMapS.

3. Rapid Assessment: Improve Data and Decision Support Tools

A national EDRR program needs to support the creation of an integrated digital decision-support system. A useful system should include real-time early warning, real-time maps, integration of risk assessments to prioritize responses, and decision support tools that harness emerging data science, including AI and machine learning. The system should be linked to relevant networks and contacts so that federal, tribal, and state agencies can easily move from the early detection of invasives to a prioritized response to an organized and rapid response effort. Although it will be challenging given the amount of available data and various needs of invasive species practitioners on the ground, this kind of decision support system can be created through an iterative and adaptive process, harnessing open innovation, mass collaboration, and leveraging new members of the federal technical workforce, including 18F, the U.S. Digital Service, AAAS Data Science Fellows, and Presidential Innovation Fellows.

4. Sourcing and Scaling New Innovations

NISC and its federal and private sector partners should develop a set of prizes or challenges, as well as harness mass collaboration, to source innovative solutions for the grand challenges posed by invasive species. These efforts should be the result of partnerships between government, state, and tribal agencies and relevant private sector entities to help with funding of the challenges and scaling potential solutions.

Through its various technology-enabling and commercialization programs, like SBIR and NSF's i-Core, the Federal Government can make a concerted and coordinated effort to move research from idea to innovation, and from innovation to the marketplace to support the uptake and scaling of technologies, like AI-equipped drones, sensors, and robotics, or advancements in portable DNA devices, etc., for EDRR efforts. The development of such technologies may be insufficient for national EDRR efforts if they are not brought to scale and out of the laboratory.

5. Communication & Campaigns: Build Social Licenses for New Technologies and Understanding the Scale of the Problem

Finally, we recommend that federal agencies move away from a one-way "deficit model" of science communication, where experts deliver information to the rest of the world without dialogue, to a "public engagement model" of communication where there is genuine discussion between sectors (government, experts, society, industry, etc.). Rather than leading campaigns for social acceptance, a national EDRR program may partner with, provide guidance to, and support local, state, tribal, or regional entities where technological EDRR solutions will be implemented. Coupled with this is a frank, transparent, and open discussion and risk assessment process that explains the risk of action and inaction. Without public understanding of the scale and impact of invasive species, we will be unable to mobilize public support and gain social license as well as harness new solvers and new solutions to turn the grand challenges of invasive species into grand opportunities.

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Table 1. A sample of existing citizen science and crowdsourcing-based programs and mobile applications (apps) designed to report, monitor, and surveil invasive species. Users submit data through websites, mobile phone applications, or through paper forms. Acronyms: (DHS) Department of Homeland Security, USDA (U.S. Department of Agriculture), APHIS (USDA Animal and Plant Health Inspection Service), USFS (USDA Forest Service), NIFA (USDA National Institute of Food and Agriculture), NPS (National Park Service), USFWS (U.S. Fish and Wildlife Service), NWRS (USFWS National Wildlife Refuge System), NASA (National Aeronautics and Space Administration), SERC (Smithsonian Environmental Research Center), USACE (U.S. Army Corps of Engineers), USAID (U.S. Agency for International Development), USGS (U.S. Geological Survey).

Program	**URL (accessed February 2017)**	**Federal sponsors /partners (if applicable)**	**Geographic range**
BioTrails	https://mdibl.org/education/citizen-science/biotrails	NPS	Acadia and Mount Desert Island
Blue Catfish Watch Chesapeake Bay	http://www.projectnoah.org/missions/38272048	SERC	Chesapeake Bay, Delaware Bay, and Delaware River
Brownskin Marmorated Stink Bug Locations	http://stinkbug-info.org		Locations with Brown marmorated stink bugs
Bugs in our Backyard	https://www.bugsinourbackyard.org		Any
Bugwood apps, Alaska Weeds ID	http://apps.bugwood.org/apps/alaska	USFWS, USFS	Alaska
Bugwood apps, Forest Insect Pests	http://apps.bugwood.org/apps/forest-insect-pests/	USFS	North America
Bugwood apps, Georgia Cotton Insect Advisor	http://apps.bugwood.org/apps/gacottoninsectadv		Georgia
Bugwood apps, Great Lakes Vegetables	http://apps.bugwood.org/apps/greatlakesvegs/		Great Lakes, US
Bugwood apps, iBiocontrol - Noxious Weeds and their BioControl	http://apps.bugwood.org/apps/ibiocontrol/	USFS	United States

Bugwood apps, Invasive Plant Atlas of New England (IPANE)	http://apps.bugwood.org/apps/ipane/		New England
Bugwood apps, Invasive Plants in Southern Forests	http://apps.bugwood.org/apps/southern-forests/	USFS	Southern U.S.
Bugwood apps, IPAlert	http://nps.eddmaps.org/	NPS	National Parks across America
Bugwood apps, IPM Toolkit	http://apps.bugwood.org/apps/ipm-toolkit/		Wisconsin
Bugwood apps, IPM Toolkit	http://apps.bugwood.org/apps/vegdr/	NIFA	Georgia
Bugwood apps, IveGot1	https://www.eddmaps.org/florida/report/	NPS	Florida
Bugwood apps, Landscape Alternatives for Invasive Plants of the Midwest	http://apps.bugwood.org/apps/landscape-alt/		Midwestern U.S.
Bugwood apps, National Wildlife Refuge Early Detection Network for New England	http://apps.bugwood.org/apps/national-wildlife-refuge/	NWRS	National Wildlife Refuges
Bugwood apps, Outsmart Invasive Species	http://apps.bugwood.org/apps/outsmart/	USDA	Massachusetts
Bugwood apps, SE Agricultural Stink Bug ID	http://apps.bugwood.org/apps/seagstinkbugid/		Southeastern U.S.
Bugwood apps, Squeal on Pigs	http://apps.bugwood.org/apps/squeal/		United States
Bugwood apps, Stink Bug Scout	http://apps.bugwood.org/apps/stink-bug-scout/		United States
Cactus Moth Detection & Monitoring Network	http://www.gri.msstate.edu/research/cmdmn/	USGS, APHIS	Southeastern US along the coast
Cape Citizen Science	http://citsci.co.za/		Fynbos, South Africa
CatchIT	https://www.stat.auckland.ac.nz/~fewster/CatchIT/		New Zealand
Chesapeake Bay Parasite Project	https://serc.si.edu/citizen-science/projects/chesapeake-bay-parasite-project	SERC	Chesapeake Bay Watershed
Citsci dot Org	citsci.org		Global
Craywatch	http://www.flickr.com/groups/craywatch		Waterways in America

Edd MapS	http://www.eddmaps.org/	USFS, USACE, NPS, USFWS, NIFA	United States
Exotic Species Sighting form, REEF.org	http://www.reef.org/programs/exotic/report	USGS	Based out of Key Largo Florida, but could be applied to anywhere dealing with invasive Lionfish
Forest Pest First Detectors	http://www.myminnesotawoods.umn.edu/forest-pest-first-detector/		
Glacier National Park Noxious Weed Blitz	http://scistarter.com/project/391-Glacier%20National%20Park%20Noxious%20Weed%20Blitz	NPS	Glacier National Park
Great Lakes Early Detection Network	http://apps.bugwood.org/	NPS	Great Lakes, US
Greater Atlanta Pollinator Partnership: A Model for Urban Pollinator Conservation	gapp.org/	USFS	Atlanta metropolitan area
iNaturalist	http://www.inaturalist.org/	NPS	Global
Introduced Reptile Early Detection and Documentation (REDDy)	http://scistarter.com/project/406-Introduced%20Reptile%20Early%20Detection%20and%20Documentation%20%28REDDy%29		Florida
Invaders of Texas	http://www.texasinvasives.org/invaders/become.php.	APHIS, USFS	Texas
Invasive Plant Atlas of the MidSouth	http://www.gri.msstate.edu/research/ipams/	USGS, NIFA	Mid-southern U.S.
Invasive Plant Citizen Science Project at Glacier National Park	http://www.crownscience.org/getinvolved/citizen-science/noxious-weeds	NPS	Glacier National Park
Invasive Species on the Duke Forest	dukeforest.duke.edu		Duke Forest
Lowcountry Algal Monitoring Program for Students	http://www.patriotspointsciencespotlight.com/project-overview.html		Ft. Johnson Marine Complex on James Island

MA-NH-ME Wetland Worries & Roadside Invasives	http://www.citsci.org/cwis438/websites/MyTreeTracker/City_Info.php?ProjectID=276&WebSiteID=7		MA, NH, ME
Marine Invasive Species Monitoring Organization	https://massbay.mit.edu/exoticspecies/crabs/		Coastal regions
Midwest Invasive Species Information Network	http://www.misin.msu.edu/		Midwestern US
Monitoring an Invasive Seaweed	https://snailsnotwhales.wordpress.com/2014/10/25/be-a-citizen-scientist-help-us-study-an-invasive-seaweed/		Georgia
Mosquito Challenge Community Campaign in GLOBE	https://www.usaid.gov/sites/default/files/documents/1864/Combating-Zika-and-Future-Threats-Nominee-Summaries-20161011.pdf	NASA, USAID	Global
My Tree Tracker	www.mytreetracker.org/		Global
National Parks Bioblitz	https://www.nps.gov/subjects/biodiversity/national-parks-bioblitz.htm	NPS	National Parks across America
National Plant Diagnostic Network (NPDN)	https://www.npdn.org/first_detector	USDA, DHS	U.S.
Non-Indigenous Aquatic Species report	https://nas.er.usgs.gov/about/default.aspx	USGS, USFWS	U.S.
Nonindigenous Aquatic Species (NAS) Program and mobile app	https://itunes.apple.com/us/app/nas-sighting/id1187981096?ls=1&mt=8		
North Mountain Plant Inventory Project	http://www.birds.cornell.edu/citscitoolkit/projects/north-mountain-plant-inventory/		North Mountain Park
Plant Census at Smithsonian's Global Change Research Wetland	https://serc.si.edu/citizen-science-research/projects/salt-marsh-census	SERC	Marshlands
Plate Watch	http://platewatch.nisbase.org/	SERC	Alaska
Potomac Highlands Cooperative Weed and Pest Management Area (CWPMA)	http://www.phcwpma.org/	NIFA, USFWS	West Virginia
Project R.E.D. (Riverine Early Detectors)	https://www.wisconsinrivers.org/our-work/project-red		Wisconsin's Waterways

Report Florida Lionfish	MyFWC.com/Lionfish#sthash.koH1XwO0.dpuf		Aquatic locations with Florida Lionfish
Stanley Park Invasive Species Mapping	http://stanleyparkecology.ca/conservation/stewardship-in-action/invasive-species-removal/		Stanley Park, Vancouver, British Columbia
The Invasive Mosquito Project	http://www.citizenscience.us/imp/		
The Sparrow Swap	www.facebook.com/sparrowswap		Range of invasive house sparrows nesting in North America
Vital Signs Maine	http://vitalsignsme.org/		Maine
What's Invasive	http://www.whatsinvasive.com	NPS	United States
Zika app	http://www.kidenga.org/		Areas affected by Zika

Table 2. Partial list of recent publications of eDNA research and detection applied to invasive species. Federal funding or author affiliation is noted if this information is included in the publication. This list is not comprehensive.

General category	**Invasive species detected**	**Federal funding or federal research collaborators**	**Geographic coverage if not U.S.**	**Citation**
Amphibians	American bullfrog *Rana catesbeiana = Lithobates catesbeianus*		France	Dejean et al. 2012
Aquatic species	Multiple species in Great Lakes commercial live bait trade	Federal funding: U.S. Environmental Protection Agency Great Lakes Restoration Initiative grant		Nathan et al. 2015
Aquatic species	Multiple species in Great Lakes commercial live bait trade	N/A		Mahon et al. 2014
Bivalves	zebra mussel (*Dreissena polymorpha*)	Federal funding: Great Lakes Protection Fund and the U.S. Environmental Protection Agency		Egan et al. 2013
Bivalves	quagga (*Dreissena bugensis*) and zebra (*D. polymorpha*) mussels	Federal funding: U.S. Environmental Protection Agency Great Lakes Restoration Initiative grant		Egan et al. 2015
Bivalves	North American wedge clam (*Rangia cuneat*)		Baltic Sea	Ardura et al. 2015
Bivalves	New Zealand pygmy mussel (*Xenostrobus securis*)		Spain	Miralles et al. 2016

Crustaceans	rusty crayfish (*Orconectes rusticus*)	Federal funding: U.S. Environmental Protection Agency grant		Dougherty et al. 2016
Crustaceans	mud crab (*Rhithropanopeus harrisii can*)		Baltic Sea	Forsström and Vasemägi 2016
Crustaceans	red swamp crayfish (*Procambarus clarkii*)		France	Treguier et al. 2014
Fish	Bighead Carp (*Hypophthalmichthys nobilis*) and Northern Snakehead (*Channa argus*)	Federal funding: United States Environmental Protection Agency Great Lakes Restoration Initiative grant		Simmons et al. 2015
Fish	Asian carps, silver carp (*Hypophthalmichthys molitrix*) and bighead carp (*H. nobilis*)	Funding: U.S. Army Corps of Engineers, Great Lakes Protection Fund, and NOAA CSCOR		Jerde et al. 2011
Fish	Aquatic invasive species	N/A		Nathan et al. 2014
Fish	Ruffe (*Gymnocephalus cernua*)	USFWS researcher; Federal funding: Environmental Protection Agency Great Lakes Restoration Initiative through Cooperative Agreement between the US Fish and Wildlife Service (USFWS) and the University of Notre Dame; National Oceanic and Atmospheric Administration Center for Sponsored Coastal Ocean Research (NOAA CSCOR)		Tucker et al. 2016
Fish	Northern Pike (*Esox lucius*)	USGS and USFWS researchers		Dunker et al. 2016
Fish	Asian carps	USGS researchers; Federal funding: The Great Lakes Restoration Initiative administered by the US Fish and Wildlife Service; NOAA CSCOR		Mahon et al. 2013
Fish	Ponto-Caspian goby species		Switzerland	Adrian-Kalchhauser and Burkhardt-Holm 2016
Fish	redfin perch (*Perca fluviatilis*)		Australia	Bylemans et al. 2016
Fish	Mozambique tilapia (*Oreochromis mossambicus*)		Australia	Robson et al. 2016
Fish	bluegill sunfish (*Lepomis macrochirus*)		Japan	Takahara et al. 2013

Invertebrates	Earthworms		France	Bienert et al. 2012
Macorinvertebrates	macroinvertebrate species in river and lake systems: *Ancylus fluviatilis, Asellus aquaticus, Baetis buceratus, Crangonyx pseudogracilis,and Gammarus pulex*		Switzerland	Mächler et al. 2014
Pathogens	Ranavirus	Funding: Department of Defense Environmental Security Technology Certification Program, National Science Foundation		Hall et al. 2016
Pathogens	Forest pathogens		Canada	Lamarche et al. 2015
Plants	*Egeria densa*		Japan	Fujiwara et al. 2016
Plants	Invasive aquatic plants		Canada	Scriver et al. 2015
Reptiles	Burmese python (P*ython bivittatus*)	USDA researchers		Piaggio et al. 2014
Reptiles	Burmese python (*Python molurus bivittatus*), Northern African python (*P. sebae*), boa constrictor (*Boa constrictor*), and the green (*Eunectes murinus*) and yellow anaconda (*E. notaeus*)	USGS researchers		Hunter et al. 2015

Table 3. Selected examples of UAVs and ROVs utilized to detect or capture wildlife or plant species, or collect biological specimens.

Name of technology or tool	Brief Description	Citation or URL
COTSbot underwater drone	The crown-of-thorns starfish (COTS) detection system uses computer vision and a machine learning system to identify COTS. If the robot is unsure of its target, it can send a picture to a person for evaluation and verification. When the COTSbot identifies its target, it delivers a lethal dose of bile salt into the starfish via a pneumatic injection arm.	Hagman 2015

CropCam	A radio-controlled model glider plane equipped with a Trimble GPS, a miniature autopilot, and Pentax digital camera. CropCam provides high resolution GPS based images on demand.	http://www.pentagonperformance.com/service_details.php?id=15
Drones over water	The drones are capable of flying to a programmed GPS position, collecting a sample from a specific water depth, testing the sample onboard, and sending the data remotely.	University of Nebraska-Lincoln 2014
Drones that pick up signals from tagged wildlife	This New Zealand-based company outfits drones with synthetic aperture radar, which can work with trees, fog, and snow. The drone picks up signals from radio transmitters on tagged wildlife.	Morton 2016
DroneSeed, administers insecticides on a plant by plant basis	DroneSeed is a company that creates and programs drones that plant seeds (for forest restoration) and administers insecticides (to eradicate invasive weeds) on a plant by plant basis.	https://droneseed.co/
Forestry Drones: UAVs that collect terrestrial specimens	UC Berkeley researchers developed drones that collect leaves, air samples, etc. for forestry research.	https://nature.berkeley.edu/garbelottowp/?p=1801
Lionfish hunting open ROV	This is an open-source project being developed in the OpenROV community. Inventors are developing an attachment for the OpenROV to cull lionfish.	https://openexplorer.com/expedition/lionfishhuntingopenrov
National Science Foundation (NSF), National Robotics Initiative (NRI)	The Deep Learning Unmanned Aircraft Systems for High-Throughput Agricultural Disease Phenotyping project is an NRI-funded initiative developing AI-drones that work side-by-side with farmers and identify specific crop diseases and assess their progress.	https://www.nsf.gov/awardsearch/showAward?AWD_ID=1527232
Open ROV	Open ROV is a movement of citizen scientists and hobbyists that use the low-cost Open ROV for ocean exploration. The Open source software is providing an opportunity for people to "hack" the equipment and code to create targeted applications.	https://www.openrov.com/
Project Premonition	Project Premonition is programming drones to safely and securely navigate complex areas. The team is applying machine learning and cloud computing to recognize visual features indicative of mosquito hotspots. Eventually, the drones will place and retrieve AI-programmed mosquito traps on their own in the field.	https://www.microsoft.com/en-us/research/project/project-premonition/

Snotbot: drone collects biological specimens from whales	The snotbot collects blow exhaled by whales. Scientists detect virus and bacteria loads in whales, analyze DNA, and look for environmental toxins that have been absorbed into the whale's system.	http://shop.whale.org/pages/snotbot
UAVs to Reduce Zika and other Threats to Public Health	WeRobotics in partnership with Joint Food and Agricultural Organization/International Atomic Energy Agency (FAO/IAEA) Insect Pest Control Lab (IPCL) will develop a release mechanism compatible with Unmanned Aerial Vehicles (UAVs) to release sterilized male mosquitoes aerially.	https://www.usaid.gov/sites/default/files/documents/1864/Combating-Zika-and-Future-Threats-Nominee-Summaries-20161011.pdf
Unmanned Aerial Vehicle with Mass Spectrometer	Mass spectrometer attached to an UAV to study in-situ volcanic plumes.	Diaz et al. 2015
Weed classification using high resolution aerial images from a digital camera mounted on a UAV	A camera is mounted on drone programmed via machine learning to generate a bank of image filters that allows the machine to discriminate between the weeds of interest and background objects.	Hung et al. 2014
Wildlife monitoring using drones	This citation lists a number of studies where camera-equipped UAVs captured imagery of large aquatic and terrestrial animals and colonial birds.	Linchant et al. 2015

Table 4. Selected examples of nanosatellite companies and basic missions.

Nanosatellite company	Brief Description	Citation or URL
Bluefield nanosatellites	Bluefield cube satellites track methane emissions. It is an example of sing remote sensing to detect chemical signatures using nanosatellites.	http://bluefield.co/
GHGSat	GHG satellites track greenhouse gas emissions.	http://www.ghgsat.com/
Planet (Labs)	Planet's constellations of satellites are able to collect an image of every location on Earth, everyday. The resolution of their imagery is 5m and 3m.	Boshuizen et al. 2014

Spire nanosatellites	These satellites monitor weather and shipping vessels. There might be an application to tracking the spread of invasives via ships and at ports.	https://spire.com/
Multiple ocean observing nano- (or small) satellites (see Table 3 in citation)	This citation summarizes ocean observing small satellites (SmallSats) that include some potentially relevant sensors for detecting or predicting invasive marine species, including: ocean color (phytoplankton presence), sea surface temperature, and ocean salinity.	Guerra et al. 2016
Tyvak	Tyvak has two nanosatellite platforms (as of 2017), the Endeavor and the PicoSat.	http://www.tyvak.com/

Table 5. Examples of machine vision-aided applications to identify plants, animals, and disease.

Brief Description		Citations or URL
Artificial Intelligence (AI) and machine learning applied to horizon scanning	AI and machine learning can speed up the process of horizon scanning. Meta is an example of an IARPA-funded company that applies these methods to the corpus of PubMed literature.	Science 2.0 2016
BirdSnap, id birds based on photos	The BirdSnap app identifies the 500 most common birds in North America from users' photographs, location data, and time of year to provide the most likely identification. The program is based on machine learning and computer vision.	Branson et al. 2014
Brown tree snake Identification, deep learning	Conservation Metrics, Inc., is collaborating with researchers at USGS to test automated recognition of invasive brown tree snakes in time-lapse images collected from camera sensors on Guam.	Klein et al. 2015
Computer vision used to identify cichlids (currently used in their native range)	Automatic classification of the Lake Malawi cichlids based on computer vision and geometric morphometrics. Cichlids are naturally occurring and not invasive, but this methodology could be applied to invasive fish species.	Joo et al. 2013

Review paper: Computer-automated animal detection in high-resolution aerial images	This 2016 paper found 35 papers involving computer-automated detection or counting of animals in aerial images collected by manned or unmanned aircraft, with 19 of those citations involving birds and 20 involving mammals.	Chabot and Francis 2016
Machine vision refinement methods for bird identification	The authors describe a computer-based photo identification algorithm that recognizes species of birds.	Branson et al. 2014
MerlinVision, identify birds based on photos	A combination of machine learning and citizen science -- people help train the Merlin algorithms by identifying birds in online photos. Once Merlin is fully trained, the program will verify the identification of birds in images submitted via eBird to the Macaulay Library. The Macaulay Library archives natural history sound, video and photography for birds, mammals, reptiles, amphibians, arthropods and fishes.	https://merlinvision.macaulaylibrary.org/ml-mediaannotation-editor/about?__hstc=75100365.a3661002d1254bf8e981c33f80fdf6c7.1476725357038.1476725357038.1476725357038.1&__hssc=75100365.13.1476725357038&__hsfp=1945213963#_ga=1.89979291.1632125495.1476725357
Decartes Labs: Nanosatellites plus machine learning to predict crop health (and other events)	Descartes Labs developed a machine-learning platform designed for forecasting, monitoring, and historical analysis of crop health and other major commodity supply chains. The Descartes Labs platform combines massive data sources—public, private or proprietary—onto a single system. There could be applications for invasive species surveillance.	Brokaw 2016
Deep Learning Unmanned Aircraft Systems for High-Throughput Agricultural Disease Phenotyping	This National Science Foundation (NSF) National Robotics Initiative (NRI) funded project will develop AI-drones that work side-by-side with farmers and identify specific crop diseases and assess their progress.	https://www.nsf.gov/funding/pgm_summ.jsp?pims_id=503641
TensorFlow™	This is an open source software tool for people to explore and create machine learning algorithms by playing with a real neural network. It was developed by researchers and engineers working on the Google Brain Team within Google's Machine Intelligence research organization for the purposes of conducting machine learning and deep neural networks research.	Sato 2016

The Frapper	Researchers are developing a lionfish-specific trap based on machine learning.	http://thefrapper.com/
Use of Machine Learning Techniques for Robust Crop and Weed Detection in Agricultural Fields (NSF SBIR Phase II, 2012)	Blue River Technology, Inc., is creating computer vision algorithms that will classify plants, crops, and weeds in real-time. The research will create an algorithm integrated into an automated weeding system.	http://www.bluerivert.com/
WhatPlant, mobile phone app based on machine vision	This is a machine vision/deep learning app using algorithms that identify plants based on smart phone photos.	Cutmore et al. 2014
Project Premonition (mosquito trap)	IARPA-funded Project Premonition aims to detect pathogens before they cause outbreaks, by trapping mosquitoes to sample pathogens in the environment. The mosquito trap was redesigned to be robotic and smart--if the wing movements of an insect match that of a mosquito, then the trap closes.	Microsoft 2015
A proposed reference process to identity bee species based on wing images	The paper proposes a reference process for bee classification based on wing images and the authors suggest that results can be extended to other species' identification and taxonomic classification.	Santana et al. 2014
Identification of individual right whales from aerial photographs	NOAA Fisheries hosted a competition on Kaggle.com to use computer vision to identify individual right whales in aerial photographs.	Bogucki 2016
Computer vision used to identify plant species based on leaf images	Authors in both papers describe automated systems that learn to classify images of leaves.	Lee et al. 2015, Wilf et al. 2016
Smart Flower Recognition System	Microsoft Research Asia collaborated with Chinese botanists to create a program that identifies flowers from smartphone images.	Wu 2016
Invasive weed identification from high resolution aerial images	Computer vision techniques were used to identify invasive weeds in high resolution images collected from cameras mounted on UAVs in Australia.	Hung et al.2014

Identification of plant diseases on leaves	Models are able to recognize 13 different types of plant diseases out of healthy leaves and can distinguish plant leaves from their surroundings.	Sladojevic et al. 2016
Acoustic-based monitoring of cane toads	Authors trained algorithms to recognize cane toad calls and are monitoring that species in Australia using a field-based acoustic smart sensor network.	Hu et al. 2010
Lemur FaceID	LemurFaceID is facial recognition system for lemurs developed to avoid dangerous physical capture and tagging of lemurs. The platform was developed, trained, and tested using images from wild red-bellied lemurs collected in Ranomafana National Park, Madagascar. It demonstrated 98.7% ± 1.81% accuracy in correctly identifying individual lemurs.	Crouse et al. 2017