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Overview article

Technological innovations enhance invasive species management in the anthropocene

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Abstract

Curbing the introduction, spread, and impact of invasive species remains a longstanding management and policy prerogative. In recent decades, globalization and environmental change have further complicated efforts to execute science-based actions that address these challenges. New technologies offer exciting opportunities to advance invasion science knowledge, enhance management actions, and guide policy strategies but are increasingly complex and inaccessible to most practitioners. In the present article, we offer a synthetic perspective of innovative technologies with applications for invasive species management related to pathway intervention, spread prevention, impact mitigation, and public engagement. We also describe tools that augment big data processing required by some methods (e.g., remote sensing, mobile application data), such as automated image and text recognition built on machine learning. Finally, we explore challenges and opportunities for successful integration of emerging technologies into invasive species management, focusing on pipelines that enable practitioners to integrate tools into practice while recognizing logistic and financial constraints.

Keywords: biosecurity, citizen science, remote sensing, mobile applications, DNA barcoding

Non-native, invasive species—species that have successfully been introduced, spread, and established beyond their native range—are responsible for profound, negative effects on biodiversity (Doherty et al. 2016), ecosystem functioning and services (Kumschick et al. 2015), human health (Ogden et al. 2019) and welfare (Jones 2017), and the economy (Haubrock et al. 2021). The importance of acting against invasive species globally is widely recognized (Pyšek et al. 2020) and includes the development of effective strategies to avoid or reduce the impacts of nuisance species in national policies (Early et al. 2016). Despite this challenge, human-mediated movement of invasive species will only continue to grow in response to synergies with other global changes (Seebens et al. 2021), widening the already significant gap between the societal need and the scientific capacity to inform management action.

Conservation technology—devices, software platforms, computing resources, algorithms, and biotechnology methods—is frequently identified as the next frontier to help scientists and practitioners address the twenty-first century biodiversity crisis (Joppa et al. 2016, Berger-Tal and Lahoz-Monfort 2018, Iacona et al. 2019). Technological innovation has created the tools needed to collate, analyze, and disseminate data at scale, and it offers new insight into how human activities are influencing biodiversity and integrity of ecosystems globally (Joppa et al. 2016). New technologies permeate all aspects of conservation by offering data on nature and people, enhancing data sharing and analytical methods, presenting new communication mechanisms, and enabling participatory governance (Arts et al. 2015, Lahoz-Monfort and Magrath 2021). Collectively, conservation technologies offer unprecedented opportunities to enhance management and policy actions both today and in the future (Lahoz-Monfort et al. 2019).

Invasion science is a rapidly evolving interdisciplinary field (Vaz et al. 2017), and technological innovation is playing an increasing role in addressing the escalating extent and impacts of invasive species. In recent years, technological advances have provided insight across all stages of invasion. From identifying pathways of introduction to controlling and eradicating established invaders, these advances have also informed public opinion in invasive species management (Martinez et al. 2020). There is a long history of co-opting new technologies for the management of invasive species, spanning initial detection with eDNA assays (Larson et al. 2020), limiting species' spread in rivers with electric barriers (Jones et al. 2021), controlling invasive predator populations with aerial baiting (Baker and Bode 2013), and aiding management and policy through hackathon-based development of public tools to track invasive species (Martinez et al. 2020). More recent developments in machine learning—artificial intelligence that allows models to learn from data—and digital interfaces offer additional prospects to improve data management and dissemination within invasion science, which, in turn, help enhance public engagement and policy efforts (Heger et al. 2021).

An ever-growing array of innovative technologies can help identify time- and cost-effective detection, deterrence, control, and eradication strategies for invasive species. However, as the number and intricacy of new approaches grow, so do the challenges to scientists to understand the choices of technology available to them and difficulties to conservation practitioners to effectively leverage these technologies for more informed management decisions. In the present article, we provide a comprehensive review of technology-based tools that aid in invasive species management, presenting examples of these approaches as they relate to specific management priorities ranging from pathway intervention to preventing spread to limiting impacts and increasing public engagement (figure 1, table 1). Although previous reviews have collated examples of some of these technologies (e.g., web scraping) within invasion ecology (Jaric et al. 2021), we include a

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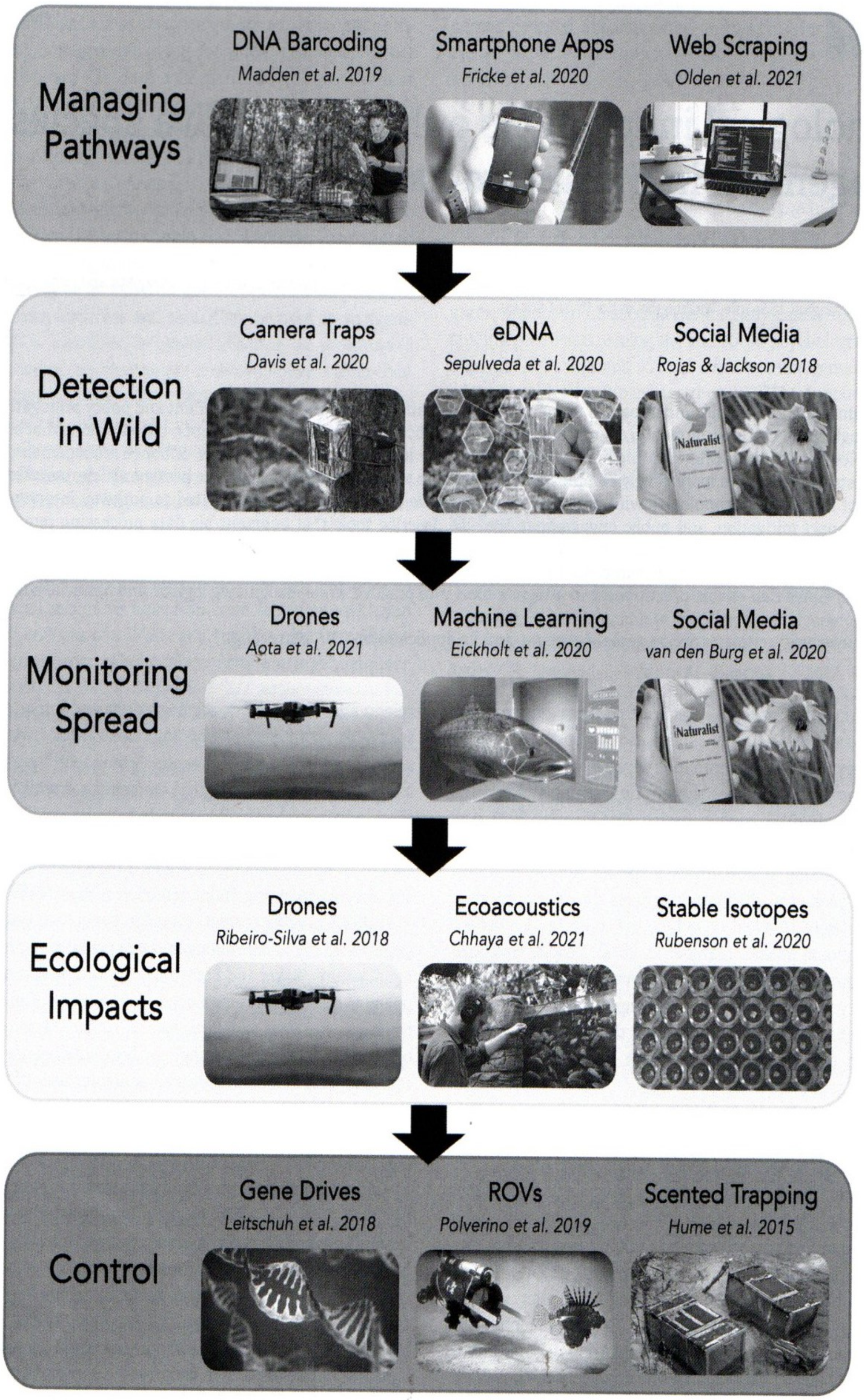

Figure 1. New technologies offer exciting opportunities to advance knowledge in invasion science, enhance management actions, and guide policy strategies. Shown in the figure are example technologies, with representative citations, grouped by the stage of invasion (left) they have been used to address. The arrows indicate the progression of introduced species through the stages of invasion. Photographs: Licensed under Creative Commons.

broader suite of technologies targeted toward explicit management goals. In addition, we propose areas to propel the use of technology within invasion science and provide guidelines for ensuring tool and data accessibility to end users. Our goal is to capture the pace and scope of recent and emerging technologies applied to invasion science and management, providing examples that are representative of this burgeoning area of innovation and discovery.

Table 1. Examples of new technologies for managing invasive species.

Technology	Strengths	Weaknesses	Stage	Citation	Summary
Acoustic barriers	Inexpensive, can be species selective, and applicable in both lotic and lentic aquatic environments.	Passage rates of native species are rarely evaluated, and efficacy has yet to be tested long term.	Spread	Jones et al. 2021	Reviewed use of acoustic and light barriers to limit the spread of aquatic invasive species.
				Zielinski et al. 2014	Showed bubble curtain can contain invasive common carp spread.
Acoustic traps	Low-impact method that does not reduce native species numbers.	Mating disruption does not impede species migration, and audio distance to attract pests is unknown for some species.	Control	Fernandez 2020	Developed a prototype acoustic trap with open-source software for invasive citrus psyllid.
				Isabella-Valenzi and Higgs 2016	Captured more invasive round goby with acoustic traps broadcasting reproductive calls than control.
Camera traps	Significantly reduces the time and cost of sampling labor, particularly for low-density species.	Trade-offs between number of cameras (most significant cost factor) and detection bias.	Detection in wild	Davis et al. 2020	Showed cameras were more cost effective than DNA or trapping to estimate invasive pig density.
				Lamelas-López and Salgado 2021	Inventoried invasive mammals on an oceanic island and estimated abundance and detection capability.
				Willi et al. 2019	Identified species in images and differentiated from nonspecies images using image recognition.
			Ecological impacts	Ribeiro-Silva et al. 2018	Identified bird nest predators from camera trap images and quantified percent depredation.
DNA barcoding	Presents cost-effective opportunity to develop an early detection system (particularly at ports).	Reference library development is needed to increase the number of cataloged species.	Introduction pathways	Borrell et al. 2017	Detected invasive invertebrates in port water with high-throughput DNA sequencing.
				Burg et al. 2014	Determined the wildlife trade origin of invasive butterflies by comparing wild and captive DNA.
				Madden et al. 2019	Identified invasive moths at US ports of entry on the basis of DNA matches.
Ecoacoustics	A unintrusive, and relatively inexpensive approach to implement over large spatiotemporal scales.	Call absence does not mean species is absent, and ability to detect distribution may be seasonally based on mating.	Ecological impacts	Gasc et al. 2018	Demonstrated the utility of reductions in cricket calls as an indicator of invasive ant presence.
				Rountree and Juanes 2017	Quantified the distribution of invasive freshwater drum by monitoring the species' distinct sound.
eDNA	Techniques such as qPCR and high-throughput sequencing are increasing available and affordable to facilitate early detection of introduced species.	Potential for false negatives and false positives, and requires technical expertise for laboratory processing or contract services.	Detection in wild	Clare et al. 2022	Collected eDNA from the air to identify mammal and bird species in a wildlife park.
				Feist and Lance 2021	Reviewed advanced eDNA methods for zebra and quagga mussel detection.
				Roy et al. 2018	Tested live trade shipments of freshwater fish for eDNA of invasive species.
				Sepulveda et al. 2018	Demonstrated the efficacy of a field-based platform to rapidly screen for invasive northern pike eDNA.
				Sepulveda et al. 2020	Showed the utility of retrofitting existing streamflow gauges with eDNA surveillance.

Table 1. Continued

Technology	Strengths	Weaknesses	Stage	Citation	Summary
Genetic manipulation	Biocontrol methods are more humane than traditional chemical controls, and may require less time to carry out that traditional methods.	Connectivity between native and invasive range may prevent implementation, and the inability to regulate gene edits once released into wild populations could result in unintended consequences for native and non-native species.	Control	Bhattacharyya et al. 2020	Optimized a model of genetically modified supermale fish introduction to eradicate invasive species.
				Evans et al. 2019	Released transgenically modified mosquitoes, and genome was incorporated into target population.
				Garbian et al. 2012	Fed honey bees RNA that is transferred to their mite parasites, inducing gene silencing and parasite decline.
				Leitschuh et al. 2018	Proposed releasing engineered mice that only produce males into island rodent populations.
				Lester et al. 2020	Suggested development of a CRISPR gene drive to eliminate invasive common wasps.
				McColl et al. 2016	Proposed release of cyprinid herpesvirus to control invasive common carp.
				Reinders et al. 2022	Showed the SmartStax PRO pesticide silences western corn rootworm genes, reducing adult survival.
Machine learning	Can enhance the speed of other innovative methods (e.g., camera traps, remote sensing) by automating image processing or even identifying species in real time.	Requires technical expertise to assemble, and may be expensive to contract assistance.	Spread	Ashqar and Abu-Naser 2019	Classified invasive Hydrangea in an image data set with neural network analysis.
				Carlier et al. 2020	Classified invasive winter heliotrope in photographs with morphological analysis.
				Eickholt et al. 2020	Automated recognition of invasive sea lamprey and Asian carp to prevent passage through barriers.
				Kedia et al. 2021	Mapped invasive vegetation in an arid region with machine learning classification of drone imagery.
				Piiroinen et al. 2018	Mapped invasive tree distribution with machine learning-based classification of drone imagery.
			Control	SSU 2019	Enhanced feral pig traps with image recognition to confirm species identity before closing.
Remote sensing	UAVs cost substantially less than manned aircraft, can survey remote environments, and can hover over regions for long time periods for temporal monitoring.	Though cheaper than manned crafts, UAVs are still costly. Furthermore, their use is not permitted in certain management areas (e.g., wilderness).	Spread	Ahmed et al. 2021	Modeled the distribution of an invasive plant in Ethiopia with satellite imagery.
				Aota et al. 2021	Detected an invasive lizard species with neural network analysis of drone imagery.
				Gong et al. 2020	Distinguished native from invasive species in the Yellow River Delta, China with satellite imagery.
				Jurdak et al. 2015	Reviewed autonomous technologies for biosecurity surveillance.

Table 1. Continued

Technology	Strengths	Weaknesses	Stage	Citation	Summary
				Kattenborn et al. 2019	Combined satellite and UAV data to map invasive woody species in Chile.
				Sladonja et al. 2022	Used drones to map the distribution of invasive plants along riverbanks in Croatia.
				Tesfamichael et al. 2018	Compared the invasive plant classification accuracy across five different satellite imagery data sets.
			Control	Brooks 2020	Compared the reduction of treatment methods for watermilfoil with drones and multispectral imagery.
				Wylie et al. 2021	Calculated the extent of invasive ants and will confirm eradication through removal treatments.
ROVs	Can be equipped with underwater cameras and sensors to identify and capture invasive species, and reduce the time and manpower needed to inspect ship for hull fouling.	Development of ROVs for specific intervention tasks can be expensive, and nonautonomous vehicles require a permanent connection to a power source.	Spread	Mehler et al. 2016	Modeled distribution of zebra/quagga mussels with underwater ROV imagery.
			Control	Codd-Downey et al. 2021	Monitored watermilfoil growth with autonomous surface vessel imagery.
				Culbertson 2015	Identified nuisance seagull nests with drones and sprayed with sterilizing fluid.
				Knight 2021	Developed a robot to identify and capture invasive red lionfish.
				Naddaf-Sh et al. 2018	Conducted in-water video surveys to aid in planning and effectiveness of removal dives.
				Polverino et al. 2019	Created a robotic predator to biomimic the behavior of invasive mosquitofish' natural predators.
				Zeidberg and Robison 2007	Quantified the range expansion of Humboldt squid with deep sea video surveys.
			Ecological impacts	Guedes and Araujo 2022	Used ROV imagery to survey fish communities across depth zones in a Brazilian reservoir.
Scented traps	Increases the efficacy of trapping, as more individuals navigate to the trap faster.	Species can respond differentially in lab and field settings, and trap effectiveness may vary by location.	Control	Hume et al. 2015	Decreased arrival time of invasive sea lamprey in traps with strategic repellent odor distribution.
				Johnson et al. 2009, 2013	Lured female invasive sea lampreys into traps with male mating pheromones.
Smartphone apps	Low-cost opportunity to crowdsource data from app users and community scientists.	Specialized app development requires significant time input and technical expertise, and app user populations can be biased.	Introduction pathways	Fricke et al. 2020	Calculated angler movement frequencies within invasive species' desiccation tolerance.
				Papenfuss et al. 2015	Quantified lake visitation and angler movement patterns from posts to a fishing application.

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Technology	Strengths	Weaknesses	Stage	Citation	Summary
			Detection in wild	Pawson et al. 2020	Described the Find-A-Pest smartphone application for reporting invasive species in New Zealand.
			Spread	Malek et al. 2018	Designed the community science mobile app "BugMap" to forecast invasive stink bug distributions.
Social media	Web and app-based platforms are a low-cost opportunity to both collate species observations and disseminate educational materials to the public.	Subject to significant biases within user populations, and access to specific platforms can change rapidly as tech companies adjust their policies. Social media data can complement, but generally not replace, expert species distribution data sets.	Introduction pathways	Monkman et al. 2018	Scraped online social media forums to quantify the spatiotemporal distribution of angling recreation.
				Harrington et al. 2021	Examined exotic pet trade by extracting information from exporters' public Facebook accounts.
			Detection in wild	Botella et al. 2018	Compared invasive species distribution models from app-based observations to expert inventories.
				Brown et al. 2018	Collated a data set of invasive harlequin ladybird observations through app and online reporting.
				Hobson et al. 2017	Quantified historic invasive parakeet abundance from eBird and iNaturalist observations.
				Mori et al. 2016	Identified new populations of invasive eastern grey squirrel with iNaturalist observations.
				Rojas and Jackson 2018	Described the first account of invasive European firebug in Canada from an iNaturalist observation.
			Spread	Allain 2019	Showed Flickr records of introduced turtles reflect the spatiotemporal distribution of traditional observations.
				van den Burg et al. 2020	Developed distribution models for invasive iguana from social media and photo-sharing websites.
			Public engagement	Daume 2016	Analyzed Tweets to understand public discourse around three common invasive species.
				Forrester et al. 2021	Organized a grassroots lionfish removal program with social media networking.
				Mehmet et al. 2018	Assessed the polarity of stakeholder attitudes toward invasive carp management.
				Mittermeier et al. 2021	Quantified Wikipedia page views for hundreds of bird species.
				Sbragaglia et al. 2020, 2021	Examined angler comments on YouTube to characterize sentiments toward invasive species.
				Wyckhuys et al. 2019	Assessed Internet salience of invertebrate biological control agents.

Table 1. Continued

Technology	Strengths	Weaknesses	Stage	Citation	Summary
Stable isotopes	Can determine the environmental history and diet of invasive species.	Requires intensive lab analysis, although the cost of sample testing has declined in recent years.	Introduction pathways	Hill et al. 2020	Demonstrated distinct stable isotope ratios of invasive wild and captive red-eared slider turtles.
			Ecological impacts	King et al. 2017	Used stable isotopes and fatty acids to understand the fish consumption of cormorant populations.
				Rubenson et al. 2020	Quantified introduced smallmouth bass impacts on Chinook salmon with stable isotopes and fatty acids.
				Sahm et al. 2020	Examined the trophic interactions of invasive amphipods with compound specific stable isotopes.
Web scraping	Facilitates identification of new species entering the exotic pet and wildlife trades.	Users often post species with colloquial names, which can make identification challenging.	Introduction pathways	Olden et al. 2021	Scraped data from online aquarium marketplaces to reveal potential trade routes for invasive species.
				Stringham et al. 2021	Provided guidance for wildlife trade surveillance through web-based interfaces.
Web tools	Can disseminate information on invasive species in a centralized, easily accessible manner.	Uptake is dependent on public choosing to actively engage with the web tool.	Public engagement	Jeschke et al. 2021	Proposed development of an open, global atlas of invasion science for public and policymakers.

Identifying and managing introduction pathways

Pathway management represents the first line of defense in preventing species invasions. Non-native hitchhikers make use of numerous transport pathways to spread from their native to introduced range, including movement associated with the intentional trade of non-native species. Unintentional examples include contaminated shipments of horticulture species and exotic pets, ballast water exchange associated with global shipping, recreational boat-facilitated movement (through hull fouling, plant entanglement, or still-water transport), and entanglement on fishing gear (Hulme 2009, Drake and Mandrak 2014). These human-assisted pathways and geographic routes of species movement have proven particularly difficult to pinpoint, characterize, and regulate (Pyšek et al. 2020, Ricciardi et al. 2021). Recently, however, spikes in smartphone use and ownership, innovations in smart fishing devices, and the proliferation of online live organism marketplaces have spurred new approaches leveraging mobile and online data to identify highly trafficked pathways for invasive species introductions.

The global pet trade is well recognized as a primary pathway for non-native species introductions, and in recent decades, pet sales have rapidly expanded from physical retail stores to include an increasing number of Internet marketplaces (Lockwood et al. 2019). In doing so, the Internet has created opportunities for new and long-distance trade routes (Lenda et al. 2014). Online pet retail has also increased accessibility to new source pools of invasive species (Seebens et al. 2018), making an already challenging biosecurity problem even more difficult. Web scraping—or extracting data from websites—allows for better understanding of this emerging introduction pathway by tracking online sales of live organisms across international borders and identifying the most active trade routes for prohibited species. For example, the use of automated web crawlers to collect data from online pet aquarium marketplaces revealed a diverse variety of freshwater species in trade and a concentrated network of trade routes that may serve as conduits of invasive species (Olden et al. 2021). In addition, systematic Internet searching of posts or groups on social media have been used to identify invasive species within wildlife trade (Stringham et al. 2021).

Interception of potential invasive species at ports of entry is essential for effective biosecurity and biosurveillance programs, but accurate identification of taxa remains a fundamental challenge because of the continued decline in systematics training and understaffing of inspection officials (Ricciardi et al. 2021). The use of molecular technologies to identify species by genetic fingerprinting, or barcoding, may help address these issues by developing a centralized database containing species information and standardized molecular markers to distinguish species (Cross et al. 2010). DNA barcoding could be especially effective for cryptic microorganisms for which traditional taxonomic classification is challenging, as Madden and colleagues (2019) demonstrated by finding DNA-based identifications of microlepidoptera (smaller moths) intercepted at US ports of entry were more often correct than morphology-based identifications. Furthermore, comparisons of simplified metabarcoding (high-throughput sequencing and DNA-based identification) approaches to conventional DNA barcoding and visual surveys suggest that metabarcoding could also be a cost-effective solution for early detection (Borrell et al. 2017).

Determining the origin of an invasive species is critical for mobilizing a rapid response to limit the transport of additional individuals through a pathway and prevent the establishment of recently introduced incursions. For example, researchers used comparative DNA barcoding between wild and captive populations of the Julia butterfly (*Dryas iulia*) in Thailand to determine that Thailand's wild populations of the species originated from traded, captive individuals in butterfly houses (Burg et al. 2014). In other cases, managers may need to differentiate recently escaped or released individuals from previously established populations. Stable isotope analysis—quantifying the ratio of elements such as carbon, nitrogen, and sulphur in organisms to trace the flow of nutrients through food webs and assess trophic interactions—can help researchers understand individuals' environmental histories. Hill and colleagues (2020) showed that wild and captive red-eared slider turtles (*Trachemys scripta elegans*) exhibit distinct stable isotope ratios, allowing for the rapid identification of individual turtles' origins.

Propagule pressure—the repeated introduction of multiple individuals of a non-native species into a new environment over time—is a key determinant of invasion success (Lockwood et al. 2005, Reaser et al. 2008). Traditional approaches to estimating human traffic across the landscape, in which non-native propagules may be entrained, involve in-person surveys or mail-in questionnaires that are limited in their spatial scope and time periods of inference (Rothlisberger et al. 2010, Anderson et al. 2014). In recent years, smartphone applications and social media have enhanced our understanding of propagule pressure in freshwater ecosystems. Papenfuss and colleagues (2015) used angler posts to a popular mobile fishing application in Alberta, Canada, to quantify patterns of lake visitation and interlake angler movement across the entire province, a spatial extent not possible using traditional creel survey data. Furthermore, an analysis of passively collected angler location data from a sonar-enabled fishing bobber (linked to a mobile application) showed that nearly half of all user movements between waterbodies in the continental United States occurred within the desiccation tolerance window of many prevalent plant and animal invasive species (Fricke et al. 2020). Text and data mining of posts to popular social media platforms can also be leveraged to understand the spatiotemporal distribution of wildlife recreation activities (Monkman et al. 2018), and these same sources could also inform risk management for human-initiated invasive species transmission. These new mobile and web-based data sources are not a replacement of traditional in-person surveys of waterbody visitation, but when coupled with site-specific data models informed by smartphone-derived data are significantly more informative (Wood et al. 2020).

Detecting and cataloging presence in the wild

Despite efforts to intercept invasive species prior to introduction, individuals repeatedly slip through to establish non-native populations. Early detection of newly introduced species is critical for enabling rapid implementation of control measures but remains challenging because of the large and diverse landscapes agencies are typically tasked with monitoring (Reaser et al. 2020). New technologies have enhanced our ability to effectively detect species outside their native range through camera traps, environmental DNA, and crowdsourcing of citizen scientist observations. The pace of detection can be further accelerated through artificial intelligence-based methods that automate species identification in imagery.

Locating target invasive species in the wild typically demands intensive and costly field campaigns that are limited by the number of personnel relative to a survey area. Remote camera traps that take photos when a sensor is triggered by the movement of an animal (using infrared and motion sensors), which increasingly transmit real-time images over cellular networks, can alleviate the long-term time commitment needed to effectively survey. For example, camera traps have been used to accurately detect invasive wild pigs (*Sus scrofa*) in South Carolina (in the United States) and invasive small and medium-size terrestrial mammals on the island of Terceira (Davis et al. 2020, Lamelas-López and Salgado 2021). Furthermore, linking camera trap images with artificial intelligence-driven classification can expedite and automate the species identification process. Convolutional neural networks (CNNs) are computing systems inspired by biological networks of neurons that are commonly applied to image analysis. Willi and colleagues (2019) demonstrated the utility of CNNs for identifying specific species (89%–93% accuracy) and differentiating from nonanimal or empty images across multiple test data sets. Next-generation camera trapping will warrant technological modifications that expand the suite of potential species surveyed to smaller and more cryptic taxa (Delisle et al. 2021).

Detecting non-native species in elusive habitats, such as aquatic environments, is particularly challenging with traditional survey methods. Innovations in environmental DNA (eDNA) sampling, which uses genetic material extracted from environmental samples (e.g., soil, water, air) to identify species' presence—such as real-time PCR (polymerase chain reaction) and high-throughput sequencing—have increased the availability of this method and alleviated some of its costs (Larson et al. 2020). eDNA has proven to be an effective surveillance tool for highly invasive quagga and zebra mussels (*Dreissena* spp.) in novel waterbodies (Feist and Lance 2021), and it has enhanced the border detection of non-native fish species through cross-referencing the eDNA of live trade shipments to DNA sequence libraries (Roy et al. 2018). Furthermore, portable field-based platforms for testing for invasive northern pike eDNA have been shown to take only a fraction of the time needed for lab-based approaches and offers an opportunity to rapidly screen for invasive species presence (Sepulveda et al. 2018). A recent feasibility study demonstrated that retrofitting existing US streamflow gauges with environmental sample processors (e.g., electromechanical robots that autonomously filter and preserve water samples) may offer a powerful way to overcome the human resource challenges of collecting samples for eDNA biosurveillance of rivers over long time periods and across large geographic areas (Sepulveda et al. 2020).

Traditionally, monitoring for invasive species has been largely dependent on organized, on-the-ground campaigns by trained professionals, which are largely limited in their time and spatial scope. Dedicated citizen-science initiatives facilitated by web or mobile application interfaces—such as iNaturalist, eBird, and apps developed to target a specific species or region—are now enhancing knowledge of novel occurrences of invasive species beyond previously feasible scales (Johnson et al. 2020). These digital sharing platforms have enabled data collection to identify new populations of invasive eastern grey squirrel (*Sciurus carolinensis*) in Italy (Mori et al. 2016) and to reconstruct the history of non-native monk parakeets (*Myiopsitta monachus*) in Mexico in relation to changes in legal regulations on pet trade importations (Hobson et al. 2017). Citizen observations can also allow managers to rapidly detect and respond to novel non-native and invasive species within their region, such as when Rojas and Jackson (2018) described the first account of the European firebug (*Pyrrhocoris apterus*) in Canada, the significance of which was recognized when the author submitted photographs to the community science project iNaturalist. Third-party expert confirmation of app-based sightings can initiate rapid response efforts, as the data processing flow for New Zealand's Find-A-Pest app exemplifies (box 1; Pawson et al. 2020).

Monitoring and limiting spread

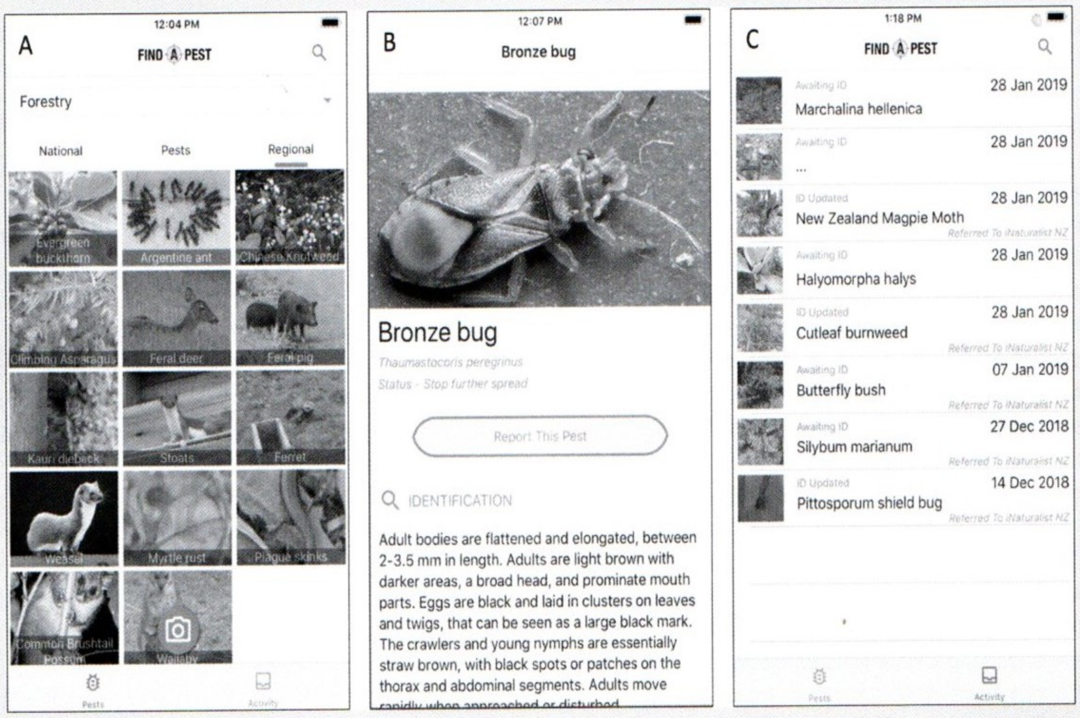
A key component of managing species invasions is limiting their spread into adjacent regions through natural dispersal. New methods based on digital image analysis, social media scraping, and remote sensing offer more time- and cost-effective means to track species' spread and respond quickly. Next-level monitoring for invasive species detection in remotely collected imagery and community science data could transform from explicit (i.e., designating invasive species of concern to search for) to implicit (e.g., automatic recognition) approaches by leveraging new advances in computer vision systems trained to automatically recognize species (Joly et al. 2016, Demertzis and Iliadis 2017).

Traditional ground monitoring approaches for invasive species are dependent on well-trained human identification of non-native species, which can be prone to long processing times and varying levels of error. Numerous breakthroughs in automating image analysis—or the extraction of information from photos by classifying objects—have facilitated new approaches to identifying invasive plant species remotely and at scale. Morphological spatial pattern analysis, which classifies and quantifies features within digital images according to shape, was more accurate at identifying invasive winter heliotrope (*Petasites fragrans*) than standard visual estimation methods (Carlier et al. 2020). Machine-learning approaches for identifying invasive *Hydrangea* built on convolutional neural networks achieved a near perfect accuracy (99.7%) on test data sets, suggesting that this is a highly effective method for automating recognition of invasive species within digital imagery (Ashqar and Abu-Naser 2019).

Mapping invasive species across vast landscapes poses challenges in regions with difficult terrain and limited access infrastructure. Traditional large-scale surveys occur predominantly from helicopters or fixed-winged aircraft, both of which can be expensive. Remote sensing—encompassing an array of tools from high-resolution satellite imagery to small, unmanned aerial vehicles (UAVs, or drones)—has been used to map the distribution of invasive animals, pests, weeds, and diseases at more than 10 times less than the cost of manned flights (box 2; Jurdak et al. 2015), and it offers an opportunity to automate data processing and species recognition. Airborne imaging spectroscopy and laser scanning were used to map the distribution of *Eucalyptus* spp. and black wattle (*Acacia mearnsii*) in eastern African regions where they are invasive, and Piiroinen and colleagues (2018) used a one-class biased support vector machine built on machine learning to identify the target species (box 3). Tesfamichael and colleagues (2018) further demonstrated the ability of remote sensing to automate invasive alien plant species identification by quantifying the efficacy of spectroradiography in distinguishing between similar invasive and noninvasive plants with narrow leaf structures; the results indicated high classification accuracies (83%–97%). Drone imagery processing with deep neural networks built on machine learning has also enabled the detection of invasive green anole (*Anolis carolinensis*) in the Ogasawara Islands of Japan (Aota et al. 2021). Although UAV use is substantially less expensive than fixed aircraft, mapping with ground surveys is often still the most cost-effective option (Sladonja et al. 2022). Remote sensing has also been employed below the ocean's surface, where deep sea video surveys have revealed the range expansion of Humboldt squid (*Dosidicus gigas*) into waters off central Florida (Zeidberg and Robison 2007).

Box 1. Mobile applications and social media data offer new avenues for streamlining species observation processing and initiating rapid responses to species invasions.

Social media and cell phone applications are dramatically altering the landscape of data available on invasive species distributions, as well as opening opportunities for the development of dedicated platforms to rapidly identify and respond to novel invasions. Social media posts to both wildlife-specific platforms (e.g., iNaturalist, eBird) and broader social sites (e.g., Twitter, Instagram) can be leveraged to identify species introductions and spread. For example, records of introduced freshwater turtles in the United Kingdom from the photo-sharing application Flickr largely reflect the spatiotemporal distribution of traditionally reported observations (Allain 2019), and researchers may be able to track the trade of exotic pets by monitoring distributors' Facebook pages (Harrington et al. 2021). Ultimately, mobile platforms that integrate species observations into expert-verified reporting systems—such as New Zealand's Find-A-Pest application—may be the most effective avenues for leveraging community science sightings and initiating a rapid response to new species invasions (Pawson et al. 2020). See figure 2. This application allows users to (a) view invasive species within a selected region, (b) peruse the profile and biography of invasive species, and (c) monitor the status of their submitted observation (e.g., awaiting identification, referral initiated). Photographs: iTunes Search API. Despite the growing number of invasive species reporting applications available, these platforms still lack the user engagement (e.g., gamification of invasive species identification and reporting) needed to promote widespread and sustained use (Howard et al. 2022).

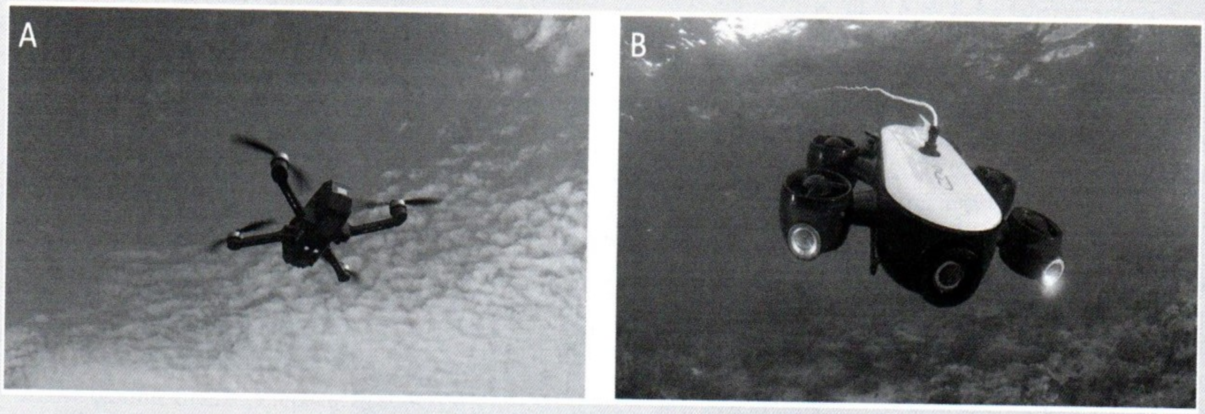


The development of predictive models to forecast invasive species spread is often hindered by limited available data on species distributions over time, because traditional ground-monitoring methods require significant time and resources. With the influx of observation data now available through species-specific mobile applications and social media, however, managers now have the option of crowdsourcing public data to inform species distribution models. Researchers and management entities designed the community science mobile application BugMap to elevate scientific understanding of invasive brown marmorated stink bug (*Halyomorpha halys*)—an agricultural pest—behavior and distribution (Malek et al. 2018). Collected data informed forecasts of the species predicted distribution in a newly invaded region of Northern Italy and led to the discovery of the insect's seasonal invasion dynamics, allowing researchers to model areas most likely to be invaded next. Community science data have also informed predictive species distribution models of plants in New England (Botella et al. 2018) and aided in tracking the spread of the invasive harlequin ladybird (*Harmonia axyridis*) in Britain and Ireland (Brown et al. 2018). Van den Burg and colleagues (2020) further demonstrated the utility of mobile data by developing species distribution models for invasive common green iguana (*Iguana iguana*) in Singapore and Thailand from photos and video on social media (Facebook, Instagram, iNaturalist) and photo-sharing websites (Flickr, iStock Photo, Shutterstock).

Containing invasive species or preventing their subsequent dispersal into new, adjacent regions can prove challenging, particularly in riverine habitats where managers are simultaneously seeking to maintain habitat connectedness for native species across physical barriers (Rahel 2013). New advances in riverine barrier management offer opportunities to limit species range expansions into new river sections. Artificial barriers that selectively allow fish passage for only native species can be implemented through high-precision classifiers that automatically identify species on their entry into a barrier passageway. For example, image recognition built on deep convolutional networks achieved a test prediction accuracy of 97% for 13 species in the Great Lakes, including invasive sea lamprey (*Petromyzon marinus*) and four major Asian carps (bighead carp, *Hypophthalmichthys nobilis*; silver carp, *Hypophthalmichthys molitrix*; black carp,

Box 2. Remote-operated vehicles and remote sensing improve invasive species monitoring.

Remote-operated vehicles (ROVs) and remote sensing have enhanced our ability to monitor and detect species underwater and in remote land regions. Satellite imagery from Earth observation systems such as Sentinel-2 and the Landsat program have enabled species distribution mapping of the invasive plants *Pinus radiata*, *Ulex europaeus* and *Acacia dealbata* in Chile, *Spartina alterniflora* in China, and *Prosopis juliflora* in Ethiopia—to name a few examples (Kattenborn et al. 2019, Gong et al. 2020, Ahmed et al. 2021). Unmanned aerial vehicles (UAVs; see figure 3), or drones (a), have further enhanced aerial mapping by allowing cameras to fly at lower elevations necessary for capturing high-resolution imagery to differentiate between species. This capability is particularly useful in arid regions where species tend to be smaller, and in finer-scale areas of species cover such as riverbanks (Kedia et al. 2021, Sladonja et al. 2022). In aquatic environments, (b) underwater remote operated vehicles (ROVs) equipped with cameras can map the distribution of invasive species such as zebra mussel (*Dresseina* spp.; Mehler et al. 2016). Video footage from ROVs has also been used to quantify spatiotemporal shifts in fish communities, providing evidence that native catfish (*Loricariichthys castaneus*, *Pimelodella lateristriga*) in a Brazilian reservoir have moved to deeper water in response to the introduction of exotic cichlids (*Cichla* spp., *Coptodon rendalli*) that prefer shallower zones (Guedes and Araújo 2022).



Mylopharyngodon piceus; and grass carp, *Ctenopharyngodon idella*; box 3; Eickholt et al. 2020). In addition, bubble curtains, strobe lights, and acoustic barriers targeting the audiovisual systems of invasive carp have also shown some success in providing selective passage for native species, although potential long-term effects of these systems on native populations and their efficacy at deterring invasive species over longer timescales remains unknown (Zielinski et al. 2014, Jones et al. 2021).

Quantifying and addressing ecological impacts

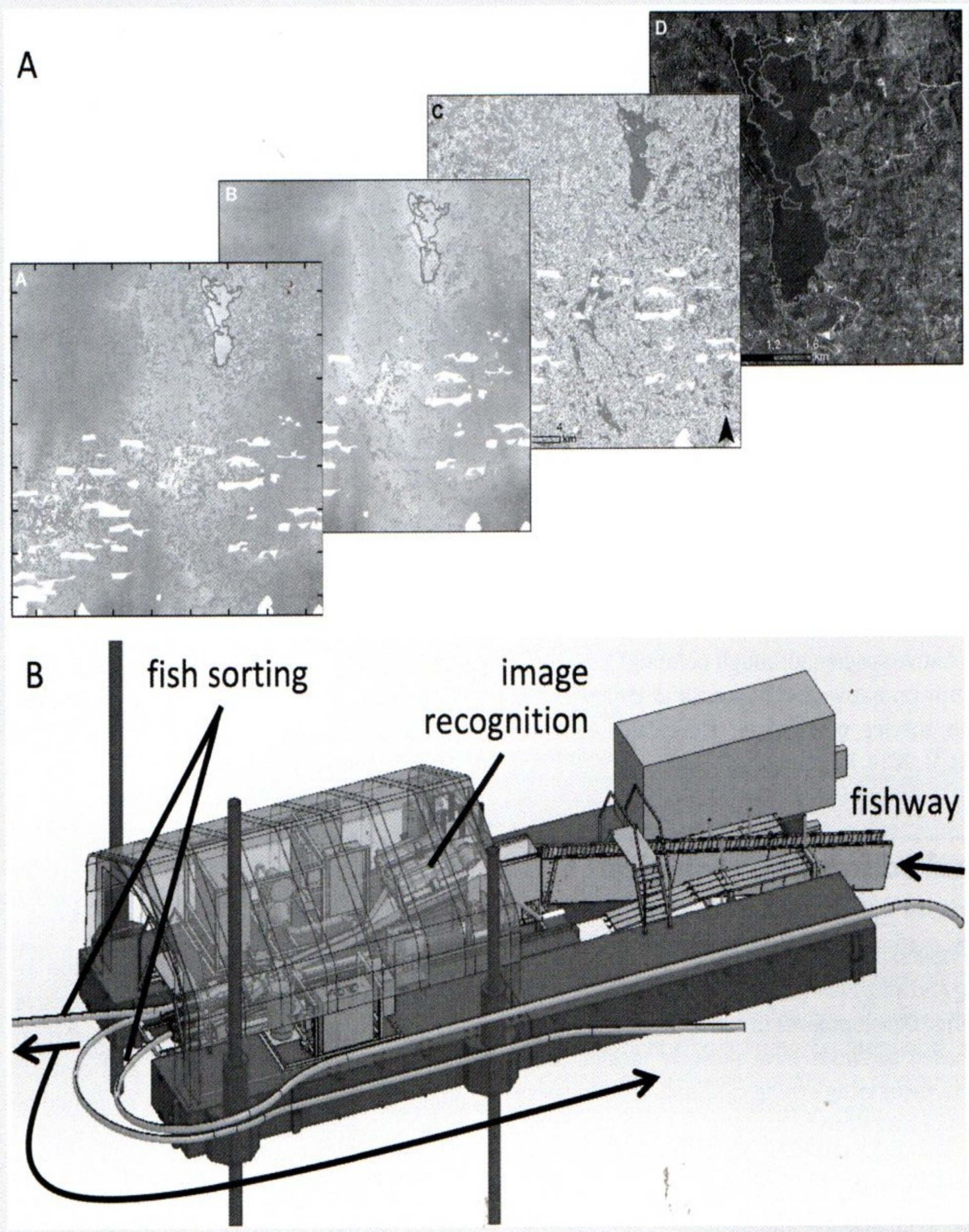
An integral part of assessing the damage leveed by invasive species is quantifying and addressing the ecological impacts to individuals to ecosystems. Developments in camera trapping, ecoacoustics, and DNA-based methods have recently tackled long-standing challenges in measuring ecological impacts of invasive species across and space and time.

Understanding interactions between invasive predators and their native prey has traditionally depended on firsthand observations of encounters between invasive and native species. However, remote cameras and vehicles now offer an opportunity to document and address these interactions in hard-to-reach locations, and genetic approaches are enabling researchers to tease apart complex interactions. For example, camera traps have been used to identify nest predators of native bird species across tropical rainforests in Brazil (Ribeiro-Silva et al. 2018). In addition, managers have recently demonstrated the use of drones to identify nuisance seagull (*Larus* spp.) nests in France and spray them with a sterilizing fluid, suggesting that remote vehicles could be an effective tactic for not only identifying but also controlling nonnative species (Culbertson 2015). To understand more complex interactions between invasive and native species, researchers have increasingly turned to fatty acids and stable isotopes as complementary biomarkers to quantify the trophic ecology of invasive species (https://doi.org/10.1101/2020.07.30.229021 [preprint: not peer reviewed]) and trace predator–prey relationships (King et al. 2017, Rubenson et al. 2020). In addition, compound specific stable isotope analysis—or the comparison of isotopic signatures for individual groups of chemicals to examine trophic relationships—revealed that the invasive amphipod *Dikerogammarus villosus* does not primarily affect native populations through predation (Sahm et al. 2020).

Documenting community change due to invasive species introduction typically relies on effort-intensive sampling of species for relative abundance and other community metrics. In support of developing more time- and cost-effective measures for quantifying community change, recent advances in ecoacoustics have proposed using sound from the activity of an animal community as an indicator of environmental conditions or ecological changes (Pijanowski et al. 2011). For example, acoustic tools have been used to monitor the distribution of invasive freshwater drum (*Aplodinotus grunniens*) in the Hudson River, New York, which produce sound with a special set of muscles in their body cavity that vibrate against the swim bladder during spawning (Rountree and Juanes 2017). Similarly, the density and presumed impact of the invasive electric ant (*Wasmannia auropunctata*) was estimated according to reductions in calls of the native cricket community in New Caledonia (Gasc et al. 2018). Acoustic techniques for detecting community structure reflect seasonal and spatial changes in species' distributions, providing real-time and constantly

Box 3. Enhancing image analysis and invasive species identification through machine learning approaches.

Machine learning is rapidly enhancing invasive species management through automated recognition and classification of image and text data. For example, Piiroinen and colleagues (2018) mapped the occurrence of invasive trees *Eucalyptus* spp. and black wattle *Acacia mearnsii* in Kenya using a combination of airborne imaging spectroscopy and laser scanning, followed by machine learning-based classification of imagery. The authors classified crowns separately for the two species of interest using a biased support vector machine algorithm—a type of one class classification approach for image recognition that only requires labeled training data for the positive class (i.e., a single tree species). See figure 4. Species occurrence in relation to environmental variables was then used to predict its distribution over the entire area, enabling region-wide mapping of occurrence for each species (a). In addition to automating image processing, machine learning can also aid in real-time identification of individuals as native or non-native. Eickholt and colleagues (2020) tested this concept by passing specimens of 13 fish species (including invasive sea lamprey and Asian carp) through a fish imaging scanner developed by Whooshh Innovations (b). Images were then classified with deep convolutional neural networks and achieved an accuracy of 97% on a test dataset of species' images, demonstrating the viability of automated, image recognition in fish passage systems.



updating information on individuals' location and movement (Chhaya et al. 2021).

Controlling and eradicating populations

Once a nuisance species has become established, managers may seek to eradicate a targeted population for a variety of ecological and economic reasons. The heterogenous nature of landscapes in which non-native species establish often makes locating and eliminating all individuals of an introduced species a daunting and near impossible task. However, enhanced capability to build robots, edit and inhibit species' genes, and identify species in real time has spearheaded novel approaches to capturing invasive individuals, limiting their reproduction, and assessing the effectiveness of removal efforts.

Significant time and personnel are often needed to execute removal efforts, such as in aquatic environments where underwater dive times are limited and surveying for mobile species' locations in advance requires an extensive additional investment. Remotely operated vehicles (ROVs) offer a solution to locate both stationary and mobile underwater species from above the surface (Sward et al. 2019), and certain models can also interact with or capture target species (box 2). By creating a robotic predator programmed to biomimic the behavior of natural predators of the invasive western mosquitofish (*Gambusia affinis*) researchers showed that even a brief (15 minute) weekly exposure to the robot effectively depletes the mosquitofish' energy reserves and deteriorates its body condition (Polverino et al. 2019). To aid spear-hunting divers in finding and identifying invasive red lionfish (*Pterois volitans*), a small ROV with an integrated camera programmed using deep learning showed success in real-time assistive identification of the species and allowed divers to plan their dive prior to entering the water, maximizing their catch under time constraints (Naddaf-Sh et al. 2018). Beta testing by private companies has gone one step further by developing an underwater vehicle, the Guardian LF1 Robot, intended to identify and capture red lionfish (Knight 2021). However, the efficacy of this ROV at trapping red lionfish over broad scales has yet to be tested.

Monitoring invaded regions during and after removal programs is fundamental to ensuring successful invasive species control (Kettenring and Adams 2011). In the past, program evaluations have depended on time-intensive repeated manual field surveys, but new breakthroughs in remote sensing with drones and ROVs are now enabling scientists to quantify the effectiveness of invasive plant removal from afar. Brooks (2020) used drones and multispectral imagery to compare the reduction level of multiple treatment methods (mechanical harvesting, biological control, and diver-assisted suction harvesting) for Eurasian watermilfoil (*Myriophyllum spicatum*) removal. Autonomous surface vessels on lakes have also been developed to monitor Eurasian watermilfoil growth through imagery and depth information collection, with future work intended to distinguish between Eurasian watermilfoil and native plants (Codd-Downey et al. 2021). Remote sensing also aided in understanding the extent of invasive red imported fire ant (*Solenopsis invicta*) in Southeast Queensland and, in the future, aims to confirm eradication of the species in regions treated with removal (Wylie et al. 2021).

Large-scale invasive species control can pose risks to the integrity of ecosystems (e.g., removing nontarget native species), and with traditional removal methods, managers must consider the trade-offs of removal and its potential repercussions (Kopf et al. 2017). The development of highly targeted invasive plant herbicide application through helicopter ballistic technology has allowed managers to significantly reduce non-native plant populations on Santa Cruz Island, in California, with limited damage to nontarget species (Cory and Knapp 2014). Recent advancements in the development of smart trapping devices equipped with sensory attractants and automated species recognition can also address this challenge by selectively attracting and capturing target species. Acoustic traps—physical traps equipped with speakers broadcasting reproductive calls—have shown promise as potential control mechanisms for invasive round goby (*Neogobius melanostomus*) in the Great Lakes (Isabella-Valenzi and Higgs 2016) and the invasive pest Asian citrus psyllid (*Diaphorina citri*) in California (Rene Fernandez 2020). Furthermore, scented traps with behavior-modifying semiochemicals are effective at capturing invasive sea lamprey (*Petromyzon marinus*) in experimental settings (Hume et al. 2015). Newly developed smart pig traps enhanced with image recognition capability detect and confirm the identity of wild pigs in traps prior to closing their doors (SSU 2019).

Large, well established, mobile, and rapidly reproducing populations of invasive species are often difficult to control because of the sheer number of individuals in the wild. However, because the potential for genetic manipulation has expanded rapidly in recent years across sectors, we now have a large suite of tools capable of influencing the trajectory of invasive species from within their own ranks (box 4). Gene drives—the use of genetic engineering to propagate a particular suite of genes throughout a population—offer managers a set of tools to influence the reproduction and survival of invasive species on the population scale (Teem et al. 2020). For example, researchers have proposed releasing engineered mice into island rodent populations that only produce male offspring to create a population incapable of reproduction (Leitschuh et al. 2018). Similarly, the development of a CRISPR gene drive targeting spermatogenesis in invasive common wasps (*Vespula vulgaris*) in New Zealand has been proposed as means to reduce or eliminate invasive species outside their native range (Lester et al. 2020). Pathogen introduction has also been proposed as a biocontrol agent, with researchers suggesting that the release of cyprinid herpesvirus 3 could be an effective control mechanism for invasive common carp (*Cyprinus carpio*) in Australia (McColl et al. 2016). However, this project is controversial given the uncertainty of potential ecosystem-wide impacts of mass fish kills. Finally, the development of large biological databases has allowed scientists to effectively screen candidate molecules that may aid as bioinhibitors in invasive species control. Raschka and colleagues (2018) demonstrated the utility of their Screenlamp modular toolkit for identifying candidate proteins that may inhibit reproductive pheromone receptors in invasive sea lampreys. Although genetic manipulation research suggests these technologies are a promising tool for invasive species management, scientists caution that acquiring public support for such programs will require substantial investment in open communication, intensive study of target nuisance species' reproductive biology and genetics, and physical and molecular containment of modified test organisms prior to implementation in the wild (Dearden et al. 2018).

Public engagement in invasive species management

Public sentiment toward invasive species management and trust in managers' ability to effectively manage non-native species can determine societal support for conservation actions (Bremner and Park 2007, Wald et al. 2019). Failure to adequately gather public perspectives could result in the public's refusal to engage in management efforts related to invasive species or outright opposition to planned actions (Kapitza et al. 2019). New innovations in social media scraping and web-based tools have enhanced our ability understand public discourse around invasive species and proactively educate and engage the public in management efforts.

Culturomics, or the study of human behavior and cultural trends through analysis of digital text and images, offers valuable insight into human attitudes around conservation and invasive species (box 5). Information on human–nature interactions and human thoughts and attitudes about conservation is available through social media, smartphone applications, and online forums, and offers data at previously unfeasible spatial and

Box 4. New methods for genetic manipulation provide opportunities to identify and suppress invasive populations.

Genetic techniques for invasive species identification and suppression—including but not limited to eDNA, gene drives, transgenes, gene silencing, and supermales—have revolutionized invasive species management. Our ability to extract and classify trace amounts of species DNA within environmental samples from land, water, and even air has expanded rapidly with increasingly accessible and affordable techniques such as qPCR (quantitative polymerase chain reaction) and high-throughput sequencing (Larson et al. 2020, Clare et al. 2022). eDNA can aid in invasive species detection by allowing managers to search widely for new species within an environment or target specific nuisance species. Transgenes—or the introduction of one or more foreign DNA sequences from another species by artificial means—could serve as an effective control method for invasive species through the introduction of modified individuals containing detrimental genes. For example, to suppress mosquito-borne diseases transgenic mosquitoes *Aedes aegypti* with a dominant lethal gene were introduced and incorporated into the genome of a mosquito population in Brazil (Evans et al. 2019). Furthermore, prevention of gene expression through gene silencing has reduced populations of the honeybee ectoparasite *Varroa destructor* and nuisance western corn rootworm *Diabrotica virgifera virgifera* (Garbian et al. 2012, Reinders et al. 2022). Finally, supermale fish—individuals with a YY sex chromosome—have been introduced into invasive fish populations to skew the gender ratio toward males, ultimately causing population eradication (Bhattacharyya et al. 2020).

Box 5. Computational social science to understand public attitudes toward invasive species management.

The study of human behavior and attitudes through analysis of digital data can inform invasion science by revealing human sentiment toward and awareness of invasive species (Jaric et al. 2021). Analyses within this subfield have quantified polarity of stakeholder attitudes toward invasive fish management, Google search volumes for invasive fire ants, Internet salience of invertebrate biological control agents, and Wikipedia page views for hundreds of bird species (Mehmet et al. 2018, Fukano and Soga 2019, Wyckhuys et al. 2019, Mittermeier et al. 2021). In addition to estimating the efficacy of invasive species management on the basis of public interest and support, computational social science also offers an opportunity to leverage digital activity for early detection of invasive species in global trade. Enhancing international biosecurity and identifying global dispersal networks of invasive species is a top priority for invasion science (Ricciardi et al. 2021). Biosecurity management could employ computational methods by monitoring digital species trade forums for mentions of new species and shipping destinations and anticipating the locations and type of potential new species' introductions in advance (Olden et al. 2021).

temporal scales (Correia et al. 2021). Data mining of existing online networks and forums within naturalist, hunting, and angling communities can provide managers valuable information about public sentiment around invasive species (Jaric et al. 2021). A manual analysis of tweets shared through the microblogging platform Twitter containing messages related to three invasive alien species (oak processionary moth, *Thaumetopoea processionea*; emerald ash borer, *Agrilus planipennis*; eastern grey squirrel, *Sciurus carolinensis*) showed that social media channels are an extensive source of observational data and elucidate the nature of public discourse surrounding invasive species (Daume 2016). In addition, Sbragaglia and colleagues (2020, 2021) demonstrated through a content analysis of angler comments on YouTube videos that anglers hold contrasting sentiments toward invasive species, and, therefore, control measures may accrue the support of only some but not all stakeholders.

When empowered with adequate tools and education, the public can also aid in removal efforts. Social media and web-based platforms provide an opportunity to solicit public assistance and make invasive species information available on a global scale. For example, social media networking was used to organize and facilitate a grassroots red lionfish removal program in the British Virgin Islands (Forrester et al. 2021). In New Zealand, the Find-A-Pest cell phone application (www.findapest.nz) was developed through a codesign effort involving indigenous tribes, agricultural and forestry sector representatives, iNaturalist, and regional and national government agencies. This mobile application allows users to report potential sightings of invasive weeds, insects, fungi, and other non-native animals via photographs or identification based on species' factsheets. App users collectively identify reported sightings via iNaturalist New Zealand, and those confirmed as potential invasive species are then forwarded to Biosecurity New Zealand. In a 3.5-month case study of 471 observations covering 176 taxa, crowdsourced citizen identifications were correct 95.5% of the time (Pawson et al. 2020). Researchers have also proposed the development of a global open, zoomable atlas of invasion science that would provide critical information to both the public and policymakers on species' distributions and impacts (Jeschke et al. 2021).

Challenges and opportunities for management success

Emerging technologies in invasion science offer much promise for expanding the scope and improving the effectiveness of management tactics and policy actions. The new technological methods we have described are often based on remotely sensed or web and cell-based data sources, which serve as cost-effective, automatically updating sources of data collection for ecological monitoring. Drones, ROVs, DNA barcoding, web scraping, smartphone applications, and image classification are just a handful of the new tools available to enhance the tracking and management of invasive species.

Although the growing utility of new technological innovations within invasion science is promising, numerous challenges related to the uptake of new technologies by practitioners in remote regions continue to hinder the integration of these data into management systems (Daume 2016). In the present article, we discuss specific barriers to the application of new approaches within invasion science and outline key areas to propel the use of new technologies in management. Enhanced technologies alone will not improve conservation; only by establishing the pipelines needed to provide these tools to end users can we hope to improve invasive species management.

Invasive species management trails other fields in its implementation of emerging technologies. Indeed, a recent survey of conservation practitioners and academic researchers found that automated processing of data streams was the greatest need to expediate the uptake of technologically innovative methods (Hahn et al. 2022). Greater investment in collaborations with disciplines possessing a longer history of implementing automated methods, such as engineering and computer science, will undoubtedly aid invasion science in the integration of new technologies. Furthermore, big crowdsourced data are not necessarily the panacea to data limitations currently facing the field of invasion science. For example, a study using the community science sourced Invasive Plant Atlas of New England found that the predictive ability of abundance models for invasive plants were poor, suggesting that the inconsistent nature of occurrence reports from applications may not effectively represent a species distribution over some scales (Cross et al. 2017).

Despite such limitations, however, we believe by addressing a handful of significant barriers, invasion science can make significant strides in harnessing new technologies for management good. First, formalizing data sharing guidelines is critical for developing regional partnerships. Data must be seen as products of research rather than as solely stepping stones to publications (Hampton et al. 2013), and data acquired through drones, remote cameras, and web scraping methods must traverse the fine line between prioritizing human anonymity and explicitly detailing how they were procured (Sandbrook et al. 2021). A recent review of community science initiatives collecting invasive species observations found that just half (54%) of programs had a practice of data sharing, which may be impeding more widespread use of these data (Johnson et al. 2020). In decision-making programs aiming to integrate multiple types of data, it is also vital that resource managers understand the strengths and weaknesses associated with each methodological approach and communicate this to future users (Kamenova et al. 2017).

Second, end users are in desperate need of powerful interfaces to readily access and disseminate the large data sets used in many of these new technological approaches. Numerous monitoring and reporting frameworks for managing invasive species across networks have been proposed, but these ambitious management schemes are only feasible through large-scale information collation supported by easy-to-use interfaces (Shackleton et al. 2020). Digitization of data collection can facilitate more timely analysis, leading to faster management decision-making during rapid response efforts (Will et al. 2014), but the pace of data integration depends on the extent of digital infrastructure connecting an observation of an invasive species to the relevant management agency. Furthermore, the most useful research outcomes may be those that directly integrate large data sets into decision support tools. For example, Bradie and Bailey (2021) developed a decision tool with Transport Canada to prioritize locations for ballast water compliance monitoring on the basis of rankings of invasive species establishment risk.

Third, the uptake of new technologies by resource managers may be further spurred by enriched interactions between technology developers, end users, and stakeholders, with a focus on identifying opportunities for cogeneration of knowledge. For many decades, researchers and managers have advocated for increased collaboration in invasive species science and management (Vaz et al. 2017), and the adoption of technologically enhanced approaches warrants a renewed emphasis on working together. Engagement of partners from other sectors, particularly computer science, engineering, and industry, could spur novel technological applications within invasive species management (Joppa 2015, Martinez et al. 2020). Collaborators should endeavor to first understand the technical knowledge of their management partners, however, because field-specific understanding can strongly influence managers' perceptions of new conservation methods (Bernos et al. 2022). Moreover, crowdsourced technologies such as community science applications and social media sites offer an opportunity to recruit contributors to conservation science, educate users, and serve as a medium for open and responsive communication of management intentions (Di Minin et al. 2015, Crowley et al. 2017).

Fourth, many new technologies are expensive and will remain out of reach to scientists and practitioners in many regions unless costs are reduced. For example, image recognition built on artificial intelligence can require significant hardware, software, and specialist staff, which may be unattainable to many (Lamba et al. 2019). Despite reductions in the cost of some technological methods since their initial development (e.g., eDNA), prohibitive cost is the most cited barrier limiting technology uptake within the conservation community (Hahn et al. 2022). Future technological development should prioritize methods that are financially accessible to practitioners globally.

Finally, training skills enabling practitioners to readily use new technologies are not universally available. Although disparities in technology accessibility are starting to narrow across the globe, support services integral to the sustained use of conservation technology (e.g., product maintenance, technical advice, and training on data collection, management, and analysis) continue to be limited (Lahoz-Monfort et al. 2019). Furthermore, projects often lack a designated technologist to offer technical support (Hahn et al. 2022). Open-source software and hardware (e.g., Raspberry Pi, Arduino) have created development environments for computational and tactile tools that may alleviate cost and access barriers, but acquiring the knowledge base to develop technical products and analyses for specific management purposes remains challenging. For management entities lacking internal technical expertise, the development of cross-boundary networks sharing technical knowledge and methods for invasive species management is crucial.

Conclusions

Uptake of new technologies within invasive species management holds considerable promise for improving our ability to recognize and respond to novel species' invasions quickly and efficiently. However, as with any new technology, one must show its equivalence or advantages over the current methods. Furthermore, for the democratization of new technologies to be fully realized, significant work is needed to implement the data sharing practices and platforms necessary to integrate big data into management networks. Future investments should also focus on supporting application in remote and low-technology environments where frontline management actions are critical. In an increasingly connected world, both physically and digitally, the potential for invasive species to occur in new locations seems limitless. Rather than solely responding to the impacts of globalization and technological innovation, it is time for invasive species scientists and managers to turn the tables and leverage technology to their advantage. In the face of rapid human-assisted movement of invasive