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REVIEW

# The early detection of and rapid response (EDRR) to invasive species: a conceptual framework and federal capacities assessment

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**Abstract** Globalization necessitates that we address the negative externalities of international trade and transport, including biological invasion. The US government defines invasive species to mean, "with regard to a particular ecosystem, a non-native organism whose introduction causes, or is likely to cause, economic or environmental harm, or harm to human, animal, or plant health." Here we address the role of early detection of and rapid response to invasive species (EDRR) in minimizing the impact of invasive species on US interests. We provide a review of EDRR's usage as a federal policy and planning term, introduce a new conceptual framework for EDRR, and assess US federal capacities for enacting well-coordinated EDRR. Developing a national EDRR program is a worthwhile goal; our assessment nonetheless indicates that the federal government and its partners need to overcome substantial conceptual, institutional, and operational challenges that include establishing clear and consistent terminology use, strategically identifying and communicating agency functions, improving interagency budgeting, facilitating the application of emerging technologies and other resources to support EDRR, and making information relevant to EDRR preparedness and implementation more readily accessible. This paper is the first in a special issue of *Biological Invasions* that includes 12 complementary papers intended to inform the development and implementation of a national EDRR program.

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## Introduction

The globalization of trade, travel, and transport dictates that we occupy a more interconnected, yet seemingly smaller and increasingly homogeneous world. It also requires that we address the negative externalities of the expanding human enterprise, including biological invasion. Species that are integral ecosystem components in their native ranges may be labelled "invasive species" and managed when relocated to new ecosystems (Mack et al. 2000; McNeely et al. 2001; Burgiel et al. 2006; Simberloff 2013; Chapman et al. 2017). The US government defines an invasive species to mean, "with regard to a particular ecosystem, a non-native organism whose introduction causes, or is likely to cause, economic or environmental harm, or harm to human, animal, or plant health." It is US policy to prevent the introduction, establishment, and spread of invasive species, as well as to eradicate and control populations of invasive species that are already established (Executive Office of the President 2016).

Here we address the role of the early detection of and rapid response to invasive species (EDRR) in minimizing the impact of invasive species on US interests. Specifically, we provide a review of EDRR's usage as a term in federal policy and planning, introduce a new conceptual framework for EDRR, assess US federal capacity for enacting EDRR through a coordinated program, and identify needs for improving federal EDRR capacities. This paper is the first in a Special Issue of *Biological Invasions* that includes 12 complementary papers intended to facilitate development and implementation of EDRR capacity nationally. Although the papers in the series have an explicitly federal focus, we recognize that effective and cost-efficient EDRR requires coordination with other countries; state, territorial, tribal, and local governments; non-governmental organizations; the private sector; and the general public.

A comprehensive approach to biosecurity, of which EDRR is a crucial component, is essential for minimizing the negative externalities of globalization (McNeely et al. 2001; Waage and Reaser 2001). Biosecurity is a long-warranted policy agenda in the United States from various national security perspectives, ranging from meeting basic food security needs to protecting the populace from bioterrorism (Meyerson and Reaser 2002a, b, 2003). The transition from a piecemeal approach to addressing invasive species to one that is more coordinated and vigilant will require greater attentiveness to information management, budgets and finances, inspection and quarantine, and eradication and control operations (Reaser and Waugh 2007; Reaser et al. 2008; Waugh 2009). A growing interest in EDRR by federal, state, territorial, and tribal agencies creates the necessary enabling environment for a national EDRR program that facilitates biosecurity across all levels of government.

## EDRR in federal definitions, policy, and planning

The term "EDRR" has become topical in invasive species science, policy, and management even though the concept has been largely undefined and inconsistently applied. Table 1 provides an overview of how US government reports and globally-scaled publications, to which the US contributed substantially over the last 25 years, describe or define EDRR. The terms "detection" and "rapid response" are first used in a 2001 report by the US General Accounting Office (GAO), where detection is regarded as the act of surveying for non-native species that have already been introduced and rapid response is any action that enables those organisms to be eradicated or prevented from spreading further.

Although EDRR is frequently mentioned as a key tenet of invasive species management in the publications through 2018, definitions are scant. In general, early detection is considered the process of searching for (surveying) non-native species to prevent the species from becoming established, spreading, and causing harm. However, definitions of early detection also include impact assessment (National Invasive Species Council 2011, 2012, 2013, 2014, 2015, 2016a) or monitoring (US Forest Service 2013). In sharp contrast to other authors, Welch (2014) considers early detection a process for evaluating change in ecological condition and management progress over the long-term. Each of these definitions requires different programmatic goals, designs, and investments, and thus use of the term "early detection" needs to indicate spatio-temporal application.

Rapid response has generally been regarded as an effort to eradicate invasive species, although some federal definitions include containment and/or control measures (National Invasive Species Council 2008, 2011, 2012, 2013, 2014, 2015, 2016a, b; US Department of the Interior 2016). In the term's broadest application, it is not clear how rapid response is to be differentiated from invasive species management as a general concept. Distinguishing what is meant by "rapid" is particularly challenging. We identified a single reference delineating a timeframe

**Table 1** Definitions of EDRR and its components

| References | Definition | Comments |
|---|---|---|
| US Congress, Office of Technology Assessment (1993) | NA | Term not included; focused on invasive species at a national scale |
| ANSTF (1994) | Not defined | Includes section on detection and monitoring which includes term early detection; focused on aquatic invasive species at a national scale |
| Executive Office of the President (EO 13112) (1999) | NA | Term not included; focused on invasive species at a national scale |
| IUCN (2000) | NA | Term not included; focused on invasive species at a global scale |
| GAO (2001) | *Detection*: surveillance for the existence and location of an invasive species that may have been introduced<br>*Rapid response*: a response conducted in time to eradicate or contain a potentially damaging invasive species | Focused on federal and state funding for invasive species |
| NISC (2001) | Not defined | Includes section of Action Plan focused on EDRR (pp 34–36); focused on invasive species at a national scale |
| McNeely et al. (2001) | NA | Term not included; focused on invasive species at a global scale |
| Wittenberg and Cock (2001) | Not defined | Includes chapter on Early Detection (pp 101–112); focused on invasive species at a global scale |
| ANSTF (2002) | Not defined | Includes mention of detection and rapid response; focused on aquatic invasive species at a national scale |
| FICMNEW (2003) | Not defined | Focused on EDRR at a national scale |
| NISC (2003) | Not defined | Focused on EDRR at a national scale |
| USFS (2004) | Not defined | Includes section on EDRR; focused on invasive species at a national scale |
| NISC (2004–2007) | Not defined | Includes section on EDRR; focused on invasive species at a national scale |
| Westbrooks (2004) | Not defined | Focused on EDRR at a national scale |
| Lodge et al. (2006) | Not defined | Includes EDRR recommendation; focused on invasive species at a national scale |
| Simpson (2006) | Not defined | Focused on EDRR at a national scale |
| ELI and TNC (2007) | Not defined | Focused on EDRR of plant pests and pathogens at a state level |
| Asian Carp Working Group (ANSTF) (2007) | Not defined<br>9 related regional plans from 2010–2018 reference EDRR but do not include definitions | Includes strategic elements and action items for EDRR; focused on Asian carp at a regional scale |
| ANSTF (2007) | Not defined | Includes mention of detection and rapid response; focused on aquatic invasive species at a national scale |
| Beck et al. (2008) | Not defined | Invasive species definitions in the US policy context |
| NISC (2008) | *Early detection*: not defined<br>*Rapid response*: a systematic effort to eradicate or contain invasive species while infestations are still localized | Includes section of national invasive species Action Plan focused on EDRR (pp 16–20) |

**Table 1** continued

| References | Definition | Comments |
|---|---|---|
| Westbrooks et al. (2008) | Not defined | Focused on EDRR at a national scale |
| Waugh (2009) | *Early detection and rapid response* (EDRR): a coordinated framework for the management of new invasive species introductions. Elements include detection, identification and vouchering, verification and archiving, rapid assessment, and rapid response | Cites Westbrooks 2004 although not defined in that paper; focused on EDRR at a global scale |
| USFS (2009) | Not defined | Focused on EDRR at the a national scale |
| NISC (2012–2017) | *Early detection*: actions taken to detect incipient invasions and assess the current and potential impact of invasions<br>*Rapid response*: a systematic effort to eradicate, contain, or control a potentially invasive non-native species introduced into an ecosystem while the infestation of that ecosystem is still localized, and to eradicate and/or contain invasive species populations while they are still localized | Focused on invasive species at a national scale |
| Simberloff and Rejmánek (2011) | Not defined | Includes chapter on EDRR (pp 169–176) by Westbrooks and Eplee; largely update of FICMNEW 2003 on invasive species at a national scale |
| Crall et al. (2012) | Not defined | Focused on EDRR at a regional scale |
| ANSTF (2012) | Not defined | Includes section on EDRR; focused on aquatic invasive species at a national scale |
| USFS (2013) | *Detection:* survey to detect new invasive species and monitor existing priority species | |
| Welch (2014) | *Early detection*: a long-term monitoring process that is "a collection and analysis of repeated observations or measurements to evaluate changes in condition and progress toward meeting a management objective"<br>Also states managers are to: (1) detect species early (that is, find a new species or an incipient population of an existing species while the infestation is small [less than 1 hectare]) and (2) respond rapidly (that is, implement appropriate management techniques to eliminate the invasive plant and all of its associated regenerative material) | Focused on early detection of invasive plants; cites Elizinga et al. (1998) |
| US Department of the Navy (2015) | Not defined | Includes EDRR action items focused on EDRR at a regional scale (Micronesia and Hawaii) |
| US Department of the Interior (DOI) (2016) | *Early detection and rapid response:* a coordinated set of actions to find and eradicate potential invasive species before they spread and cause harm<br>*Early detection*: a 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<br>*Rapid response*: a process that is employed to eradicate the founding population of a non-native species from a specific location | Focused on EDRR at a national scale |

**Table 1** continued

| References | Definition | Comments |
|---|---|---|
| Executive Office of the President (EO 13751) (2016) | NA | Term not included; focused on invasive species at a national scale |
| NISC (2016b) | Same as DOI 2016 | Focused on invasive species at a national scale |
| CAFF and PAME (2017) | Same as DOI 2016 | Focused on invasive species at a regional scale (Arctic) |

for eradication: Lodge et al. (2006) indicates that eradication efforts must proceed within weeks or, at most, 1–2 years for a rapid response to be successful. Because invasion scenarios are unique, the timeframe to achieve eradication is context-specific.

Two publications explicitly combine early detection and rapid response as a single, defined concept. Waugh (2009) refers to EDRR as a coordinated framework for the management of new invasive species introductions, while the US Department of the Interior (DOI 2016) regards EDRR as a coordinated set of actions to find and eradicate potential invasive species before they spread and cause harm. Both definitions emphasize (1) a need for coordination (among government agencies and a wide range of non-governmental stakeholders) and (2) a focus on taking action at the introductory stage of the invasion process.

Although the Federal Interagency Committee for the Management of Noxious and Exotic Weeds (FICMNEW 2003) and Westbrooks (2004) do not define EDRR, they provide a series of statements about EDRR that contrast with other presentations of the concept (Table 2). These authors, and perhaps the weed science community more generally, may view EDRR in a manner that differs from those focused on other taxonomic groups. This ambiguity further underscores the need for a clear, consistent use of terminology to avoid confusion regarding goals and procedures.

Further confusion over the meaning of EDRR arises relative to the concept of prevention. Authors typically argue that prevention—the action of stopping invasive species from being introduced or spreading into a new ecosystem (Executive Office of the President 2016)—is the most cost-effective strategy for addressing potentially invasive species before they can cause harm (McNeely et al. 2001; Leung et al. 2002; US Forest Service 2004; Lodge et al. 2016). However, prevention measures at points of entry (jurisdictional or ecological) and along invasion pathways (the mechanisms and processes by which non-native species are moved, intentionally or unintentionally, into a new ecosystem [Executive Office of the President 2016]) are insufficient to intercept all invasive organisms (Meyerson and Reaser 2003; Reaser and Waugh 2007). Authors thus frequently state that when prevention fails, the next imperative is to detect and manage (eradicate or control) the invasive organisms as quickly as possible, maximizing cost-effectiveness while minimizing non-target impacts (National Invasive Species Council 2003; Simpson 2006; Environmental Law Institute and The Nature Conservancy 2007). In accordance with these assessments, EDRR is thus considered the second line of defense (FICMNEW 2003; National Invasive Species Council 2003, 2008, 2016b; Westbrooks 2004; Waugh 2009).

The United States defines the term "introduction" to mean, "as a result of human activity, the intentional or unintentional escape, release, dissemination, or placement of an organism into an ecosystem to which it is not native" (Executive Office of the President 2016). In order to prevent an invasive species from being introduced into a new ecosystem, it must be detected and removed from the ecosystem as quickly as possible. From this perspective, early detection and rapid response could thus be regarded as approaches for enacting the goal of prevention (preventing jurisdictional entry or spread among ecosystems), rather than as a separate, secondary concept, framework, or method.

Despite lack of a clear, operational definition of EDRR or its components, federal agencies have been investing in EDRR. Recognizing that budgetary policy can unite agencies in a common purpose or pit them against each other, Reaser and Waugh (2007) recommended that the National Invasive Species Council

**Table 2** A comparison of EDRR frameworks

| References | FICMNEW (2003), Westbrooks (2004) | NISC (2003) | Westbrooks et al. (2008) | Waugh (2009) | USFS (2009) | DOI (2016) |
|---|---|---|---|---|---|---|
| Component I | Early detection and reporting | Early detection | Early detection and reporting | Detection | Identify potential threats | Preparedness |
| Component II | Identification and vouchering | Rapid assessment | Identification and vouchering | Reporting | Detect actual threats | Early detection |
| Component III | Record verification | Rapid response | Record archiving | Record verification | Assess impacts | Rapid assessment |
| Component IV | Record archiving | | Rapid assessment | Identify/initiate response options | Respond | Rapid response |
| Component V | Rapid assessment | | Rapid response | Further evaluation and response | | |
| Component VI | Rapid response | | | | | |

(NISC) undertake an annual, government-wide budget analysis to elucidate broad trends in federal funding for invasive species activities over time, encourage federal agency cooperation for shared responsibilities, and facilitate cost-effectiveness. NISC began coarsely quantifying EDRR spending in 2004 but did not implement the recommended standardized approach to interagency budget reporting until 2011. Table 3 summarizes EDRR expenditures for those NISC agencies that provided accounting information during the 2011–2016 time period. The variation in relative scale of spending reflects the perceived relevance of EDRR to agency missions, with agencies having agriculture (including livestock), natural resource, and/or land management obligations devoting the most funding to EDRR. Due to variations in agency accounting and the inherent challenges in tracking relevant funds not explicitly appropriated under the designation "invasive species," these numbers should be considered a conservative estimate of EDRR expenditures.

The overall scale of EDRR funding as a percentage of total invasive species spending by the reporting federal agencies is less than 50%. With the exception of what the Department of Homeland Security reports as prevention, review of the comprehensive budget analyses (NISC 2011, 2012, 2013, 2014, 2015, 2016a) reveals that more federal agency resources are being devoted to the control of already established invasive species instead of reducing the risk of future invasion. These financial allocations are inconsistent with White House directives (Executive Office of the President 1999, 2016) for cost-efficiency.

Although the effectiveness of federal EDRR programs has not been comprehensively assessed, authors have regarded effective EDRR as rare (Simberloff 2003a) and pointed to informational, managerial, and financial constraints as barriers to success (GAO 2001; Crall et al. 2012). In recent years, several high-profile invasive species were detected early in the invasion process, but the lack of a well-coordinated, rapid response effort prevented eradication (DOI 2016). However, case studies of effective EDRR-relevant initiatives involving federal agencies and their partners are increasing and have appeared in federal reports (US Forest Service 2009, 2013; DOI 2016; Wallace et al. 2018) and elsewhere (Simberloff 2003a; Waugh 2009). Submissions for the federal EDRR capacity assessment (discussed later; Supplementary information) informed the NISC Secretariat's recently published narratives on federal successes in invasive species prevention and management (Holland et al. 2018). Here, in order to build on existing case studies and develop a more comprehensive approach, we provide an integrated and iterative conceptual EDRR framework, an assessment of federal capacity, and a summary of key findings.

**Table 3** Federal EDRR interagency budget 2011–2016 (in millions)

| | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 |
|---|---|---|---|---|---|---|
| Total spending[a] | $2239 | $2205 | $2146 | $2204 | $2298 | $2287 |
| Department of Homeland Security | 646.3 | 665.4 | 647.6 | 704.6 | 745.0 | 782.5 |
| Department of Commerce (National Oceanic and Atmospheric Administration) | 0.75 | 0.25 | 0.09 | 0.07 | 0.19 | 0.03 |
| Department of Defense (United States Army Corps of Engineers) | 9.02 | 7.86 | 8.40 | 9.20 | 14.07 | 15.30 |
| Department of the Interior | 8.12 | 7.54 | 8.17 | 13.51 | 15.70 | 16.80 |
| Department of State | 0.00 | 2.83 | 2.77 | 2.56 | 0.73 | 0.80 |
| US Agency for International Development | 1.09 | No data | No data | No data | 1.01 | 1.13 |
| US Department of Agriculture | 242.58 | 262.46 | 262.11 | 264.97 | 277.35 | 287.31 |
| Total EDRR spending | 907.86 | 946.34 | 929.14 | 994.91 | 1054.05 | 1103.87 |
| % of Total federal invasive species spending | 41 | 43 | 43 | 45 | 46 | 48 |

[a]Total spending on invasive species by Department/Agency. Department of Transportation (DOT) and National Aeronautics and Space Administration (NASA) provided crosscut figures, but did not report spending on Early Detection and Rapid Response (EDRR). Department of Homeland Security (DHS) classifies all of its spending under Prevention. It is classified as EDRR for the purposes of this table since much of this activity is focused on interception at ports of entry. Environmental Protection Agency (EPA) is responsible for administering funding under the Great Lakes Restoration Initiative (GLRI), which includes work on EDRR by a number of federal and state agencies. However, Environmental Protection Agency does not provide detailed accounting for GLRI across the National Invasive Species Council (NISC) crosscut categories

## A conceptual EDRR framework

We define early detection and rapid response (EDRR) as a guiding principle for minimizing the impact of invasive species in an expedited yet effective and cost-efficient manner, where "detection" is the process of observing and documenting an invasive species, and "response" is the process of reacting to the detection once the organism has been authoritatively identified and response options have been assessed (i.e., risk and feasibility screening completed; discussed below).

Although frameworks differ in the manner in which EDRR components are combined or split, there is general agreement regarding (1) the necessary components of the process and (2) that operational frameworks function most effectively with integrated communication chains between authoritative decision-makers and field-based implementers (DOI 2016). In practice, EDRR is a non-linear, iterative, self-referential process. Therefore, we portray EDRR as the tenet for an integrated system (Fig. 1) rather than a step-wise set of components addressed in a linear manner, as has been typical of other EDRR frameworks (Table 2). We discuss all of the Fig. 1 components below, as well as in complementary papers in this Special Issue. Note that our framework places emphasis on target analysis and feasibility screening, two components not explicitly identified in other models.

### Target analysis

The effort and costs required to detect a species are inversely proportional to its population size (Lodge et al. 2006). However, it is necessary to conduct intensive surveys for organisms that occur at low densities in order to keep the populations from expanding (Simberloff 2003a) and/or assess the scale of the problem from the outset. Target analysis is an examination of the potential for detecting an invasive species at a specific locality and time, using a particular approach and/or technologies. It is employed to maximize the effectiveness and cost-efficiency of invasive species detection when the target species is known, mobile, self-perpetuating, and rare (Morisette et al. 2019, this issue). Invasive species surveillance is particularly important near high risk areas, including airports, shipping/transfer ports, distribution warehouses (GAO 2001; Lodge et al. 2006), and potential recipient ecosystems that have previously been invaded or otherwise disturbed (Morisette et al. 2019, this issue). Sampling

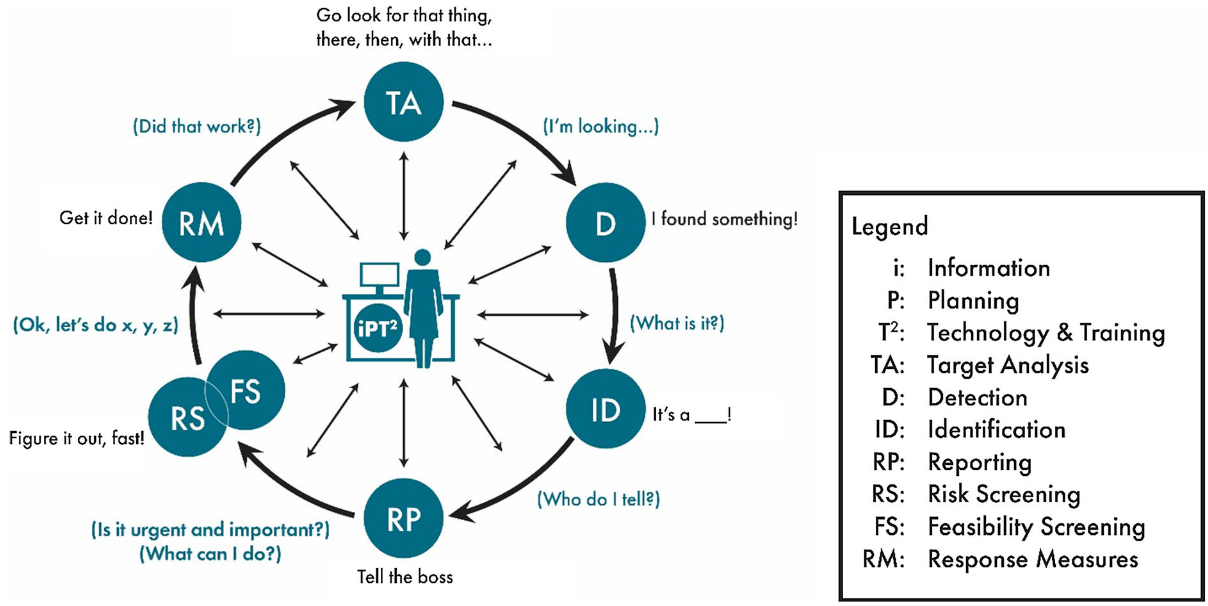


**Fig. 1** EDRR: a comprehensive system. In this model, the blue circles represent the primary actions (components) that need to be enacted in a step-wise manner for the effective detection of and response to a biological invasion. A legend clarifies the meaning of the letters in the circles. The associated commentary reflects the primary questions, observations, and directives that guide the process from one component to the next. At the core of the process, represented by the person and work station, are the informational and technical inputs necessary for the system to function. Arrows point in both directions in an effective system because the information and other outputs generated by one component are strategically utilized by other components. As is true of all models, this is a simplistic depiction of reality; implementation of EDRR is a complex, iterative process that requires context-specific adaptation

techniques that maximize search area per unit cost and minimize laboratory (or other analytical) costs are likely to return the best cost–benefit ratios (Hayes et al. 2005).

## Detection

We define "detection" as the process of observing and documenting an invasive species. The observation may be made via a survey undertaken with the specific intent of locating invasive species (targeted detection) or during other routine activity (incidental detection), including biological surveys undertaken for other purposes (Welch 2014). Detection is commonly cited as a best management practice for the eradication or control of species that are newly introduced to an ecosystem (Wittenberg and Cock 2001; Westbrooks 2004; Crall et al. 2012), although detections can also be of established species in areas not previously surveyed or organisms overlooked during previous surveys (Welch 2014). US Department of Agriculture (USDA) officials suspect that the Asian long-horned beetle (*Anoplophora glabripennis*) was in the United States for up to 10 years before it was reported in New York in 1996. *Caulerpa taxifolia*—a highly invasive seaweed—was likely introduced 4 years prior to being reported in California in 2000 (GAO 2001). Historically, detection has been considered an explicitly site-based activity that relies heavily on visual encounter surveys. However, advances in technologies are enabling remote detection of invasive species (Martinez et al. 2019, this issue). The purpose of documenting the organism is to (1) collect sufficient information to record locality (ideally, point location using GPS coordinates) in a manner that facilitates response measures and (2) provide sufficient information (ideally, a voucher specimen) to obtain an authoritative identification of the organism(s) (see next section). Until the identification has been authoritatively established, detection of an invasive species should be considered tentative and response measures handled accordingly.

### Identification

We define "identification" as the provision by an expert of a taxonomic identity to an organism to a degree that avoids/minimizes confusion between taxa with different biological properties and that allows access to information about (1) the taxon to which it belongs, (2) risk analysis and (3) if appropriate, management measures to be put in place. Identifications may be made based on morphological and/or genetic traits. Although an increasing number of informatics tools are available to assist with identification (Martinez et al. 2019, this issue), identification as used for the purposes of this paper implies identification by a taxonomic authority whose findings can be considered conclusive and warrant the investment of further authoritative actions (Lyal and Miller 2019, this issue).

### Reporting

We define "reporting" as providing an account of an invasive species (detection and identification information) to the authority ("The Boss"; Fig. 1) responsible for assessing the necessity, capacity, and/or form of response measures. The most appropriate authority (individually and institutionally) to which to report may vary depending on the species identified and its location, relevant legal and policy frameworks, and each authority's available resources. Under some circumstances (e.g., when an emergency response plan is in place), reporting may involve a single action from one authority (taxonomic identifier) to another (natural resources director). However, it is more likely that the reporting process will involve multiple players and multiple channels of communication.

Reporting might also involve disseminating alerts to increase survey vigilance and the additional reporting of detections, especially when the species has previously not been intercepted or considered high risk or both. Ideally, these alerts are made publicly available to encourage engagement of non-governmental and citizen scientists (Lodge et al. 2006). Ultimately, reporting outputs should also include entry of information into publicly available databases (Reaser et al. 2019a, this issue) and the peer-reviewed literature, such as presented by McCullough et al. (2006).

### Risk screening

We define "risk screening" as a rapid characterization of the types and degree of risks posed by a population of non-native species in a particular spatio-temporal context. Risk screening is employed to efficiently ascertain if the identified impacts are (a) "low," as to warrant no response measures other than making these findings publicly available; (b) "high," as to warrant immediate, priority action as feasible, including consistency with regulatory frameworks that might require a more detailed risk analysis as a next step (Burgos-Rodríguez and Burgiel 2019a, this issue); or (c) "uncertain" due to a paucity of reliable information, as to warrant more extensive data collection and analysis before response measures are considered. In the context of EDRR, it is essential that risk screening approaches are designed to facilitate processing speed and outcome accuracy. Meyers et al. (2019, this issue) explicitly address risk screening in the context of federal EDRR capacities.

### Feasibility screening

The likelihood that response measures will be effective depends largely upon the species in question and the context in which it is detected; both have implications for the logistical feasibility of a response (Simberloff 2003a; Waugh 2009). We define "feasibility screening" as a rapid assessment (ideally, hours to days) employed to measure the ability and likelihood of successfully completing response measures (defined below), taking all relevant factors into consideration (including financial, technological, legal, and scheduling variables). Ideally, each feasibility screen results in a publicly accessible feasibility report that is delivered to the authority for directing response measures (which may be multiple entities). If insufficient information is available to conduct a feasibility screen, a more extensive evaluation (including additional data collection) may be warranted. However, because invasive species are mobile and self-perpetuating, additional feasibility conflicts may emerge between the time required to ascertain information (for any EDRR component) and the ability to eradicate or contain the organisms of concern.

## Response

We define "response" as the process of reacting to the detection once the organism has been authoritatively identified and response options adequately assessed. Response measures may fall into four general (non-exclusive) categories: (1) documentation, (2) further analysis, (3) eradication, and (4) control (containment). "No response" should not be regarded as an acceptable response option; at a minimum, information obtained during the target analysis (if there was one), detection, identification, risk screening, and feasibility screening should be made publicly available for future reference (i.e., documentation only). If the risk and/or feasibility screening did not provide sufficient information on which to base a management action, then further analysis may be warranted (Meyers et al. 2019, this issue).

The federal government defines "eradication" as "the removal or destruction of an entire population of invasive species" and "control" as "containing, suppressing, or reducing populations of invasive species" (Executive Office of the President 2016). Public perception plays a substantial role in determining which species, pathways, and ecosystems warrant management. Eradication and control measures are generally focused on species perceived as high risk and assets perceived to be of high value (Reaser and Waugh 2007; Waugh 2009). Eradication is the ideal management response because it provides for a one-off investment in resource protection. Eradication should not be regarded as a cheap, one-step action, however. Eradication efforts may require substantial financial resources, be socio-politically challenging, and take years to accomplish. See Simberloff (2003a) for a review of eradication measures in the invasive species context and Martinez et al. (2019, this issue) for information on advances in eradication technologies.

When eradication is not possible, it may be necessary and feasible to control the most threatening populations to protect key assets and/or prevent populations from proliferating to the point that they overwhelm or forestall any future management measures. Invasive species control measures are largely reported for individual projects, but only a few comprehensive reviews of control methods are available (e.g., Wittenburg and Cock 2001; Hussner et al. 2017). We emphasize the need for response measures to be tailored to specific contexts in order to be effective. We encourage practitioners to regard control not as an end goal, but as a strategy to minimize the spread and impact of invasive species while new approaches are developed that could enable future eradication (especially advanced technologies; Martinez et al. 2019, this issue).

EDRR does not end with the enactment of eradication and/or control measures. The adequacy of these actions needs to be assessed and surveys conducted through time (i.e., monitoring) to protect valued assets from future invasions of the same or other non-native species of concern. Ideally, target analyses are undertaken to ensure the effectiveness and cost-efficiency of these follow-up actions. If new detections occur, then the process begins anew. Thus, from some vantage points, most eradication and control can be considered prevention strategies; we protect recipient ecosystems by increasing their resistance and resilience to biological invasion and ameliorate the environmental and socio-cultural conditions that facilitated the introduction and spread of invasive organisms into specific ecosystems.

The EDRR system described above is enabled by several core components: information systems, planning, technology, and training (Fig. 1). All aspects of EDRR require these core components for effective operation, albeit to varying degrees and in different forms.

## Information

NISC (2008) states that EDRR depends upon the timely ability to answer critical questions, such as, (a) What is the species of concern, and has it been authoritatively identified? (b) Where is it located and likely to spread? (c) What harm may the species cause? (d) What actions (if any) should be taken? (e) Who has the needed authority and resources to respond? and (f) How will the efforts be funded?

Thus, EDRR effectiveness depends on the availability of accurate, up-to-date information at every stage in the process (Fig. 1; Reaser et al. 2019a, this issue). The lack of adequate scientific and technical information relevant to the invasive species in question may be one of the most substantial barriers to enacting EDRR (Reaser et al. 2019a, this issue). Although nearly all EDRR components require information on the current distribution and abundance of non-native organisms (Crall et al. 2012; Lodge et al. 2016), there has been relatively little attention to or investment in collecting and reporting non-native species until recently (Reaser et al. 2019a, this issue). Also, numerous organisms have yet to be identified at the species or sub-species level, and we lack the knowledge of basic biology for a large percentage of those species for which we do have a taxonomic name (Lyal and Miller 2019, this issue). Absent this information, we may not be able to undertake target analyses and risk screening or determine best practices for eradication or control measures. Sustained investment in collecting, reporting, and species identification is thus a fundamental need for effective EDRR.

Although biological information is a vital component of the EDRR process, we want to emphasize that a lack of species-specific data does not justify inaction. Certainty is far more concept than reality in natural systems. In order for responses to be rapid and thus effective, eradication and containment measures need to be enacted based on the information available at the time of detection. As more data become available, response measures can be modified in line with adaptive management principles. For further discussion on the implications of "imperfect" data for EDRR, see Simberloff (2003b).

## Planning

Systematic planning and preparedness are essential to ensure agencies are ready to address invasive species incursions (US Forest Service 2009). Advance, detailed (yet flexible) planning is fundamental to all the aforementioned EDRR components. At the institutional level, planning must not only include the establishment and enforcement of the laws and policies that direct and facilitate EDRR (Burgos-Rodríguez and Burgiel 2019a, this issue), but also clearly establish roles, responsibilities, and accountability. A GAO (2001) study revealed that disagreements over who had the authority to assume various leadership roles (including funding commitments) has hampered response capacities, efficiency, and effectiveness in the past. Waugh (2009) points out that the challenges and impacts posed by invasive species are consistent with the federal government's National Response Framework (see US Department of Homeland Security 2016 for the most recent version) and thus should be addressed consistent with emergency response planning (see also Burgiel 2019, this issue).

Depending on the agency involved and the complexity of the EDRR target, planning may be streamlined or tiered with supporting components. For example, the Asian Carp Regional Coordinating Committee—comprised of federal, state, municipality, and Canadian agencies—has an overall national plan, which is further detailed in regularly updated plans focused on more specific aspects (e.g., action plans, monitoring and response plans, contingency plans). Such plans clarify the suite of ongoing actions (e.g., surveys and monitoring), as well as the process and criteria that trigger a response. At the ground level, this could culminate in implementing on-site Incident Command System (ICS) responses that guide further actions (Burgiel 2019, this issue).

Planning should also include scientific and technical analyses that enable greater EDRR preparedness and the establishment of clear program priorities. For example, horizon scanning, which we define as the systematic analysis and reporting of information about future threats or opportunities to inform decision making at specific time intervals, is used increasingly as a tool for addressing biological invasion (US Environmental Protection Agency 2008; Roy et al. 2014; Ricciardi et al. 2017).

## Technology

We define "technology" as the outputs of mental and physical effort, including tools and machines, intended to serve a societal value. In EDRR, technology applications range from basic computing to genetic tools (e.g., gene editing, eDNA) for species detection or population eradication and/or control. Recent reviews particularly relevant to invasive species EDRR include an assessment of current methods for tracking the spread and impact of invasive species (Kamenova et al. 2017), a summary of advanced genetic technologies for invasive species detection and management (Invasive Species Advisory Committee 2017), and an extensive overview of emerging technologies for addressing invasive species (Martinez et al. 2019, this issue).

Training

We take a broad perspective on training, regarding it as the act of building the capacity of individuals and/or institutions to effectively implement a particular (ideally, standardized) action, skill, procedure, or protocol. Some aspects of EDRR require more highly skilled and consistently repeated actions than others. For example, shooting invasive goats from a helicopter necessitates extensive experience by the pilot and the hunter, including the flexibility to alter methods as terrain and population size dictate. Approaches to target analysis, risk screening, and feasibility screening should ideally be standardized to enable comparability and consistency in policy application and may benefit from some degree of automation if the requisite databases and associated analytical tools were developed.

## Federal capacities assessment

The *2016–2018 NISC Management Plan* includes several action items intended to advance EDRR (NISC 2016a). These action items involve recommendations set out by DOI (2016) in response to the White House's Council on Climate Preparedness and Resilience priority agenda (Climate and Natural Resources Working Group 2014).

In order to implement the NISC management plan directive, the NISC Secretariat invited the twelve Executive Branch Departments and Agencies represented by Council leadership as of August 2016 (https://www.doi.gov/invasivespecies/about-nisc) to respond to a survey (Supplementary information). Table 4 provides a summary of agency responses by survey topic. Gathering information via federal survey is notoriously challenging due to variations in how agencies communicate information (requests/responses might not reach key personnel), competing priorities and frequently heavy staff workloads, and concerns that information will be misinterpreted or used to the agency's detriment (e.g., for future budget cuts). In the case of the EDRR survey, three data limitations need to be considered: (1) not all agencies responded (some do not have missions relevant to EDRR), (2) the depth of responses varied widely among agencies, and (3) agencies may have initiatives relevant to EDRR but not identified as such by the agency because the program was developed with different goals in mind. Whenever possible, the authors of the EDDR assessments featured in this Special Issue thus augmented the federal survey information with agency staff interviews, reviews of information available through federal websites and reports, peer-reviewed literature, and their own programmatic expertise. The findings reported in this paper arise from this comprehensive approach to information gathering.

Noteworthy gaps in the federal capacity assessment remained despite best efforts to gather sufficient data. The EDRR programs and federal institutional frameworks currently being used by the federal agencies to implement EDRR were not evaluated for duplication, potential improvement, or effectiveness. Insufficient time and staffing prevented us from being able to assess the types of response measures used by the agencies and their effectiveness across context and taxa, or to determine the applicability of federal and federally-funded biodiversity inventory and monitoring programs to EDRR. Finally, the agencies were challenged in their ability to provide information on and examples of decision support tools used as part of an EDRR framework. While gaps occur in agency responses, the information provided enables a coarse-scale evaluation of agency perspectives on EDRR, insight into existing programs and their operational mechanisms, shared challenges and needs, and reports of species and locality-specific successes (case studies).

The papers in this Special Issue focus on various aspects of the federal capacity assessment: incident response (Burgiel 2019, this issue), information management (Wallace et al. 2019, this issue; Reaser et al. 2019a, this issue), law and policy (Burgos-Rodríguez and Burgiel 2019a, b, this issue), risk screening (Meyers et al. 2019, this issue), systematics and taxonomy (Lyal and Miller 2019, this issue), target analysis (Morisette et al. 2019, this issue), tools and technology advancement (Martinez et al. 2019, this issue), and watch lists (Reaser et al. 2019b, this issue). The collective findings and recommendations are synthesized in an EDRR blueprint (Reaser 2019, this issue). Here we summarize the cross-cutting assessment findings that have substantial implications for high-level policy and planning, as is consistent with NISC's mission:

**Table 4** Federal EDRR survey response

| | Federal EDRR programs | Legal authorities | Assessing risks | Inventory and monitoring programs | Identification and reporting | Information systems | Tools and technology |
|---|---|---|---|---|---|---|---|
| Department of State | X | X | X | – | – | – | – |
| Department of the Treasury | – | – | – | – | – | – | – |
| Department of Defense | X | X | X | X | X | X | – |
| Department of the Interior[a] | X | X | X | X | X | X | X |
| Department of Agriculture[b] | X | X | – | – | X | X | X |
| Department of Commerce | – | – | – | – | – | – | – |
| Department of Health and Human Services | – | – | X | X | X | X | – |
| Department of Transportation | X | X | – | – | – | – | X |
| Department of Homeland Security | – | – | – | – | X | – | – |
| National Aeronautics and Space Administration | X | – | X | – | – | – | – |
| Environmental Protection Agency | – | – | – | – | – | – | X |
| US Agency for International Development | – | – | – | – | – | – | – |
| Office of the United States Trade Representative | – | – | – | – | – | – | – |

[a]Responses from the DOI were provided by the Bureau of Indian Affairs, Bureau of Land Management, National Park Service, US Fish and Wildlife Service, and US Geological Survey

[b]Responses from the USDA were provided by National Institute of Food and Agriculture and Agricultural Research Service

## Terminology

The GAO (2001) noted a need to clarify what constitutes EDRR before there can be any progress in relevant legislation and funding levels. Our assessment indicates continued inconsistency in definition and application of EDRR-related terminology among and within federal agencies, resulting in miscommunication, resource inefficiencies, and operational ineffectiveness. Of particular note is a failure of federal agencies to standardize their use of the terms “non-native” and “invasive species,” despite the federal definitions having been established in Executive Order 13112 in 1999 (Executive Office of the President 1999).

In this context, terminology is not an issue of semantics; terminology has a strong influence on decision-making. Words are the hooks on which policies and regulations are hung. They determine prioritization and resource allocation, and they can frame biological and socio-economic analyses. Without transparent application and agreement on terminology, we will be unable to develop a clear, consistent, and comprehensive understanding of EDRR objectives, strategies, and operational procedures. It will thus be impossible to develop a coordinated, national EDRR framework or initiatives in which participants can contribute to a common vision and effectively enact their roles and responsibilities.

Federal leadership niche

The federal government does not have the authority or capacity to unilaterally operate a national EDRR program. It does, however, have specific responsibilities that need to be met (Executive Office of the President 1999, 2016) to minimize the burden on other sectors. Collectively, federal leadership roles include (a) detection and interception at points of national entry and, in some cases, along inter-state transport pathways; (b) conducting EDRR in federally owned and managed lands and waters, as well as in other circumstances where federal funding is being applied; (c) programmatic guidance and support for the core EDRR inputs (Fig. 1) to strengthen the capacity of all individuals and institutions; and (d) providing grants or other forms of assistance to increase operational capacity, especially to states, territories, and tribes.

Federal engagement

Federal agency engagement in EDRR reflects the extent to which agencies regard addressing invasive species as central to their mission and are willing to prioritize support for EDRR in an atmosphere of resource scarcity. The survey responses suggest that some agencies are not fully aware of the assets they have to contribute to a national EDRR program; in several instances authors of the papers in the Special Issue were aware of relevant programs not identified by the agency respondents. Historically, federal investments in EDRR have been largely oriented towards the protection of crops and livestock (GAO 2001). However, our assessment reveals that all federal land management agencies are, to some degree, enacting EDRR. This includes agencies that do not have agriculture or natural resource protection as a primary mission area (e.g., Department of Defense, National Aeronautics and Space Administration). The data and other resources necessary to support EDRR are frequently provided by agencies other than those leading on-the-ground EDRR efforts. Fundamentally, our findings indicate that there is a co-dependency among agencies for enacting effective EDRR and, thus, a whole-of-government approach to a national EDRR framework is warranted.

Operational structure

To date, EDRR efforts (federal and otherwise) have been largely reactive, facilitated on an ad hoc basis, species-specific, and locally coordinated. Memoranda of agreement or understanding among agencies and with non-federal partners are used to institutionalize EDRR planning and operational measures in specific contexts. However, many agencies lack the ethos, legal authority, and managerial directives necessary for EDRR preparedness, including ongoing investment in the core inputs (Fig. 1), undertaking of relevant analyses (e.g., horizon scanning), development of authoritative response plans (e.g., ICS), and establishment of rapid response funding mechanisms.

Species identification

The GAO (2001) reported inadequacies in detection capacity for microscopic, aquatic, and cryptogenic organisms. Our assessment indicates that EDRR initiatives continue to be strongly biased, largely toward invasive insects and pathogens that impact crops ("quarantine pests") and invasive plants in general. However, it also reveals that substantial progress has been made in addressing aquatic invasive species (e.g., Fuller and Neilson 2015). The National Park Service also recently recognized the need for increased efforts to address invasive terrestrial animals (Redford et al. 2017; Resnik 2018).

Information access and sharing

Because every EDRR component relies on readily available, accurate, up-to-date information, the strength of any EDRR initiative is determined by the ease of information access. As standard practice, federal agencies do not internally share (within or across agencies) or make publicly available much of the information needed to support a national EDRR program (Fig. 1). Exceptions may include laws and policies (Burgos-Rodríguez and Burgiel 2019a, this issue), as well as some non-native species occurrence data (Reaser et al. 2019a, this issue), alerts, and watch lists (largely agricultural or forestry-related; Reaser et al. 2019b, this issue).

## The response toolkit

Because no two invasion scenarios are identical, a large, diverse, flexible toolkit is needed to achieve invasive species detection, eradication, and control. To date, this toolkit has proven too limiting for many species managed by federal agencies; the government and its partners are spending millions of dollars annually to manage single, high-impact species, such as Asian carp (e.g., silver carp, *Hypophthalmichthys molitrix*), brown tree snakes (*Boiga irregularis*), zebra mussels (*Dreissena polymorpha*), and Asian long-horned beetles (*Anoplophora glabripennis* (Martinez et al. 2019, this issue). However, an increasing number of examples demonstrate that federal investments in technology are paying off, literally and figuratively (Conservation X Labs 2017a, b; Holland et al. 2018; Martinez et al. 2019, this issue). Waugh (2009) noted that the United States could become a world leader in detection and response capacity if the invasive species issue was given priority in government policy commensurate with the risk that it poses to the national economy and biological resources. This perspective is consistent with the emphasis on technology advancement found in Executive Order 13751 (Executive Office of the President 2016).

## Programmatic investments

If the federal capacity assessment focused purely on initiatives explicitly designed to support invasive species EDRR, or some component of it, we would conclude that the federal government lacks adequate resources. Although agencies can certainly justify their calls for additional resources (discussed below), there are also substantial opportunities to capitalize on existing programs in which the federal government has already invested hundreds of millions of dollars over decades. These include biodiversity surveillance and monitoring programs, information systems, research and development programs, and environmental education and outreach initiatives that have historically focused on native species. In many cases, small investments in programmatic "retrofitting" could substantially increase our ability to detect and respond to invasive species. Opportunities also exist in the agriculture and human health sectors to clarify that many of the programs focused on pests or disease are, by definition, invasive species programs and warrant greater linkages with invasive species-related initiatives in the environmental sector. The One Health approach could be an asset in this regard (http://www.onehealthinitiative.com, accessed 13 September 2019).

The case for federal financial investments in EDRR is typically made based on the understanding that failure to rapidly detect and respond to invasive species results in far greater expenditures by agencies and a wide range of stakeholders than would otherwise be necessitated (GAO 2001; DOI 2016). Consistent with the GAO's (2001) and DOI's (2016) findings, agencies routinely report insufficient funding for EDRR preparedness and enactment, particularly rapid response measures. The annual NISC interagency budget analysis was terminated in 2017, making it even less likely that a multi-agency approach to better resourcing of EDRR could be developed in a well-informed, strategic, and justifiable manner. Waugh (2009) cautions that it is not realistic to rely on Congressional appropriations for funding and points to programs (e.g., boll weevil management) in which responsibility is shared between the federal government, industry, and other stakeholders who otherwise would be incurring the costs of impacts.

## Effective EDRR

Where agencies have successfully implemented EDRR, or at least some aspects of it, those initiatives have been characterized by (a) adequate information provided to authoritative decision makers in a standardized and timely manner; (b) effective coordination (often pre-established through agreements) among neighboring land owners/jurisdictions; (c) enactment of detection and response measures prior to species establishment in a new range; (d) institutionally, logistically, and socially well-supported response measures; (e) response measures that include actions taken to prevent the re-invasion or spread from invaded sites or both; (f) incorporation of lessons learned from previous EDRR experiences, both successful and non-successful; and (g) investments made in preparation to address future invasion. These findings are largely consistent with those reported elsewhere (e.g., GAO 2001; NISC 2003; Waugh 2009; DOI 2016).

## Key findings and conclusion

EDRR should be considered a first principle of effective and cost-efficient strategies to address invasive species. While developing a national EDRR program is a worthwhile goal, the federal government and its partners will need to overcome a substantial number of conceptual, institutional, and operational challenges if success is to be achieved. Addressing these challenges will require a federal initiative that focuses on foundational needs and progresses in an iterative manner to construct a logical framework that is well integrated across agencies, from senior decision making to field implementation levels. The following is a list of the cross-cutting foundational needs revealed through the federal capacities assessments:

1. *Legal structure and institutional framework* In accordance with Executive Orders 13112 and 13751, as well as other complementary executive guidance, delineate and communicate a national legal and institutional framework for enabling EDRR across taxa and geographies.
2. *Terminology* Clear definitions of relevant terms need to be standardized as feasible, institutionalized, and well-communicated. Ideally, this would be accomplished through an executive order and/or legislation.
3. *Operational plan* Once terms have been clarified, a strategic communications initiative needs to be implemented to demonstrate the relevance of invasive species EDRR to agency missions. The ideal output would be a regularly updated, online plan or related directory that provides information on agency roles and responsibilities relevant to the EDRR components listed in Fig. 1, including contact information for authoritative focal points.
4. *Asset inventory* A clear understanding of how invasive species relate to an agency's mission is necessary to enable agencies to identify their most important assets for supporting a national EDRR program. An asset inventory should include programs currently focused on addressing invasive species as well as those programs that could be cost-effectively modified to expand federal capacities for addressing invasive species. The results of the recent EDRR survey and additional information contained within this series of federal capacity assessments provide a useful starting point.
5. *Interagency budget* The asset inventory will enable NISC member agencies to develop a more accurate and useful EDRR cross-cut budget, one that can be used as a reference point for more effective leveraging of existing agency resources and development of multi-agency funding proposals to address common needs for additional resources. The US Office of Management and Budget (OMB) could take a leadership role in this process, guiding coordination and helping to optimize cost-efficiencies.
6. *Information accessibility* The capacity for federal agencies and their partners to effectively enact EDRR could be increased substantially simply by facilitating greater access to existing information. An online clearinghouse could be developed to curate the outputs of various detection reference materials (e.g., keys, watch lists), relevant analyses (e.g., target analyses, risk analyses, feasibility analyses), reports on the effectiveness of response measures, and training course curricula, for example. The clearinghouse could be informed by and/or integrated with databases being developed to meet some of these information needs (e.g., the Canadian Risk Assessment Database (https://www.invasivespeciescentre.ca/learn-about-invasive-species/risk-assessments, accessed 13 September 2019) and Great Lakes Aquatic Nonindigenous Species Information System (GLANSIS) Risk Assessment Database (https://www.glerl.noaa.gov/glansis/riskAssessment.html, accessed 13 September 2019).
7. *Decision support* Further effort is needed to determine what, how, and how effectively agencies are applying EDRR decision support tools. Ideally, decision support tools will be standardized across the agencies and their outputs made publicly accessible. Papers in this Special Issue provide guidance for incident command systems, watch lists, target analysis, and risk screening. Further work is needed for advance feasibility screening, including the provision of data on the dynamic socio-economic and cultural factors that influence response capacity. The latter is also needed to inform science-based social marketing

campaigns that address socio-economic and cultural barriers to response feasibility.

The federal government has a substantial and ever-growing responsibility to safeguard the nation from invasive species. To invoke the hackneyed but nevertheless meaningful phrase, "an ounce of prevention is worth a pound of cure," various government and non-government entities have been calling for greater attention to EDRR for decades. Although we propose a more systematic approach to EDRR than has been published elsewhere, our general findings are consistent with those of previous analyses and recommendations. The question thus remains, what is the difference that will make a difference? How can we transition from general concept to effective operational system? We hope that the answer emerges in the form of proactive leadership, cooperation, and engagement rather than a reactive and uncoordinated response to a potentially avoidable national crisis.

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REVIEW

# Envisioning a national invasive species information framework

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**Abstract** With a view toward creating a national Early Detection and Rapid Response Program (EDRR) program, the United States *National Invasive Species Council Management Plan* for 2016–2018 calls for a series of assessments of federal EDRR capacities, including the evaluation of "relevant federal information systems to provide the data and other information necessary for risk analyses/horizon scanning, rapid specimen identification, and rapid response planning." This paper is a response to that directive. We provide an overview of information management needs for enacting EDRR and discuss challenges to meeting these needs. We then review the history of relevant US policy directives for advancing invasive species information systems and provide an overview of federal invasive species information system capacities, including current gaps and inconsistencies. We conclude with a summary of key principles and needs for establishing a national invasive species information framework. Our findings are consistent with earlier studies and, thus, emphasize the need to act on long-recognized needs. As a supplement to this paper, we have cataloged federal invasive species databases and information tools identified through this work.

**Keywords** Invasive species · Early detection and rapid response (EDRR) · Information systems · Data infrastructure · Federal capacities

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## Introduction

The early detection of and rapid response to invasive species (EDRR) is considered a guiding principle for minimizing the impact of invasive species in an expedited yet effective and cost-efficient manner (Reaser et al. 2019a). With a view toward creating a national EDRR program, the United States *National Invasive Species Council (NISC) Management Plan* for 2016–2018 calls for a series of assessments of federal EDRR capacities, including the evaluation of "relevant federal information systems to provide the data and other information necessary for risk analyses/horizon scanning, rapid specimen identification, and rapid response planning" (NISC 2016). This paper is one of five assessment outputs responding to the Management Plan directive with regard to federal information management system capacities. Wallace et al. (2018) provide a broad overview of responses to a federal survey of information system capacities, which is discussed later in this paper. Martinez et al. (2019, this issue) include information technology capacities and needs as identified via a federal survey. Wallace et al. (2019, this issue) provide guidance for improving access to and analysis of invasive species information. As a complement to our paper, Simpson et al. (2019) have published the first catalog of databases and information tools key to the establishment of a national EDRR program.

EDRR is dependent on the ready availability of high-quality information at every stage in the process (Reaser et al. 2019a, this issue). Following the EDRR framework proposed by Reaser et al. (2019a Figure 1, this issue), practitioners need easy access to information that enables them to establish the legal and institutional frameworks that enable EDRR planning and enactment (Burgos-Rodríguez and Burgiel 2019a, b, this issue), develop effective and cost-efficient decision support tools (Meyers et al. 2019, this issue; Morisette et al. 2019, this issue), intercept non-native organisms, and accurately and quickly identify the organism(s) (Lyal and Miller et al. 2019, this issue). They also need the capacity to report the authoritatively identified organisms to appropriate decision-makers, and then to the decision implementer(s) in a relatively short amount of time (see Reaser et al. 2019a, this issue, for discussion on "rapidness"). Information is also necessary to support institutional and programmatic planning (Burgiel 2019, this issue), for the development and appropriate application of the various technologies (Martinez et al. 2019, this issue), and for skills training applied during EDRR enactment (Burgiel 2019, this issue).

While the need for accurate, readily accessible information to support EDRR may be conceptually obvious, it has thus far proven challenging to establish invasive species information systems that effectively serve the needs of policy and management decision-makers at national and regional scales over the long term (Ridgway et al. 1999; Ricciardi et al. 2000; Fornwall and Loope 2004; Graham et al. 2008). The reasons for this are multiple:

*Type of data collected and reported*. Until recently, biodiversity data collection and reporting has largely focused on information relevant to native species. Non-native species were often excluded from biodiversity inventory, monitoring, and research initiatives and thus data on occurrence outside of the native range, biology in novel environments, and observable impacts were not included as information fields in biodiversity datasets (Simpson 1964).

*Data sharing concerns*. There are numerous reasons why there is resistance to making species-locality data publicly available, and limits to data sharing may be one of the most substantial challenges to enacting a well-integrated information framework (Jarnevich et al. 2007). For example, in the context of threatened and endangered species, there are concerns that rare species would be collected for illegal trade or destroyed to avoid regulatory restrictions on land management (Ruhl 1998; Lueck and Michael 2003). With regard to non-native species data, the private sector may have concerns about protecting the commerce information associated with invasive species interceptions at points of entry or along invasion pathways. Those trade data might also eventually be used to "make the polluter pay" for invasive species impacts (Jenkins 2002; Knowler and Barbier 2005). Resource managers recognize the risk that already-introduced non-native species may be collected and intentionally spread to new locations for harvest (e.g., sport/food) (Hernández et al. 2018) or beautification (especially ornamental plants) (Blaustein 2001; Keil and Hickman 2014; Linz et al. 2007). Information system managers may also have limited data-sharing capacities due to the (a) various security restrictions that can provide political and technical barriers to data movement, and (b) lack of sufficient policy and personnel support, especially when sharing data is perceived to be beyond the core mission of a particular initiative.

*Data quality and definition*. Invasive species information systems and their outputs are only as good as the data contributed to them. The time and expense required to ensure that data are of high quality can be substantial and are notoriously difficult to secure institutionally. Being able to authoritatively define the applicability of data (fitness for use) is one aspect of ensuring data quality (Anderson et al. 2016; McGeoch et al. 2016). Because definitions of non-native species and invasive species vary, particularly with regard to the applicable scale of the definitions (e.g., ecosystem vs. political jurisdiction) (Richardson et al. 2000; Colautti and MacIsacc 2004; Beck et al. 2008; Simpson and Eyler 2018), data definition, valuation, and comparison can be difficult to achieve even within a single information system that serves as a repository of data from multiple sources.

For the purposes of this paper, unless otherwise distinguished to make a specific point, we use the term "non-native species data" to include the subset of data that could be defined as "invasive species." However, in keeping with programmatic norms, we refer to "invasive species information systems" and a "national invasive species information framework" as inclusive of all non-native species data, not just data backed by analyses of harm.

*Information system cost and sustainability*. The startup and maintenance costs of any given system need to be considered in the context of returns on investment over the long-term and across the scale of influence. Although an information system cost–benefit analysis is beyond the scope of this paper, we emphasize the need for institutional recognition and commitment to information systems as their value increases over time. Due to financial and institutional limitations, there is a long history of biodiversity information system collapse, including for information systems focused on invasive species. This collapse includes total information system shutdown [e.g., the Invasive Species Information Node of the National Biological Information Infrastructure (Huber 2012)] and failure to update and/or quality control data over time even if the system still exists in name ["information system languish," e.g., the Global Invasive Species Information Network and the Invasive Plant Atlas of the MidSouth (Gore and Hossler 2006)]. Many of the databases relevant to invasive species management identified by Ridgway et al. (1999) no longer exist or have been inadequately maintained over the last two decades.

*Information system independence and access*. Biodiversity information systems are developed for many purposes by government agencies, non-governmental organizations, academic institutions, the private sector, and individuals. In many cases, the systems were not developed with the explicit intent of making the data publicly accessible or sharable among information systems and for more synthetic and overarching monitoring and analysis (e.g., Cooperative Agricultural Pest Surveys at https://napis.ceris.purdue.edu/home, Accessed 26 September 2019; Centre for Agriculture and Bioscience International's [CABI's] Crop Protection Compendium at https://www.cabi.org/cpc, Accessed 26 September 2019). Although the quantity and quality of non-native species data have been improving over time, the information systems containing the data have often remained difficult to access and integrate (Groom et al. 2015; Western Governors' Association 2018).

*Focus on environmental professionals*. Traditionally, biodiversity information systems have housed data collected by environmental professionals. While this reflects the valid need to ensure that data are accurate and thus reliable for decision-making, it has also limited the scale of information input and information system support by a contributing public. Citizen scientists have demonstrated a strong will and capacity to contribute valuable biodiversity information (Amano et al. 2016; Chandler et al. 2016, 2017).

Because of the wide range of information needed to enable a national EDRR program (Table 1 and further discussed below), efforts must be focused on building a comprehensive national invasive species information framework (sometimes termed "cyberinfrastructure"; Graham et al. 2008). A national EDRR program thus depends on the capacity of the federal government and other information collectors and providers to overcome these basic biodiversity information system challenges. Progress is being made in this regard. For example, information systems are being developed at national and regional scales that focus on non-native species data (e.g., Western Governors' Association 2018), and pre-existing biodiversity information systems are being adapted to enable the uptake, sharing, and analysis of non-native species data (e.g., Simpson et al. 2009; Schimel et al. 2011). In a few cases, the provisioning of these non-native species data is undertaken with the stated intent of serving EDRR applications (e.g., Bargeron and Moorhead 2007; Lombard and Boettner 2014; Fuller and Neilson 2015).

Analytical tools are now widely available to make it more time- and cost-efficient to provide quality control of data (Vandepitte et al. 2015). Increasingly, data collected by citizen scientists is recognized as of equal value to data collected by environmental

**Table 1** Information needed to support a national EDRR program

| EDRR step | Information needs | Information sources | Output reporting | Comments |
|---|---|---|---|---|
| Target analysis (TA) | What are the known/projected species occurrence?<br>What are the species/pathway associations?<br>What are the species/ecosystem associations?<br>What tools work to detect which species under what circumstances? | Species distribution mapping/modeling<br>Pathway mapping/modeling<br>Niche mapping/modeling<br>Biological profile<br>Best practices reporting | Internal agency documents, if reported at all | Target analyses are not yet routinely enacted as a component of the EDDR system |
| Detection (D) | What to search for?<br>Where to search?<br>When to search?<br>With what tool to search? | Target analysis<br>Regulatory directive | Programmatic reports<br>Email or other correspondence<br>Social media site | Detection may also be incidental |
| Identification (ID) | To what taxonomic level is identification necessary?<br>What is it? | Taxonomic experts<br>Collections data<br>Genetic analysis<br>Identification guides and apps<br>Internet search<br>Social media crowdsourcing | Species occurrence database<br>Vouchers<br>Programmatic reports<br>Email or other correspondence<br>Social media site | Ideally, once authoritatively identified, incident information is rapidly provided to a relevant open source database |
| Reporting (R) | To whom does the information need to be reported?<br>How does the information need to be reported? | Regulatory requirements<br>Policy guidelines<br>Incident response plan<br>Internet search<br>Social media crowdsourcing | Standardized alerts (internal and/or public)<br>Email or other correspondence<br>Social media<br>Publications (professional and popular press) | Ideally, reporting process pre-established in incident response plan/policy guidance<br>Currently, reporting is likely to be chaotic and may not reach the most appropriate person |
| Risk Screening (RS) | What is it?<br>What are its potential impacts under what circumstances? | Authoritative identifier<br>Biological profile<br>Impact assessments | Internal program reports<br>Program websites | Results may indicate that a more in-depth risk analysis is warranted<br>Ideally, would be reported in risk screening report clearinghouse |
| Feasibility Screening (FS) | What is the response goal?<br>What response measures are authorized and by whom?<br>What technical, logistical, and financial resources are needed?<br>What relevant resources are available? | Regulatory review<br>Programmatic review<br>Incident response plan | Internal program reports | Often, the costs of "doing nothing" can be higher than the costs of attempting containment, conducting research, and monitoring effectiveness of EDRR |

**Table 1** continued

| EDRR step | Information needs | Information sources | Output reporting | Comments |
|---|---|---|---|---|
| Response measures (RM) | Who is in charge?<br>Who is taking what action?<br>What is to be done?<br>How can it be done as effectively and cost-efficiently as possible?<br>How well did it work? | Regulatory requirements<br>Best practice guidelines and policies<br>Incident response plan<br>Context-specific maps, models | Institutional (per regulatory requirements)<br>Public (websites, social media, etc.) | Ideally, would be reported in standardized database of response measures |

professionals and is thus being contributed into biodiversity information systems at various scales (Delaney et al. 2008). The popularity of citizen science initiatives is now driving the development of biodiversity identification and data collection apps to be employed on mobile phones (Martinez et al. 2019, this issue).

Open access and inter-operable information systems have become a cultural standard in the information management community writ large (Mauthner and Parry 2013), including among those working in the environmental field (Reichman et al. 2011). The NISC Secretariat recently released guidelines for invasive species information standardization and sharing to facilitate this process (Wallace et al. 2019, this issue).

Recommendations for developing an effective invasive species information framework have been made previously for national, regional, and global scales of application (Ricciardi et al. 2000; Federal Interagency Committee for the Management of Noxious and Exotic Weeds 2003; Fornwall and Loope 2004; Graham et al. 2008; Magarey et al. 2009; Helf 2011). Building on this previous body of work and consistent with the framework in Reaser et al. (2019a, this issue), we provide in Table 1 our perspective on the components required of an invasive species information framework intended to serve a national EDRR program. The following constitute the core operational principles for an invasive species information framework supporting EDRR:

(a) Adoption of standards, formats, and protocols that enable the interoperability of relevant information systems (Wallace et al. 2018, 2019, this issue);

(b) Ability to handle increasingly large data sets (i.e., big data);

(c) Inclusion of data (ideally, authoritatively verified) on non-native species occurrence within the US according to species, point locality, and date of observation;

(d) Ability to distribute alerts of non-species occurrence (ideally, authoritatively verified) to those responsible for response needs assessment;

(e) Ability to notify data users when data corrections are made;

(f) Inclusion or link to data on the biological characteristics, documented impacts, and response measures for the non-native species globally;

(g) Capacity for data to be readily transferred into high-performance analytical and decision support tools that, at a minimum, enable target analyses (Morisette et al. 2019, this issue), risk screening (Meyers et al. 2019, this issue), cost–benefit analyses of potential response measures and response prioritization (feasibility screening), and response planning; and.

(h) Cataloging of information products (ideally, standardized) resulting from data analyses mentioned in points c–f (i.e., an open-access information product clearinghouse), including public-friendly species identification guides and watch lists (Reaser et al. 2019b, this issue).

The benefits of building a national invasive species information framework extend well beyond the direct application to invasive species prevention, eradication, and control. For example, resource managers could use occurrence data for highly flammable invasive grasses along with other relevant information to project fire risk (Pilliod et al. 2017), and infrastructure managers could use data on the occurrence of burrowing invasive species (such as non-native termites) to identify structures that may be at high risk of failure, especially during extreme weather events (Invasive Species Advisory Committee 2016). The cost savings to the public and the private sector from just these two additional applications could be in the billions of dollars annually.

## US Government policy

The US federal government has responsibilities for information management at every stage in the EDRR process (Figure 1 in Reaser et al. 2019a, this issue; Table 1); agencies collect, manage, and share information, and they provide funding for non-federal information management activities that meet federal needs. Although specific visions have varied through time, the need for a strong federal invasive species information infrastructure (a key component of a national framework) has been recognized for at least two decades (Reaser et al. 2019a, this issue). For example, the Davis Declaration, which emerged out of a 2001 workshop held by the US Geological Survey (USGS) and the Global Invasive Species Programme in Davis, California, recognized the need for governments to have access to the information services and tools necessary for invasive species prevention, eradication, and control. It also acknowledged that invasive species information services were proliferating, but not being sufficiently coordinated. The authors of the Declaration noted a need to efficiently address overlapping and/or duplicative efforts and to minimize major gaps in coverage for some taxonomic groups and regions of the world. Among other things, the Davis workshop participants called for greater support for information system coordination, informatics tool development, and capacity building for information services (Fell 2001; Davis Declaration 2001).

Two decades later, it is difficult to quantify progress made by the US federal agencies in responding to the Davis Declaration and similar calls to action. Some of the shortcomings may be in keeping with the information management challenges outlined at the beginning of this paper: large focus on native species data (Simpson 1964); restrictions on data sharing (Ruhl 1998; Lueck and Michael 2003); and data fitness for use (Anderson et al. 2016; McGeoch et al. 2016). Others are due to the routine changes in federal policy priorities associated with administration turnover, such as the discontinuance of the US Invasive Species Early Detection Rapid Assessment and Response National Framework with the shutdown of the National Biological Information Infrastructure (Huber 2012). Fundamentally, the problem may reflect a general lack of recognition of the value of biological data and the returns on investment (economically, politically, and otherwise) that come from access to and analysis of reliable biodiversity information (Juutinen 2008; Laurila-Pant et al. 2015). This is a long-standing problem worldwide (Heywood 1995, Lindenmayer et al. 2012). The most relevant high-level directives for federal invasive species information system advancement in the US are outlined below.

In 1999, Executive Order 13112 charged NISC with establishing a coordinated, up-to-date information-sharing system that emphasized the use of the internet for documenting, evaluating, and monitoring impacts from invasive species on the economy, the environment, and human and animal health (Executive Office of the President 1999). Acknowledging that relevant databases already existed for various purposes and that their current structures did not make for ease of information sharing (Ridgway et al. 1999), the first *National Invasive Species Management Plan* (NISC 2001) devoted a section to priority actions for advancing federal invasive species information management. Although the US Department of Agriculture (USDA) National Agriculture Library's National Invasive Species Information Center (https://www.invasivespeciesinfo.gov, Accessed 28 September 2019) was inspired by the Plan's intent and provides a gateway to relevant information resources, the envisioned information management outputs of the Plan remain largely unachieved. Specifically, the Plan's item 50, "an invasive species assessment and monitoring network comprised of on-the-ground managers of federal invasive species programs and appropriate technical specialists," has not been implemented. Item 51, "guidance for managing information concerning invasive species in aquatic and terrestrial environments… developed in consultation with [relevant agency bodies as listed], and other stakeholders, [to include] emerging technologies for information collection [and] lower-cost information tools for wide distribution" was not developed, and "standard protocols for information collection and sharing, including taxonomy, identification, inventory and mapping, monitoring, and assessments of invasive species populations" were developed by the non-governmental North American Weed Management Association in 2002, but only for mapping weeds (North American Invasive Species Management Association 2019). The Plan's item 53, a North American invasive species compendium, was not completed until 2012 and is global in scope (CABI 2019). To the authors' knowledge, the Plan's item 54, a comprehensive "locator for occurrences of invasive species in the United States within each county" has not been attempted.

The *2008–2012 National Invasive Species Management Plan* (NISC 2008) included a section focused on enhancing data standards and quality to improve access and ability to search across databases and federal data sources. The majority of the action items were either a continuance of the actions identified in the previous plan (e.g., develop the Invasive Species Compendium), or tasks involving expansion of existing information systems (e.g., the PLANTS database [Natural Resources Conservation Service 2019] and NISbase, a database integrator now abandoned) and greater engagement in multi-national invasive species information initiatives (e.g., the Global Invasive Species Information Network, now largely abandoned for lack of funding). Much of this work, such as a plant pathogens database and an invasive species pathways database, also remains to be done.

The *2016–2018 NISC Management Plan* (NISC 2016) included two action items intended to advance federal invasive species information management. The first was to establish guidance for data management standards, formats, and protocols. The output is included in this Special Issue (Wallace et al. 2019, this issue). As a follow-on to recommendations made in an interagency document broadly addressing federal EDRR capacities (US Department of the Interior 2016), the second priority action called for an assessment of "relevant federal information systems to provide the data and other information necessary for risk analyses/horizon scanning, rapid specimen identification, and rapid response planning" in the context of a national EDRR program. Our paper is one of three assessment outputs (see also Wallace et al. 2018 and Wallace et al. 2019, this issue).

Most recently, Executive Order 13751 (Executive Office of the President 2016) directed federal agencies to (a) develop, share, and utilize similar metrics and standards, methodologies, and databases and, where relevant, platforms for monitoring invasive species; and (b) facilitate the interoperability of information systems, open data, data analytics, predictive modeling, and data reporting necessary to inform timely, science-based decision-making. Collectively, the Council was directed to advance national incident response, data collection, and rapid reporting capacities that build on existing frameworks and programs and strengthen early detection of and rapid response to invasive species, including those that are vectors, reservoirs, or causative agents of disease.

In the remainder of this paper, we summarize the current capacities and needs for securing the federal information infrastructure, as a component of a national invasive species information framework, to support a national EDRR program. Although the directive and review are federally focused, we underscore the need for federal information systems to make data publicly available and to be able to interface with non-federal information systems domestically and internationally (particularly those of neighboring countries and trade partners). States have also recognized this need for data sharing, aggregation, and integration (Bois et al. 2011; Western Governors' Association 2018).

## Review of federal capacities

In response to the aforementioned *2016–2018 NISC Management Plan* directive, the NISC Secretariat invited the sixteen US federal bodies represented by Council leadership (https://www.doi.gov/invasivespecies/about-nisc, accessed 28 September 2019) to respond to a survey (Reaser et al. 2019a, Appendix S1, this issue). Reaser et al. (2019a, this issue) provide an overview of the summary process and general outputs. The results of the information management component have been summarized by Wallace et al. (2018). In general, their report echoes previous findings (e.g., Ridgway et al. 1999; Bruno et al. 2001; Davis Declaration 2001), indicating that the US government lacks a coordinated invasive species information infrastructure at all levels (interdepartmental, department/agency, bureau, and even among sites within the same bureau); agencies have not yet cataloged information systems relevant to invasive species EDRR nor strategically assessed how their existing information systems could be improved to support EDRR; and biodiversity data collection among and within agencies is driven by multiple, dynamic factors (e.g., grant availability and project goals) that lead to inconsistent data collection (scope and frequency), highly variable data management (esp. data fields and frequency of updating), poor data and database standardization, and challenges with information system sustainability.

Federal agencies responding to the survey generally recognize a need for more consistent funding, site-specific data on non-native presence (occurrence), absence (lack of detection), and documented impacts (especially economic impacts) by species in a locality. There is also a growing need for expanded information system functionality (e.g., ability to send or broadcast alerts of recent occurrences) and interoperability (i.e., sharing data into a limited number of data integrators allowing for more extensive data analyses). The survey also revealed a co-dependency between federal and non-federal information systems. Federal agencies rely heavily on generally more taxonomically or geographically focused non-federal information systems for data needed to advance key components of an EDRR system (e.g., occurrence, species identification, risk screening, response measure options), while many non-federal information systems rely on federal funding, endorsement, data input, and/or analytical support.

Three limitations should also be considered with regard to the findings of Wallace et al. (2018): (1) not all agencies responded (some do not host relevant information systems), (2) the depth of response varied widely among agencies, and (3) agencies may have information systems that are relevant to EDRR but not identified as such by the agency because the information system was developed with different goals in mind.

While gaps in agency responses exist, the review by Wallace et al. (2018) does provide a coarse-scale picture of how non-native species data are collected and used by various federal agencies. The responses from these agencies also express common challenges to information system capacity and substantial needs for improving the capacity of relevant information systems. The responses further indicate that federal government approaches to information management are unique to each agency. For example, some agencies are more engaged in cross-agency information sharing and/or working with non-federal partnerships than others. These findings suggest that any effort to build a multi-agency information framework to serve EDRR nationwide will need to carefully consider the differences in agency culture and how to foster a unified mission.

To garner a more comprehensive understanding of the information resources that federal agencies are using to enact EDRR and the remaining needs for building a comprehensive federal information infrastructure, we expanded on Wallace et al. (2018) by augmenting their findings through a five-pronged approach: (1) reviewing the survey results for findings not previously reported but of particular importance in the context of this paper, (2) adding information from previous invasive species information system assessments (Ridgway et al. 1999; Bruno et al. 2001), (3) including current programmatic information available online, (4) summarizing discussions with federal information system managers, and (5) including the expertise of the authors (all have experience establishing, managing, or routinely using federal invasive species information systems). The results of this effort have been published by Simpson et al. (2019) as a supplement to this paper.

Key issues not previously raised by Wallace et al. 2018 include:

(a) The definitions agencies use for non-native and invasive species affect what data are collected, how they are collected, and how they are reported. Relevant terms (e.g., quarantine pest, injurious wildlife) are frequently established in laws and policies without regard to the implications for data collection and analysis (Burgos-Rodríguez and Burgiel 2019a, this issue).
(b) Federal agencies are not consistently using the Integrated Taxonomic Information System (ITIS) Taxonomic Serial Numbers (TSNs) to ensure the consistency of scientific names, which has implications for the searchability and analysis of species occurrence data. The National Park Service (2019), for example, uses two additional taxonomic systems: NPSpecies Semi-permanent Names (Taxonomy records added by the NPSpecies system owner), and

NPSpecies Temporary Names (Taxonomy records added by the NPSpecies user community). USDA's Agricultural Research Service (2019) has its own cadre of taxonomic experts with names that do not always appear in ITIS.

(c) Among the information systems used by federal agencies and as noted in Simpson et al. 2019, there are substantial differences in the timeframe in which species occurrence data are uploaded into publicly available information systems, ranging from immediate entry to a year or more. For EDRR applications, data need to be rapidly reported for authoritative identification and responsive decision-making (Simpson et al. 2009).

(d) Accessibility to data on non-native species intercepted at points of entry by APHIS and the Department of Homeland Security (which is not openly shared, National Agricultural Pest Information System 2019) could substantially increase the preparedness and response capacity of land and pathway (e.g., transportation) management agencies such as the Department of Transportation's Federal Highways Administration.

(e) Non-governmental information platforms, particularly those accessed through smartphones, are rapidly becoming standard operational tools for federal agencies (Wallace et al. 2016). However, the databases to which these data are contributed may not be interoperable with the federal databases used to analyze regional or national patterns and trends. This means that data collected by federal agencies may not be readily available in the federal invasive species information EDRR infrastructure (e.g., iNaturalist and eBird are contributed to the Biodiversity Information Service Our Nation [BISON] information system but not rapidly enough to support EDRR).

(f) Information systems that include non-native species data as a subset of all biodiversity data (e.g., BISON at USGS and the USDA Plant List of Attributes, Names, Taxonomy, and Symbols [PLANTS] in the federal system, and iNaturalist and eBird in the private sector) are not being fully leveraged by federal agencies for their non-native species occurrences. For example, some federal survey responses (described in Wallace et al. 2018) suggest that agencies may be unaware of these large information resources and/or their potential application to EDRR.

(g) In general, non-native species data are not being sufficiently managed to enable a wide-range of analytical applications. For example, the data contained in many information systems are not processed and/or delivered in a manner that makes them readily useable for species distribution modeling, especially for projecting future patterns and trends (Elith et al. 2006). Museums that collect data important to taxonomic relationships may only secondarily provide the exact location of the species (which can be used for distribution modeling). Issues regarding "fitness for use" are not uncommon because data are often collected for reasons narrower than the possible applications that emerge through time (Guillera-Arroita et al. 2015). Cost efficiencies may improve when data are retroactively "made fit" in lieu of new data collection (Frank 1998), but this depends on the type of data and purpose of application.

Our review enabled us to create the first catalog of databases and information tools (Simpson et al. 2019) that federal agencies are using to enact EDRR. In total, 44 databases and 51 information tools were identified (e.g., apps). It should be noted that the distinction between database and information tool may not have been readily apparent or warranted. Thus, the same information system may be included in both catalogs, and some information system managers may have different opinions with regard to placement in the catalog. Also, our compilation represents a snapshot in time. Nevertheless, static versions of these catalogs have been published, and it is our intention to make periodic updates to this catalog available via USGS's ScienceBase online system. The dynamic versions will serve as living resources for federal agencies and their partners, but the current version is frozen for archival purposes. These databases and tools are the foundation on which a comprehensive federal invasive species information infrastructure can be built and contribute to a national EDRR program.

By creating the catalog, identifying the database or tool attributes, and reviewing the outstanding information system needs identified by the federal agencies, we were able to summarize the status of federal information system capacities in accordance with each of the EDRR components identified in Table 1. This status is summarized in Table 2. Information gaps are apparent for each EDRR component, but particularly remarkable for supporting target analysis, sharing the outputs of target analyses, performing risk and feasibility screening, and implementing response measures. This lack of capacity greatly undermines the ability of government agencies to institutionalize and enact effective incident command structures (Burgiel 2019, this issue).

## Summary of principles and needs identified

Developing the national invasive species information framework to support a national EDRR program is a formidable task. Based on our assessment of current capacity and lessons learned from previous efforts (Federal Interagency Committee for the Management of Noxious and Exotic Weeds 2003; US Department of the Interior 2016), success will largely depend on the ability of government agencies and their partners to agree to a common vision and leadership mandates, secure vital information systems over the long term, motivate data reporting and sharing, improve current information system capacities, and invest in—or otherwise promote—the development of associated analytical tools. Adherence to the following operational principles will facilitate information framework development.

*No single information system can do it all*. A coordinated framework of interoperable information systems, federal and non-federal, is required (Graham et al. 2008).

*Think and act openly*. Open-access information systems are now a "best practice" for information management. The federal government has established open-access policies (https://www2.usgs.gov/quality_integrity/open_access, Accessed 26 November 2018). However, there is still a need to mobilize non-public federal data into publicly accessible information systems. This is particularly true of species occurrence (intercept) data collected at points of entry (National Agricultural Pest Information System 2019).

*Information systems not initially designed for EDRR can support EDRR*. Well-established biodiversity databases can help advance an invasive species information framework by encouraging the collection and reporting of non-native species data. For example, the US Geological Survey's BISON database (https://bison.usgs.gov) recently expanded its services to support identification and searchability for the more than 14 million non-native species data points that it already had (Simpson and Eyler 2018).

*Existing information systems represent substantial investments in time and money*. In most cases, it will be more cost-effective to improve existing information systems rather than create new ones. If new information systems are developed, they should be designed according to established guidelines for inter-operability (e.g., Wallace et al. 2019, this issue).

Many of the following identified actions build on previous assessments of federal invasive species information needs (e.g., Ridgway et al. 1999; Bruno et al. 2001) and summarize what we see as a proactive way forward.

*Establish common vision and goals*. An invasive species information framework needs to be guided by strategic vision and long-term goals that advance the mission of federal agencies and their partners to prevent, eradicate, and control invasive species in a well-coordinated, effective, and cost-efficient manner. The vision must be sufficiently compelling to motivate agencies to overcome long-standing challenges to biodiversity information management. The goals need to (a) be achievable within realistic resource capacities and timeframes and (b) allow progress and returns on investment to be measured (Lindenmayer et al. 2012).

*Designate leadership roles and responsibilities*. A government-wide invasive species data management policy can be used to establish data custodial roles and management responsibilities from agency to programmatic levels, address relevant legal and policy issues (including privacy and security), and institutionalize invasive species information management guidelines (Wallace et al. 2019, this issue). While the policy should be authoritative and specific enough for agencies to discern their obligations, it will need to be sufficiently flexible to account for unanticipated needs and emerging opportunities (Epanchin-Niell et al. 2018).

*Identify and sustain vital information systems*. The invasive species information framework needs to clearly identify the federal information systems that are vital to the operation of a national EDDR program (Simpson et al. 2019), assess their relationships (e.g., for duplicative or integrative functions), and include a

**Table 2** Gaps in information by EDRR component

| EDRR framework component (See Reaser et al. 2019a) | Gaps identified through the federal survey information (Wallace et al. 2018), agency staff interviews, reviews of information available through federal websites and reports, peer-reviewed literature, and the authors' collective expertise (Simpson et al. 2019) |
|---|---|
| Target analysis (TA) | There are defined federal processes and related information on pre-border risk screening and there are information systems related to sampling at ports of entry, though these are not public and are concentrated on agricultural systems. There is a lack of any federally coordinated system for sampling along other points of entry and recipient ecosystems, or for coordinating analyses and tools nationally or across taxonomic groups |
| Detection (D) | Federal systems are available for recording and mapping occurrences (e.g., USGS' Biodiversity Information Serving Our Nation and Nonindigenous Aquatic Species databases), and the private sector is cooperating (e.g., iMapInvasives & EDDMaps). However, a lack of data mobilization from non-federal, hidden systems (especially in state and local governments) presents a challenge. Rapid deployment of new data is also significantly resource limited |
| Identification (ID) | Several systems supporting detection ensure some level of checking to ensure proper identification. However, metadata on this confirmation is often lacking. There are existing systems for standardizing names (e.g., the Integrated Taxonomic Information System) and tools (e.g., artificial intelligence applied to photos and DNA barcoding) that can support identification, but there is a serious shortage of expert taxonomists for confirmation and vetting |
| Reporting (RP) | There is general information available (like who the county weed manager is). There are also systems that provide alerts related to species of concern and pre-defined geographies. However, there are no public information systems that provide information management pertaining to properly identified occurrence observations being reported to a responsible party in a timely manner. This is particularly concerning for occurrences on public lands where federal agencies are responsible for action |
| Risk screening (RS) | There are some open-access coordinated federal information systems that tracks risk screening but only from one or a few components; thus lacking the holistic perspective. These systems are species and region-specific |
| Feasibility screening (FS) | There does not appear to be any open-access coordinated federal information that tracks feasibility screening at the granularity of individual events for any taxa or region |
| Response measures (RM) | No national system existing to report or query at the level of individual or specific response measures. Examples exist where treatments can be noted (EDDMapS) or information on the occurrence status is maintained (USGS' Nonindiginous Aquatic Species database) |

plan for sustaining these systems over the long-term. Partnerships with industries, especially those trading in live commodities or their parts, could lead to cost-sharing for the collection of invasive species data that are of clear benefit to public and private sectors (Pattberg and Widerberg 2016). Collaborative agreements must clarify respective partner roles, open access to data, and data ownership.

*Resolve sensitive data issues*. As mentioned previously, one of the greatest challenges for administering an invasive species information framework will be motivating and enabling the sharing of sensitive data. Ideally, information systems associated with trade data (e.g., the US Fish and Wildlife Service Law Enforcement Management Information System [LEMIS]) should be designed to allow for sharing species occurrence data (absent links to proprietary information) rather than being entirely restricted (Ridgway et al. 1999). In addition to the adoption of an overarching data policy (discussed above) and information management guidelines (Wallace et al. 2019, this issue), there is a need for data-sharing agreements (especially between data providers and data integrators; Fornwall and Loope 2004) that clearly state goals and procedures for data handling. Ultimately, the system may require a process for de-resolving and providing limited access to particularly sensitive data (Jarnevich et al. 2007) while ensuring data are still useful and correct. For example, data obfuscation methods in the US Forest Inventory

Analysis program (Bechtold and Patterson 2005) can have significant consequences for re-use (Coulston and Reams 2004).

*Launch a data mobilization campaign*. The cultural challenge of data sharing at individual and institutional levels will need to be overcome (Simpson et al. 2006), because partnerships with non-federal data providers will be vital to enacting a national invasive species information framework (Ridgway et al. 1999). A national non-native species data mobilization campaign is needed to (1) create a shared identity for those contributing to the operation of the national invasive species information framework, (2) focus information acquisition and sharing for filling data gaps in taxonomic and locality coverage, (3) articulate clearly the institutional and individual benefits of data reporting and sharing, and (4) motivate additional resource allocations. The campaign could emphasize the ability of a national invasive species information framework to leverage limited resources (time, money, personnel) with minimal additional cost and effort (Crall et al. 2006) by, among other things, enabling the following:

(a) Mining of data for which there has already been financial investment (including databases, published literature, museum collections, gene banks);
(b) Ongoing improvement of non-native species lists at various scales to assist detection targeting and encourage reporting (Crosier and Stohlgren 2004);
(c) Combining occurrence data with various models to identify data needs and improve forecasting and projection models from spatial and temporal perspectives (Crosier and Stohlgren 2004); and.
(d) Establishing and sharing EDRR information tools such as watch lists (Rejmánek and Pitcairn 2002; Reaser et al. 2019b, this issue), identification guides (Silvertown 2009), and reporting apps (Graham et al. 2011) that help prioritize and target resources.

*Improve information system capacities*. Wallace et al. (2018) indicate that the federal information systems key to building a national invasive species information framework (and thus a national EDRR program) need further support. Nearly all the responding agencies expressed a need for increased funding, additional data (type and volume), improved functionality to serve EDRR needs, and improved interoperability for data sharing. For example, in the agency survey described by Wallace et al. (2018) the National Park Service said that their National Invasive Species Information Management System (NISIMS) would need to be updated more frequently and include an alert system to be particularly useful for EDRR applications.

*Foster analytical tools*. A wide range of informatics tools are needed to support a national EDRR program. These include specialized data search tools for distinguishing what is invasive in what context and with what consequences (ideally, distinguishing invasive from simply non-native at the ecosystem level); mapping tools for illustrating species occurrence information, ideally in association with relevant ecological, geographic, and jurisdictional information (Wallace et al. 2016); apps for assisting in species identification (Graham et al. 2011; Lyal and Miller 2019, this issue; Martinez et al. (2019), this issue); and decision support tools for (a) standardized risk analyses (Meyers et al. 2019, this issue), (b) horizon scanning and other relevant spatio-temporal modeling (Sutherland and Woodruff 2009; Morisette et al. 2019, this issue), and (c) evaluation of the effectiveness, costs, and risks of various response measures in particular contexts (Ridgway et al. 1999). To successfully foster these analytical tools, broad partnerships are needed, such as the new Invader Detectives initiative (Frey 2018) being piloted by the Capital Area Partnership for Regional Invasive Species Management (PRISM; https://www.inaturalist.org/guides/5799, Accessed 26 November 2018) and the Wild Spotter campaign that promotes invasive species reporting and response in natural areas in the United States (https://wildspotter.org, Accessed 27 November 2018).

*Establish report clearinghouses*. Respondents to the federal information survey repeatedly called for open-access, searchable clearinghouses for the reports arising from target analyses (Morisette et al. 2019, this issue), risk evaluations (Meyers et al. 2019, this issue), feasibility screening, and response measures. The Great Lakes Aquatic Nonindigenous Species Information System (https://www.glerl.noaa.gov/glansis/riskAssessment.html, Accessed 26 November 2018) supported by the National Oceanic and Atmospheric Information System and US Environmental Protection

Agency is an example of a regional risk evaluation clearinghouse.

## Conclusion

The challenges to envisioning and sustaining a national invasive species information framework are numerous and substantial. Perfection is an unrealistic ideal [e.g., all taxonomic groups and localities will not be served equally (Graham et al. 2008)] but making substantial advances in our capacity to enact EDRR is a realistic and necessary goal if we are to spare the nation the wide range of costly impacts of invasive species.

The federal component of a national invasive species information framework will become more feasible as (a) the inherent value of data is increasingly recognized by the public and private sectors, (b) there is an increase in the number of partnerships between the federal government and the private sector to support big data initiatives and associated analytical capacities, and (c) early and effective action for invasive species detection and removal, enabled by more reliable and integrated data, eventually reduces funding needs for invasive species control. There may also be opportunities to engage stakeholders impacted by invasive species who could benefit from investing in the information that would help protect their assets.

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REVIEW

# Enabling decisions that make a difference: guidance for improving access to and analysis of invasive species information

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**Abstract** The issue of how to detect and rapidly respond to invasive species before it is economically infeasible to control them is one of urgency and importance at international, national, and subnational scales. Barriers to sharing invasive species data—whether in the form of policy, culture, technology, or operational logistics—need to be addressed and overcome at all levels. We propose guiding principles for following standards, formats, and protocols to improve information sharing among US invasive species information systems and conclude that existing invasive species information standards are adequate for the facilitation of data sharing among all sectors. Rather than creating a single information-sharing system, there is a need to promote interfaces among existing information systems that will enable them to become inter-operable, to foster simultaneous access, and to deliver any and all relevant information to a particular user or application in a seamless fashion. The actions we propose include implementing a national campaign to mobilize invasive species occurrence data into publicly available information systems; maintaining a current list of invasive species data integrators/clearinghouses; establishing an agreement for sharing data among the primary US invasive species information systems; enhancing the Integrated Taxonomic Information System to fully cover taxonomic groups not yet complete; further developing and hosting data standards for critical aspects of invasive species biology; supporting and maintaining the North American Invasive Species Management Association's mapping standards; identifying standard metrics for capturing the environmental and socio-economic impact of invasive species, including impacts and management options; continuing to support US engagement in international invasive species data sharing platforms; and continuing US membership in the Global Biodiversity Information Facility.

**Keywords** Invasive species · Data management · Guidelines · Standards · Formats · Protocols

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## Introduction

The capacity of governments to prevent and respond to biological invasions depends on ready access to the best available scientific and socio-economic information (Convention on Biological Diversity 2006). Recognizing this, Presidential Executive Order (EO) 13112 (Executive Office of the President 1999) called for "the establishment of a coordinated, up-to-date information sharing system that utilizes, to the greatest extent practicable, the Internet."

At this time, numerous online species information systems exist within the United States that provide data and other information resources relevant to addressing the invasive species issue at state, regional and national levels (Marsico et al. 2010; Richardson and Rejmánek 2011). Another manuscript within this special issue (Reaser et al. 2019, this issue) has an associated catalog of more than fifty online tools and databases that receive federal funding to deal with some aspect of invasive species early detection and rapid response (Simpson et al. 2019). Each of these information systems was developed to meet different goals, objectives, and standards. Rather than creating a single information-sharing system, there is a need to promote interfaces among existing information systems that will enable them to become inter-operable, to foster simultaneous access, and to deliver any and all relevant information to a particular user or application in a seamless fashion (Reaser et al. 2019; Ricciardi et al. 2000).

A number of data providers and users, including the National Invasive Species Council (NISC) and its partners and contractors, the Invasive Species Advisory Committee (ISAC), and the Western Governors Association (WGA), have called for the development of the standards, formats, and protocols needed to facilitate the inter-operability of information systems (Davis Declaration 2001; Fell 2001; Invasive Species Advisory Committee 2017; Island Conservation 2018; Western Governors Association 2018).

For example, the 2016–2018 *National Invasive Species Management Plan* states that,

> "In order to facilitate inter-operability of data and other information resources relevant to addressing the invasive species issue, establish guidance for data management standards, formats, and protocols. The guidance should target the most relevant (high priority) information systems, capitalize on existing standards, and take into consideration the work that the Global Invasive Alien Species Information Partnership already initiated to explore options for information system inter-operability" (NISC 2016).

Additionally, Presidential Executive Order 13751 (2016), which updated EO 13112, directed that,

> "to the extent practicable, Federal agencies shall…develop, share, and utilize similar metrics and standards, methodologies, and databases and…facilitate the interoperability of information systems, open data, data analytics, predictive modeling, and data reporting necessary to inform timely, science-based decision making."

Finally, the Western Governors' Association supports a number of initiatives to advance coordinated invasive species management, including development of data management standards, formats, and protocols (WGA 2016).

In drafting this guidance, the authors recognize that:

(a) Decision making on invasive species necessarily requires access to and analysis of information on non-native species that have not been quantitatively evaluated for evidence of harm or likelihood of harm in a particular ecosystem (references to invasive species data herein are meant to encompass the full suite of non-native species data; Reaser et al. 2007).
(b) A considerable amount of work has already been undertaken at national and international scales to identify, promote, and agree to formats, standards, and protocols for the exchange of biological information (WGA 2018; North American Invasive Species Management Association 2014; Wieczorek et al. 2012).
(c) There are substantial benefits, including cost-efficiency and the scale of analytical capacity, to aligning with the existing agreements made by standard-setting bodies, both domestic and international, that guide the exchange of biological information (Hartley 1945, OMB 2005).
(d) Data relevant to addressing the invasive species issue are contained in a wide-range of governmental and non-governmental information systems that vary in purpose, structure, operation, and public accessibility (Reaser et al. 2019, this issue).
(e) While this guidance has been drafted to improve access to and analysis of invasive species information to meet US policy and management needs, invasive species frequently originate in other countries and information held in other countries is critical to meeting US goals (Perrings et al. 2010).

(f) Likewise, information held in US information systems is vital to addressing invasive species by other countries, as well as cooperatively among regions and along invasive pathways (Perrings et al. 2010).
(g) Inter-operability is urgently needed to foster scientific and technical cooperation and information dissemination and exchange, within the constraints of the infrastructure currently available (Simpson et al. 2009).
(h) The capacity to make effective policy and management decisions on invasive species issues reflects the willingness and ability of federal, state, territorial, tribal, and local governments, as well as academic institutions, non-government organizations, and the private sector, to access and utilize each other's data to the fullest extent warranted.

## Guidance on standards, formats, and protocols in US invasive species information systems

In order to maximize the accessibility, cost-efficiency, and applicability of invasive species information systems, we encourage information system managers to adhere to the following guiding principles and best practices (Convention on Biological Diversity 2002), ensuring

(a) open access;
(b) open standards in common and future usage;
(c) future extensibility and backward compatibility;
(d) phased, incremental development;
(e) use of existing services and capabilities;
(f) scalability;
(g) inclusion (e.g., facilitation of local-language queries) in design applications;
(h) language neutrality in the design of applications;
(i) inter-operability which fosters cost-efficiencies and institutional cooperation;
(j) incorporation of scientific and technical cooperation and capacity development;
(k) respect for intellectual property rights and cross boundary issues;
(l) respect for applicable rules and regulations; and
(m) cooperation across sectors and governments (domestically and internationally).

Adoption og the standards set forth in Box 1 will maximize opportunities for information system inter-operability. to. Below we provide a description of the standards that warrant further emphasis and clarification.They are critical to ensuring the timely accessibility and reliability of invasive species occurrence data.

The Integrated Taxonomic Information System (ITIS) Taxonomic Serial Number is used to identify the species or taxon (https://www.itis.gov, accessed 29 March 2019) under consideration. In many data collection programs, shorthand or codes are used to key in species names. Many taxonomy databases have their own code (e.g., USDA Plants Database has their Plants Symbol (USDA 2018); and Mycobank has their unique number as MB# International Mycological Association 2018), but are also narrow in focus. ITIS serves all taxa occurring in the United States and has several global taxonomic treatments.

A universally unique identifier (UUID) should be assigned to each species record and then registered/maintained with a Digital Object Identifier (DOI) (or equivalent) by the resource originator. Multiple concerns arise with regards to data sharing, including issues relevant to data authenticity, duplication, correction, and updating. Version 4 UUID are a series of letters and numbers separated by hyphens in an 8-4-4-4-12 character format that are not housed or regulated by any organization but have only a 1 in $2^{122}$ chance of duplication (Chen 2016). Use of a UUID allows for duplicate record checks and error correction as data are shared. A UUID can be automatically generated by many commonly used databases (Esri 2016; Integrated Digitized Biocollections 2014) or through websites (e.g., https://www.uuidgenerator.net/version4, accessed 29 March 2019) and added to records.

Use of a DOI enables reference to the exact information source and, per membership in a DOI assigning organization such as DataCite (https://www.datacite.org, accessed 29 March 2019), any changes in location/URL to the information must be reflected in the metadata of the DOI database to avert broken links or inaccessibility (International DOI Foundation 2017). DOIs are available through services which have a membership with the International DOI Foundation (https://www.doi.org, accessed 29 March 2019), including data set repositories, journal publishers, and more (International DOI Foundation 2017).

**Box 1** Recommended standards, formats, and protocols

Although most standards development occurs at a global level, the authors encourage all US invasive species data managers to adopt the following formats, standards, and protocols in order to enable policy and management decisions that lead to the prevention, eradication, and control of invasive species in a timely and cost-effective manner

Recommended standards:

- Darwin Core II (http://rs.tdwg.org/dwc, accessed 29 March 2019)
- North American Invasive Species Management Association (NAISMA) mapping standards (https://www.naisma.org/programs/mapping-standards, accessed 3 July 2019)
- Global Invasive Species Information Network (GISIN) (https://github.com/tdwg/gisin, accessed 29 March 2019)
- International Digital Object Identifier (DOI) Foundation (https://www.doi.org/, accessed 29 March 2019)
- International Organization for Standardization (ISO) 19115 spatial metadata (National Oceanic and Atmospheric Administration 2012)
- ISO 23950 interoperability (ISO 1998)
- ISO 25964-1:2011 thesauri (ISO 2011)
- ISO 3166 country codes (ISO 2013)
- ISO 639-2 language codes (Library of Congress 2013)
- ISO 8601 time and date representations (https://en.wikipedia.org/wiki/ISO_8601, accessed 29 March 2019)
- Integrated Taxonomic Information System (ITIS) (https://itis.gov, accessed 29 March 2019)
- Internet Engineering Task Force (ietf) Requests for Comment (rfcs) – various (https://www.ietf.org/download/rfc-index.txt, accessed 29 March 2019)
- Open Geospatial Consortium (http://www.opengeospatial.org/docs/is, accessed 29 March 2019)
- Version 4 Universally Unique Identifier (UUID) (https://www.uuidgenerator.net/version4, accessed 29 March 2019)
- Worldwide Web Consortium (W3C) (https://www.w3.org/standards, accessed 29 March 2019)

Recommended formats:

- JSON (https://www.json.org, accessed 29 March 2019)
- HTML (https://www.w3.org/TR/html52, accessed 29 March 2019)

Recommended protocols:

- HTTPS (Basques 2018)

It is important that invasive species occurrence data be exportable and fully compatible with the North American Invasive Species Management Association (NAISMA 2018) mapping standard format. Invasive species occurrence data are often inconsistent in formatting, field definitions, and data type per field. This limits data sharing and quality control capacities. In order to overcome this challenge, NAISMA (formerly North America Weed Management Association) is in the process of revising their standards for mapping invasive species data. NAISMA has had mapping standards in place for plants since 2002 and revised these standards in 2014 and 2018 to address all taxa of invasive species.

Invasive species data holders are encouraged to make data public and digitally available to data aggregators using recognized standards. While multiple regulations have been signed that direct federally funded data and information to be made open, transparent, machine readable, free, and rapidly accessible (Office of Management and Budget 2016; Office of Science and Technology Policy 2014; Interagency Working Group on Open Data Sharing Policy 2016; Burwell et al. 2013; Executive Office of the President 2013; Holdren 2013), the compliance and promotion of these policies have been lacking. To ensure that data (not just information summaries) are available, any research proposal, grant funding, or contractual agreement should include a plan for data management, preservation, and accessibility. Promotion and adoption of the NAISMA standards (NAISMA 2018) and other standards listed in this document will aid data incorporation into aggregate databases, making the data more broadly available and applicable to timely and reliable decision making.

Finally, data aggregators (who might also be regarded as data integrators) need to be compelled and supported to ensure data attribution, accuracy, authority, and timeliness, as well as to enable interoperability with emerging technology platforms for data acquisition and analysis. Data aggregators have the responsibility to ensure that the information publicly available through their information platforms is sufficiently reliable for policy and management decision-making, as well as ensuring adequate and appropriate attribution to their data sources (Reichman et al. 2011). They also have a role in establishing a seamless relationship between the information systems they manage and the best available analytical and decision support tools.

## Priority actions

To make effective use of this guidance, additional priority actions will need to be accomplished. We encourage relevant federal and state agencies and their partners to undertake the following actions, which are echoed and expanded upon in Reaser et al. (2019), this issue.

(a) Create and implement a national campaign to mobilize invasive species occurrence data into publicly available information systems according to the principles, standards, formats, and protocols described in this paper. Effective policy and management decisions on invasive species issues necessitate that all levels of government, as well as academic institutions, non-government organizations, and the private sector, are willing to make invasive species occurrence data publicly accessible. Data need to be actively mobilized from a wide range of sources (e.g., databases, technical reports, peer-reviewed and gray literature, social media) to information systems that are managed according to the guidance herein.

(b) Create and routinely update a list of data aggregators/clearinghouses through which relevant data can be openly shared. A considerable amount of invasive species data is not currently available in widely accessible information systems (e.g., data generated from individual research projects, biological surveys not intentionally focused on invasive species, and environmental impact assessments). Lack of accessibility limits our capacity to apply this information for policy and management decision-making. A listing of repositories or clearinghouses is needed to help mobilize federal and non-federal data sets, with the ultimate goal of encouraging data contribution for data application. The public availability of information also enables greater expert review and data quality assurance. Ideally, this list would be accessible on the NISC website, but also include reference to non-federal information systems.

(c) Establish an agreement for sharing data among the primary information systems for non-native/invasive species occurrence data in the United States. As a minimum, this should include the USGS Biodiversity Information Serving Our Nation (BISON) all-species information system (https://bison.usgs.gov, accessed 29 March 2019), Early Detection and Distribution Mapping System (EDDMapS; https://www.eddmaps.org, accessed 29 March 2019), iMap Invasives (https://www.imapinvasives.org, accessed 29 March 2019) data management system, and the USGS Nonindigenous Aquatic Species (NAS; https://nas.er.usgs.gov, accessed 29 March 2019) information resources. It should also be open to participation from organizations facilitating the collection of invasive occurrence data by citizen scientists (e.g., iNaturalist; https://www.inaturalist.org, accessed 29 March 2019) and others.

(d) Mobilize invasive species occurrence data into central data aggregators that are coupled with appropriate analytical and decision support tools. At a minimum, BISON should be utilized in this capacity (WGA 2018). A broad, openly accessible, authoritative all-species database that meets the standards, formats, and protocols described herein is needed to serve as the national focal point for invasive species occurrence data. Multiple federal agencies and non-federal partners have already made substantial investments in BISON to achieve this aim (Jackson et al. 2016; Sutton and Armsworth 2014). BISON contributes to the USGS National Biogeographic Map, which is a prototype application designed to provide a platform for data analysis packages about what species are where, how well protected they are, how vulnerable they are to stressors, and what management options will have the greatest benefit for conservation of biodiversity (USGS 2019).

(e) Enhance the Integrated Taxonomic Information System (ITIS) to fully cover taxonomic groups not yet complete, with particular emphasis on those from taxonomic groups prone to invasiveness. Currently, ITIS has virtually complete taxonomy for plants, bacteria, vertebrates, most insects, and other important groups but is lacking in some other categories of increasing importance for invasions, such as many fungi and viruses. As there are many invasive diseases caused by fungi and viruses, ITIS should ensure all invasive pathogens and parasites are included in its system and seek resources to comprehensively address fungi and working with the community to develop and adopt a single consistent classification for viruses. It also needs to be quickly informed of any new non-native species that arrive in the United States so that its treatment of invasive species is comprehensive. The current effort to fully deploy the ITIS global taxonomic workbench to dramatically streamline the name addition and vetting process should be fully supported. ITIS providing taxonomic serial numbers across all taxa will facilitate data sharing and reduce errors in taxonomy due to inconsistent, shorthand, or custom species coding, as this number never changes, even when the accepted names evolve (Integrated Taxonomic Information System 2018).

(f) Develop and host data standards for critical aspects of invasive species biology and population parameters (e.g., resource use, pathways of movement, types and degree of impacts). Work on these standards has been initiated by Global Invasive Species Information Network (GISIN 2018), but priority attention is warranted. These metrics are needed to help distinguish which non-native species are invasive (i.e., harmful), as well as to prioritize and plan response measures. The appropriate global platform for invasive species data standards development is the Biodiversity Information Standards working group (also known as the Taxonomic Database Working Group (TDWG; https://www.tdwg.org/community/tnc/, accessed 3 July 2019).

(g) Support and maintain the NAISMA mapping standards. NAISMA standards are being modified to include aquatic standards and in the 2014 version there are fields that are unresolved for data type (NAISMA 2014). NAISMA is updating their mapping standards with information gathered from multiple recent workshops. NAISMA will also seek endorsement from multiple agencies and organizations to promote the adoption of the standards as broadly as possible. Fields in the NAISMA mapping standard, as appropriate, should be mapped to or harmonized with their Darwin Core II equivalent.

(h) Identify the standard metrics for capturing the environmental and socio-economic impacts of invasive species. Risk analyses necessitate both ecological and socio-economic impact metrics. The Environmental Impact Classification for Alien Taxa (EICAT; https://www.iucn.org/theme/species/our-work/invasive-species/eicat, accessed 3 July 2019) and Socio-economic Impact Classification of Alien Taxa (SEICAT; Bacher et al. 2017) standards should be assessed for relevant applicability. While there are an increasing number of ecological impact assessments, socio-economic impact studies lag far behind. In general, impact research tends to be very narrowly focused and ill-defined. An expert's consultation to define "socio-economic impact" parameters and then identify the metrics by which to evaluate species for actual or predicted impact would aid in clarifying communication between stakeholders and scientists (Jeschke et al. 2014; Bacher et al. 2017). Once these metrics are identified and agreed to, various analytical tools can be developed, tested, and utilized in tandem with existing predictive models, such as weed risk assessments.

(i) Encourage and accommodate information on invasive species impacts and management options. Information on invasive species impacts and management approaches could provide valuable insight to the wider invasive species policy and management communities. This could include not only background information on management options, but specifics on when and where such management was applied, the resources required for the actions, and the effectiveness of the action. Ideally, this information would be linked to occurrence data to enable context-specific interpretation of the impact and management parameters and options.

(j) Continue to support US engagement in international information frameworks and platforms that advance invasive species data sharing in keeping with the guidance herein. For example, support TDWG's ongoing effort to develop and publish a formal Darwin Core II extension for invasive species data. Given that the bulk of invasive species occurrence data globally is held (or exportable) in Darwin Core II format, a well-designed and documented enterprise extension to accommodate the salient business rules and required augmentations of the NAISMA standards is needed. This would allow for the seamless accommodation of a much larger group of relevant data in the software systems and analysis libraries that already exist for Darwin Core II.

(k) Continue US membership in the Global Biodiversity Information Facility (GBIF; https://www.gbif.org, accessed 29 March 2019) to enable invasive species data sharing and analyses at multi-national scales, including those data relevant to understanding invasion risks and pathways. The National Science Foundation, USGS, and many other US organizations contribute and provide leadership to GBIF and play a critical role in mobilizing data, promoting standards, and providing access to data. BISON serves as the US hub for GBIF and includes within it all GBIF species occurrence data for the United States and Canada (Hanken 2013).

## Conclusion

The invasive species issue is one of urgency and importance at international, national, and subnational scales. Broad collaboration among government agencies, non-governmental organizations, academia, and the private sector is needed to ensure that "We can do this!"—we can minimize the impact of invasive species on the environment and economy, as well as human, animal, and plant health. Substantial public will, financial resources, and institutional collaboration have been invested to this end; it is thus imperative that we achieve effectiveness and cost-efficiency by maximizing the return on these investments. Barriers to sharing invasive species data—whether in the form of policy, culture, technology, or operational logistics—need to be addressed and overcome. Existing standards for biodiversity information (such as those listed listed in Box 1) are adequate for the facilitation of invasive species data sharing among all sectors. What we need now is the will to enable the greatest possible benefits to all.

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REVIEW

# Invasive species watch lists: guidance for development, communication, and application

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**Abstract** A watch list is a list of invasive species to be prioritized for surveillance, reporting, and other possible responses in order to reduce the risk of impact to valued assets. Watch lists are basic, yet multi-functional tools for the early detection of and rapid response to invasive species. There is, however, a need to substantially improve watch list standardization, accessibility, and associated communication strategies. We provide guidance to achieve these aims, including an overview of guiding principles and a list of questions to consider when one develops, communicates, and applies invasive species watch lists. Our guidance is intended to support invasive species watch lists development and application globally.

**Keywords** Invasive species · Watch list · Detection · Survey · Early detection and rapid response (EDRR) · Guidance

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## Introduction

An invasive species is, “with regard to a particular ecosystem, a non-native organism whose introduction causes or is likely to cause economic or environmental harm, or harm to human, animal, or plant health” (Executive Office of the President 2016). The *2016–2018 National Invasive Species Council (NISC) Management Plan* (NISC 2016) calls for an assessment of the US government’s capacity to produce invasive species watch lists. For the purposes of this paper, we define a watch list as a list of invasive species to be prioritized for surveillance (pre-discovery), reporting, monitoring (post-discovery), and other possible response measures in order to reduce the risk of impact to valued assets. Herein, we provide guidance for the standardized development, communication, and application of watch lists with a view towards supporting a national program for the early detection of and rapid response to invasive species (EDRR). Although this guidance is provided in the context of a US government directive, the manuscript is applicable to invasive species watch lists worldwide.

In the context of EDRR, it is important to clarify the relationship between a watch list and a checklist. Typically, a checklist is a list of species that have been documented (observed and identified) within a specific area. It reflects knowledge of species occurrence. By comparison, species included on a watch list may or may not have already been detected and identified within a specific area. A watch list is intended to guide surveillance and reporting by including species that pose a risk of introduction as well as those thought to already be introduced, but not yet reported; consequently, watch lists do not necessarily reflect species occurrence.

Checklists can, however, be vital tools for creating watch lists. For example, a state may reference a neighboring state's checklist in order to determine what invasive species have been detected there that they wish to keep from spreading and establishing in their own state. Likewise, a country may review a trading partner's national invasive species checklist (or their species occurrence data more generally) in order to develop a ports of entry watch list. At the national scale, the US Geological Survey's Biodiversity Information Serving Our Nation (BISON; https://bison.usgs.gov, accessed 19 September 2019) information system is being enhanced to provide non-native species occurrence data and analytical tools (Reaser et al. 2019a, this issue). At the global scale, the Global Register of Introduced and Invasive Species (GRIIS; http://www.griis.org, accessed 19 September 2019) and associated products of the IUCN Invasive Species Specialist Group, Global Biodiversity Information Facility (GBIF; https://www.gbif.org, accessed 19 September 2019), and CABI Invasive Species Compendium (https://www.cabi.org/isc, accessed 19 September 2019) are particularly useful resources.

A survey and supporting assessments conducted to inform responses to the aforementioned NISC Management Plan directive (Reaser et al. 2019b, this issue) revealed that some federal agencies are routinely employing watch lists while others use them on an ad hoc basis. In general, watch list development, communication, and application has not been standardized within or among agencies and issues may arise regarding the authoritative nature and timeliness of watch lists. The following guidance is intended to advance the capacity of government agencies and their partners to effectively employ watch lists, particularly in the EDRR context.

## General principles

Watch lists are products of and tools applied within a systematic approach to EDRR preparedness and operation (Reaser et al. 2019a, this issue). Watch lists may be necessitated by various laws and policies in order to meet regulatory priorities in an effective and cost-efficient manner (Burgos-Rodríguez and Burgiel 2019, this issue). Watch list development and updating must be driven by the best available science. Watch lists need to be backed by the accurate identification of species and accurately communicate the characteristics for species identification (Lyal and Miller 2019, this issue). Although organizations have used expert opinion to develop watch lists at a range of scales, risk evaluation is necessary to produce scientifically informed and legally defensible watch lists (Meyers et al. 2019, this issue). Watch lists are also valuable tools for informing the target analyses intended to increase the likelihood of invasive species detection (Morisette et al. 2019, this issue).

Watch lists provide guidance for prioritizing invasive species surveillance and reporting in a particular area defined in ecological and/or jurisdictional terms. Agencies responsible for inspecting cargo and equipment as they enter a country may produce watch lists for specific ports of entry (e.g., Animal and Plant Health Inspection Service 2012; https://pestlens.info, accessed 31 August 2018). Frey (2017) developed a watch list for plants in US national parks spread across a region of less than 25,000 km$^2$. Drucker et al. (2008) provide a case study for watch list development in Colorado. The Environmental Law Institute (2004) has provided guidance for creating invasive species watch lists for the Great Lakes states. Faulkner et al. (2014) describe a watch list system for South Africa. Because biological invasion is a dynamic process, watch lists are spatially and temporally limited and, as a standard operating procedure, need to be updated accordingly. The value of having a particular species on a watch list will change with time in keeping with changes in the risk posed by the species. If the species is verifiably eradicated from an invasion pathway or neighboring area, continuing to prioritize monitoring and surveillance may be a poor use of limited resources. The return on investment for surveillance may also drop considerably if the species bypasses prevention measures and becomes well established in a given area.

Although all watch lists serve as tools for guiding surveillance and reporting priorities, there are a wide range of goals for invasive species surveillance and reporting. These non-exclusive goals may include preventing the introduction of invasive species (especially regulated species; Burgos-Rodríguez and Burgiel 2019, this issue), limiting the spread of already established invasive species, collecting data for scientific research to better understand the biology and distribution of the species, monitoring for species after response measures have been taken in order to ascertain effectiveness and/or detect reinvading organisms, training surveillance personnel (professional staff and/or citizen scientists), and raising public awareness of and engagement in the invasive species issue. Reducing impact risk is frequently an overarching goal for addressing invasive species. In the context of watch list development, the risks in question must be clearly defined: risk to what, where, and when.

The criteria for placing invasive species on a watch list vary according to the goals. Three of the most important criteria to consider are (a) the regulatory foundation for detection and response measures, (b) the level of scientific rigor necessary to inform the watch list in accordance with risk evaluation (which may be established in law and/or policy), and (c) the feasibility for response to detected species (beyond regulation). If there is a low feasibility for response, then there will be little motivation for surveillance and reporting. Watch list developers must also consider the geographic area and species diversity that need to be addressed to meet project goals; the number of taxa and area of coverage influence practicality and the willingness of people to engage in surveillance and reporting. If potential surveyors feel intimidated or overwhelmed by expectations, the watch list may decrease rather than increase overall detection and reporting capacity.

The series of actions to be taken once a species on a watch list has been detected will also vary according to the goals. The roles and responsibilities need to be apparent to the potential detectors and supported by relevant authorities and clearly defined communication strategies. For example, Burgiel (2019, this issue) addresses Incident Command Systems in the EDRR context in a complementary guidance paper.

As standalone tools, watch lists are unlikely to be effective. Ideally, watch lists are employed as part of a programmatic communication strategy that takes social marketing principles into consideration. In the EDRR context, watch lists are needed to help (1) enlist as many well-informed people in surveillance as possible and (2) increase the likelihood that target species are rapidly and accurately reported to the appropriate authorities. Success, therefore, depends on an understanding of what will maximize the motivation and technical capacities of the watch list user (i.e., the target audience). If there are multiple target audiences, multiple approaches to watch list execution may be necessary.

When watch lists are used as part of a regulatory framework that has implications for trade and/or land management practices, it is imperative that the process for developing watch lists is science-based, standardized, up-to-date, and transparent to the public. It is advisable to include information on whom to contact if concerns arise over watch list accuracy, what actions the individual detecting a species is requested to take, and what laws are relevant in the detection and response context.

## Watch list considerations

The following is a list of questions to consider when developing, communicating, and applying invasive species watch lists. These questions are intended to help identify the criteria that need to be met to ensure that watch lists are as effective as possible, particularly when employed as an EDRR tool.

(1) What is the goal(s) for the watch list?
(2) What is the regulatory or policy framework(s) (if any) that supports this goal(s)? What agency authority and specific parameters does it convey that are applicable to watch lists?
(3) What geographic/jurisdictional area is to be covered by the watch list?
(4) What scientific information and tools are available to inform watch list development? How will they be applied initially and used to inform watch list updates?
(5) What standard process is used to determine what goes on the watch list, and how will this process be transparently communicated to the public?
(6) Who is the target audience(s) for the watch list and what actions are they expected to take?
(7) How will the target audience know about and obtain the watch list?

(8) What skill sets does the target audience have for species identification? What resources are available to assist with species identification?
(9) What format(s) (e.g., poster, brochure, smartphone app) will be most effective in communicating the watch list to the target audience?
(10) What motivates the target audience to conduct surveillance and reporting? What will keep the target audience motivated if the chances of encountering the target organism(s) are rare?
(11) How will the target audience know what to do once they detect a target organism?
(12) How long is the watch list good for, who is responsible for updating, and what is the process for updating and communicating those updates?
(13) What are the implications for errors or out of date information on the watch lists, and who is accountable?

A catalog of invasive species lists at various geographic scales is available through the National Agricultural Library (https://www.invasivespeciesinfo.gov/resources/lists.shtml, accessed 19 September 2019). Each of these examples can be evaluated according to the above criteria in order to test the likelihood of effectiveness in specific contexts.

## Conclusion

Watch lists are basic, yet multi-functional tools for invasive species EDRR. There is, however, a need to substantially improve watch list standardization, accessibility, and associated communication strategies. Undoubtedly, increases in computing power and application, as well as advancements in other EDRR support tools (especially risk screening), will lead to growing demands for watch list use and quality. The guidance offered herein is not intended to be prescriptive or comprehensive, rather it provides a general reference point for developing and employing invasive species watch lists, particularly when the goal is to detect and respond to invasive species as rapidly and effectively as possible.

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REVIEW

# Instituting a national early detection and rapid response program: needs for building federal risk screening capacity

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**Abstract** The invasive species issue is inherently a matter of risk; what is the risk that an invasive species will adversely impact valued assets? The early detection of and rapid response to invasive species (EDRR) requires that an assessment of risk is conducted as rapidly as possible. We define risk screening as rapid characterization of the types and degree of risks posed by a population of non-native species in a particular spatio-temporal context. Risk screening is used to evaluate the degree to which various response measures are warranted and justifiable. In this paper, we evaluate the US government's risk screening programs with a view towards advancing national EDRR capacity. Our survey-based findings, consistent with prior analyses, indicate that risk evaluation by federal agencies has largely been a reactive, ad hoc process, and there is a need to improve information sharing, risk evaluation tools, and staff capacity for risk screening. We provide an overview of the US Department of Agriculture's Tiered Weed Risk Evaluation and US Fish and Wildlife Service's Ecological Risk Screening Summaries, two relatively new approaches to invasive species risk screening that hold promise as the basis for future work. We emphasize the need for a clearinghouse of risk evaluation protocols, tools, completed assessments and associated information; development of performance metrics and standardized protocols for risk screening; as well as support for complementary, science-based tools to facilitate and validate risk screening.

**Keywords** Early detection and rapid response (EDRR) · Invasive species · Non-native species · Risk analysis · Risk assessment · Risk screening · Target analysis

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## Introduction

Executive Order 13751 defines invasive species to mean, "with regard to a particular ecosystem, a non-native organism whose introduction causes or is likely to cause economic or environmental harm, or harm to human, animal, or plant health" (Executive Office of the President 2016). Inherent in this definition are questions about risk: What is the risk that a non-native species will be introduced into a new ecosystem? What is the risk that it will cause harm to certain valued assets if introduced into said ecosystem? The answer to both of these questions is the same—it depends. It depends on variables that are context-specific and dynamic, changing in ways that can be difficult to predict with high certainty. The severity and cumulative nature of invasive species impacts are often substantial and require action despite uncertainties. Risks need to be assessed and response options weighed against the costs of inaction.

Definitions of the term "risk analysis" vary widely and thus may instill confusion when protocols are not transparent and/or are inconsistently applied (Roy et al. 2018). The *2016–2018 National Invasive Species Council (NISC) Management Plan* defines risk analysis as the set of tools or processes incorporating risk assessment, risk management, and risk communication, which are used to evaluate the potential risks associated with a non-native species or invasion pathway, possible mitigation measures to address the risk, and the information to be shared with decision-makers and other stakeholders (NISC 2016). Ideally, risk analyses provide a framework for considering the costs (harm) and benefits of the movement of a particular species via a particular pathway (mode of transport) to a particular locality in the near-term, as well as into the future (i.e., when considering climate change) (US Environmental Protection Agency 1992, 1998; Anderson et al. 2004; Lodge et al. 2016). Increasingly, risk analyses are mandated by international, national, and sub-national policies to improve measures to prevent invasive species from entry into across jurisdication borders and/or introduction into a novel ecosystem (Burgiel et al. 2006; Burgos-Rodríguez and Burgiel 2019, this issue). Risk analyses function as decision support systems for developing and enforcing laws and regulations, justifying restrictions on certain commodities (trade, as well as industry and consumer behavior), informing environmentally responsible and sustainable decisions by industries, hobbyists, and consumers, and prioritizing detection (surveillance) and post-detection response measures (Roy et al. 2017).

In the United States, ecologically-oriented risk analysis frameworks emerged out of the need to implement the National Environmental Policy Act (NEPA) adopted in 1969 (Burgos-Rodríguez and Burgiel 2019, this issue). In 1993, the US Congress Office of Technology Assessment's (OTA) review of invasive species issues (termed "harmful, non-indigenous species" in the report) identified risk analysis as a critical tool for federal decision-making. The authors concluded that the US Department of Agriculture (USDA) and US Department of the Interior (DOI) needed to strengthen their capacities for taking a science-based approach to risk analysis (OTA 1993). In 1999, the National Science and Technology Council's (NSTC) Committee on Environment and Natural Resources (CENR) undertook a review of ecological risk assessment across the federal government (NSTC 1999). The study included a focus on invasive species (termed "nonindigenous species" in the report) and, among other things, recommended that federal interagency cooperation be improved to help reduce redundancy and focus limited resources.

The criteria for undertaking a comprehensive risk analysis to address invasive species consistent with regulatory frameworks have been proposed and reviewed in detail elsewhere (e.g., Meyerson and Reaser 2003; Anderson et al. 2004; Stohlgren and Schnase 2006; Lodge et al. 2016; Roy et al. 2018). It is important to note that holistic and comprehensive risk analyses can be expensive and time-consuming, particularly if relevant biological and/or socio-economic data are not readily available. This reality runs counter to one of the most important premises in invasive species management: response measures are far more likely to be cost-efficient and effective if taken either prior to an organism's introduction into the United States or early in the invasion process (as soon as feasible after the non-native species has been detected and accurately identified) (Leung et al. 2002). Fundamentally, we need to determine how to balance the mandate to assess risk as accurately as possible with the imperative to act as quickly as possible.

In general terms, risk screening has been regarded as the use of simple tests to identify individual species that have risk factors or are at the early stages of exhibiting an adverse impact for which there is not yet clear symptomology or other evidence of harm. For the purposes of our paper, we regard risk screening as a rapid characterization of the types and degree of risks posed by a population of non-native species in a particular spatio-temporal context. Risk screening is employed to efficiently ascertain if the likelihood and scale of impacts are (a) "low," warranting no response measures other than making these findings publicly available (per discussion in Reaser et al. 2019a, this issue); (b) "high," warranting immediate, priority action as feasible, including consistency with regulatory frameworks that might require more detailed risk analyses as a next step (Burgos-Rodríguez and Burgiel 2019, this issue); or (c) "uncertain," due to a paucity of reliable information, which necessitates more extensive data collection and analysis before response measures are considered.

At a minimum, science-based risk screening requires accurate taxonomic identification of the species (Lyal and Miller 2019, this issue) and the best available data on the biology of the species, habitat associations, distributions in native and introduced ranges, and the species' impact in similar ecological contexts. A wide range of specific biological and environmental parameters have been used by risk assessors, including diet, fecundity, competitiveness, propagule pressure, dispersal patterns (pathways), detectability, and longevity (Ruesink et al. 1995; Kolar and Lodge 2002; Bartell and Nair 2003; Fujisaki et al. 2010; Reed et al. 2012). Risk screening can function as a meta-analysis. If sufficient data are available, various analytical tools (e.g., climate matching, niche modeling) can be used to improve the confidence level of risk screening outputs. Specific examples of risk screening processes and their informational components are described later in this paper.

Influenced by the aforementioned OTA and NSTC assessments, NISC's first national management plan stated that NISC would develop "a fair, feasible, and risk-based screening system" for intentional non-native species introductions by 2003 (NISC 2001). Although a resulting guidance document emphasized the importance of conducting "rapid risk assessments" to inform decision-makers of potential management decisions (NISC 2003), development of a screening system was deferred to NISC's second national management plan (NISC 2008). In response to this direction, USDA and DOI independently developed risk screening systems, most notably the Weed Risk Assessment Process (USDA 2016) and Ecological Risk Screening Summaries (US Fish and Wildlife Service 2016).

Recognizing the need for the federal government and its partners to adopt and implement a standardized risk screeding framework consistent with federal regulatory requirements (see Burgos-Rodríguez and Burgiel 2019, this issue), the *2016–2018 NISC Management Plan* called for an assessment of "the capacity of the Federal government to conduct the risk analyses and horizon scanning necessary to produce timely and well-informed watch lists of potentially harmful species" (NISC 2016). For the purpose of this paper, we use the term "risk screening" (per the earlier definition) to stress the inherently rapid nature of the evaluation. Ideally, risk screening is conducted in hours to days in order to minimize conflicts with the commerce, tourism, and other economic activities that, in accordance with relevant laws and policies, may need to be put on hold until risk levels and appropriate mitigation measures are determined. However, a lack of the necessary data inputs, sufficient staff to conduct the analyses, and coordination among federal and non-federal institutions frequently result in delays that negate the opportunity for "rapid" response.

Reaser et al. (2019a, this issue) illustrate where risk screening fits into a comprehensive EDRR system. Complementary guidance for the application of target analysis (Morisette et al. 2019, this issue) and watch lists (Reaser et al. 2019c, this issue) to EDRR are addressed elsewhere in this special issue. The remainder of this paper explores the current capacities and needs for establishing a science-based invasive species risk screening system. Although this paper is focused on risk screening in the federal context, a standardized risk screening system would ideally meet the needs of states, territories, tribes, and regional collaboratives of those entities, as well as serve as a decision-support tool for the private sector.

## Approach

In response to the *2016–2018 NISC Management Plan* directive to assess federal capacity for EDRR, the NISC Secretariat invited the sixteen federal agency members represented by Council leadership (https://www.doi.gov/invasivespecies/about-nisc, accessed 12 February 2019) to respond to a survey on federal EDRR implementation capacity (SI 1, Reaser et al. 2019a, this issue), including their ability to enact a range of tools and processes to evaluate invasive species risk. In the survey's glossary of terms, risk screening was described as "a preliminary assessment of the consequences of the introduction and of the likelihood of establishment of an alien species using science-based information. Identification of potential adverse consequences in the risk screening could lead to a full risk assessment." Although this definition is not identical to the one used herein, we regard them as identical in intent and thus comparable for the purposes of analysis and reporting (Reaser et al. 2019a, this issue).

The findings, discussion, and recommendations presented herein are based on the survey responses provided by the federal agencies, augmented by discussions with risk assessment experts (within and outside the federal government), programmatic information available online, and the expertise of the authors. The findings need to be considered in light of the fact that (1) the management plan directive and data call used the term "risk analysis" when a focus on "risk screening" was more appropriate in the EDRR context (terminology might have limited explicit reporting on risk screening activities conducted by federal agencies), (2) not all agencies responded (risk screening may not be applicable to their mission), and (3) the depth of responses varied substantially among agencies (see Reaser et al. 2019a, this issue, for further discussion on agency responses).

## Results

Survey responses were received from the Department of Defense (DOD), DOI (Bureau of Land Management [BLM], National Park Service [NPS], US Fish and Wildlife Service [USFWS], and the US Geological Survey [USGS]), Department of State (DOS), Department of Health and Human Services (HHS), and the National Aeronautics and Space Administrations (NASA) (Table 4 in Reaser et al. 2019a, this issue). Those responses, in combination with the information gathered to augment them, revealed that numerous semi-quantitative, quantitative, and qualitative risk evaluation protocols have been employed by federal agencies. Many of the protocols are permutations of each other rather than unique protocols. While similar in intent, they differ in various parameters, including the content and scope of questions asked by subject matter experts, scoring methodologies, and species traits being assessed. Although these differences may be viewed as minor in concept, any difference in protocol design could result in differences in protocol outputs, and thus variations in the interpretation of risk and appropriateness of response measures.

Our evaluation of the survey results led to the following major observations regarding the federal government's current capacities to enact "a fair, feasible, and risk-based screening system" for invasive species:

1. Mandates and terminology for invasive species risk evaluation vary among the agencies, potentially leading to differences in risk communication and management.
2. In general, agencies are not sufficiently supported (including funding, staffing, training, and guidelines) to meet risk evaluation needs. This can result in substantial time delays (potentially years) for outputs, and thus well-informed and timely action.
3. Due to resource limitations, many federal agencies frequently collaborate with, or rely wholly upon, state agencies' or nongovernmental organizations' risk evaluations.
4. There is no standardized approach to invasive species risk evaluation within or among federal agencies, and approaches may even differ at the site level (e.g., among DOD installations).
5. There is a need for adequate information inputs. See Reaser et al. (2019b, this issue), for further discussion of information management capacity needs.
6. The technical competency of risk screening personnel is essential to ensure timely, accurate outputs. Training needs to be standardized, routine, and include assessment measures.
7. Risk evaluation tools are frequently developed in response to funding opportunities rather than in response to specific agency mandates and criteria.
8. Public access to agency risk evaluation frameworks and/or risk evaluation outputs via agency websites is mostly poor (authors frequently encountered outdated information, inconsistent information, and broken links to documents).
9. While some federal agencies have a track record of applying risk analyses or risk assessments in their efforts to prevent the introduction or spread of invasive species, far less attention has been given to the development of risk screening protocols and tools for EDRR.
10. Invasive species risk screening has mostly focused on species characterization. Very limited pathway risk screening has been conducted by federal agencies.

The lack of consistency in risk evaluation approaches across the federal government contributes to operational inefficiencies: miscommunication, time delays, and duplicative effort. A detailed operational evaluation is needed to document case studies and ascertain how to better standardize risk evaluation while maintaining process requirements that, in some cases, are directed by long-standing regulations and/or enculturated practices. Below we highlight two agency invasive species risk evaluation approaches that we believe hold promise for application within a national EDRR program, if modified as necessary to function as compatable, standardized risk screening tools.

## Ecological risk screening summaries

The USFWS' Fish and Aquatic Conservation (FAC) invasive species program comprises 65 offices in eight regions that collaborate with other federal agencies, tribes, states, territories, Canada, Mexico, private landowners, and nongovernmental organizations. To advance the development of risk screening tools called for in the *2008–2010 NISC Management Plan*, the USFWS Midwest Region developed a model rapid screening process. During development of that process, USFWS received input from the Aquatic Nuisance Species Task Force's (ANSTF) Mississippi River Basin Regional Panel on Aquatic Nuisance Species (MRBP). Later, MRBP peer-reviewed the model process. Following that review, the Nonnative Wildlife Screening Workgroup, which operated under the joint aegis of ANSTF and NISC also peer-reviewed the model rapid screening process. A final peer-review of that process and associated products were conducted pursuant to the Office of Management and Budget's policies for influential science. This work provided a foundation for developing the Ecological Risk Screening Summaries (ERSS), a protocol designed to provide an efficient and cost-effective, rapid risk assessment for non-native species, In particular, the ERSS process was developed to evaluate the risks posed to US assests by (1) species native to parts of the United States but established outside their native range within the United States (e.g., red swamp crayfish [*Procambarus clarkii*]); (2) species in trade in the US but not known to be established in the US; (3) species not known to be in trade within the US, but known to be in one or more trade pathways globally or continentally (e.g., golden mussel [*Limnoperna fortunei*]); and (4) species not known to be in trade within the United States and not known to be in global trade, but of some concern because of well-documented impacts elsewhere (e.g., certain freshwater stingrays).

The ERSS quantitatively compares the location (or likely location) of species introduction in the United States to the present climate niche elsewhere in the world. It also evaluates the historical invasiveness of the subject species (Hayes and Barry 2008). The ERSS process thus combines relevant databases, scientific literature, and either of two climate-niche matching tools: (1) CLIMATCH, a long-established Australian model that evaluates risk that the subject species may become established outside the species' native range (https://climatch.cp1.agriculture.gov.au/climatch.jsp), accessed 16 September 2019); or (2) a faster and more user-friendly Risk Assessment Mapping Tool (RAMP) that is based on the CLIMATCH algorithm and was developed by USFWS (Sanders et al. 2014). Ultimately, the ERSS is a decision support tool; it enables a wide variety of policy and management decisions, particularly when a rapid response is required (See Fig. 1).

The results of both climate-niche matching tools provide an approximate geographic range in the United States within which climate is similar to other locations where the subject species is established (Bomford 2008; Bomford et al. 2010; Howeth et al. 2016). Evaluation of the history of invasiveness determines if there is clear, convincing, scientifically-reliable evidence of adverse impacts by the subject species outside its native range. Sources of information used to categorize history of invasiveness are either prescribed lists of scientific resources or other reliable information. Significant adverse effects and detailed descriptions of the impacts are listed in the ERSS. An ERSS is developed either in response to requests from jurisdictions or based on prioritized species lists resulting from global horizon scanning. It may be used by governments, industries, and other stakeholders to characterize risks associated with species, and to support either sustainable supply chains nationally and regionally, or appropriate regulatory or non-regulatory risk management decisions and subsequent actions.

The USFWS, in consultations with the US Forest Service, has developed a second peer-reviewed tool to

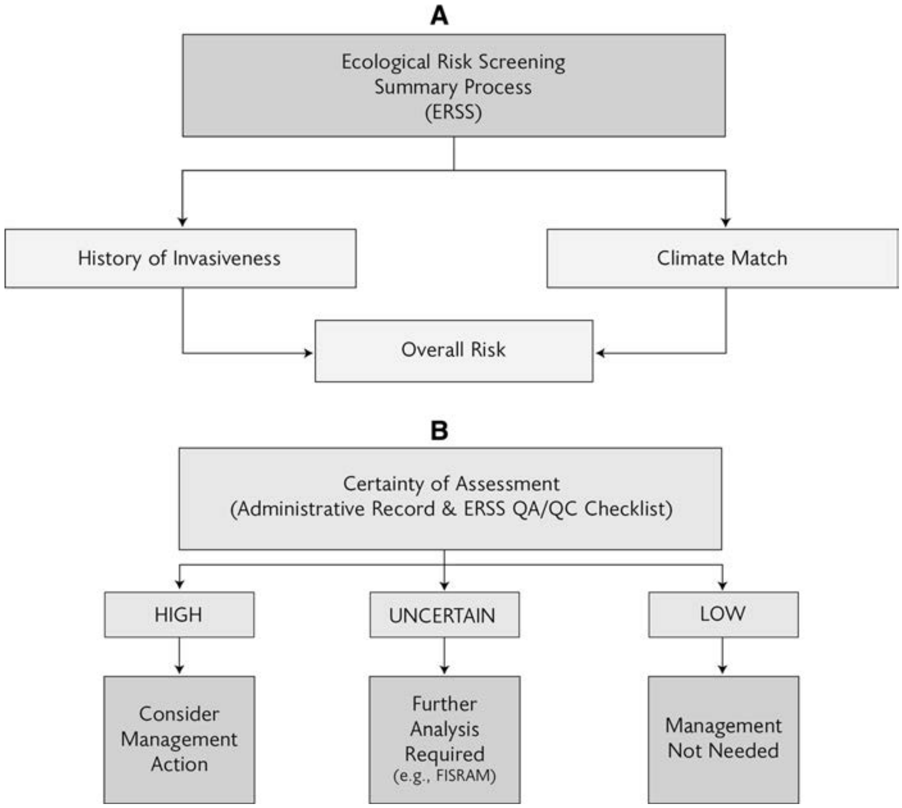


**Fig. 1** **a** Illustrates the two key information inputs (data needs) to determine the overall risk of a specific non-native species. **b** illustrates the three options qualifying the certainty of a risk screen determination: high, uncertain, and low. The quality and quantity of data available to determine the history of invasiveness and climate match will have a strong influence on output certainty

be used when the overall risk level of a freshwater fish species assessed through the ERSS process is uncertain. The tool is a Bayesian risk assessment model called the Freshwater Fish Injurious Species Risk Assessment Model (FISRAM), which predicts invasiveness of a species based on the known and projected characteristics of the species that may not be accounted for in the ERSS (Marcot et al. 2019). FISRAM was used to assess risk of African longfin eel (*Anguilla mossambica*) aquaculture in Michigan (Wyman-Grothem et al. 2018). The USFWS is developing a similar Bayesian Crayfish Invasiveness Risk Assessment Model (CIRAM) (C. Martin, pers. comm).

To facilitate an assessor's use of the ERSS process, the USFWS published a detailed standard operating procedures (SOP) manual containing a template for report completion, data sources for aquatic and terrestrial animals and plants, details of how to complete the report template, and a comprehensive quality assurance and control checklist to enable a reviewer to determine if the ERSS process has been completed properly (USFWS 2016). The SOP requires inserting scientific data, information, and summaries into the ERSS template. Completed ERSS templates document the best available scientific information on native species range and status in the United States, biological and ecological information, adverse impacts of any introductions, global distribution, US distribution, and results of climate-niche matching. The materials in each completed ERSS categorize risk as low, high, or uncertain. Each completed ERSS template is accompanied by a completed quality assurance/quality control checklist to ensure the ERSS product is in compliance with the SOP. Where climate matching is either high or medium within the United States, habitat matching may be completed for portions of the United States. Habitat matching approaches may be qualitative or quantitative and depend on the availability of quantitative habitat matching tools for the subject species. Integrated species, pathway, and locational risk analyses have been completed for Asian carp in the Great Lakes and other situations. The integrated risk analysis for Asian carp in the Great Lakes was the foundation for the early detection program developed and implemented by the Midwest Region of the USFWS. User manuals for RAMP (USFWS 2019a) and FISRAM (USFWS 2019b) are available to facilitate implementation of the suite of ERSS assessment tools.

After an ERSS has undergone internal USFWS review, the ERSS is posted online (https://www.fws.gov/fisheries/ANS/species_erss_reports.html, accessed 27 September 2019) and catalogued by taxonomic groupings and level of assessed risk. The USFWS website enables public comment on individual ERSSs. The ERSS is a screening process that can either stand alone or serve as the basis for further risk evaluation. Completed ERSSs are intended to identify high-risk species for which preventative measures could be implemented, and low-risk species (nationally, regionally, by jurisdiction) for which outreach to the supply chain can categorize a species, region, and pathway as sustainable. A categorization of high risk can be used to inform states and the private sector (such as importers of live animals) of the risks of importing or transporting assessed species, as well as USFWS's injurious wildlife listing process under the authority of the Lacey Act (18 USC § 42). ERSSs can be utilized to prioritize the higher risk species for initiating the highly detailed and lengthy injurious wildlife listing process, which also includes opportunities for public comment. Prioritization for each species can be assigned using ERSS outputs and a USFWS scoring system.

As of the end of 2017, USFWS had conducted an initial evaluation of about 40,000 species, including 33,500 fish species from Fishbase (http://www.fishbase.org/search.php, accessed 27 September 2019). Criteria for including non-native species in the risk screening process included one or more of the following: (1) currently established in the US, (2) presence in US trade but not yet established in the US, (3) not established or in trade in the US but in trade pathways elsewhere that present concern for US entry, and (4) not known to be in trade but of concern for other reasons (e.g., known impacts elsewhere or associations with invasive species). The scanning process involved detailed evaluation of invasive species databases, review of scientific literature, and consultations with scientists from around the world. Based on evidence and expert opinion, USFWS utilized the ERSS approach to select approximately 1800 species from the initial scan for further risk screening. Some of those species have also been evaluated using the FISRAM tool. FISRAM model outputs are typically completed in a day or less. A trained assessor with a sufficient expertise in the ecology of the taxa being evaluated, as well as familiarity with operating climate-niche matching software, may be able to use the USFWS SOP to complete a draft ERSS assessment in 2–4 h. However, when the acquisition of data, information, and expert input are insufficient, the process may take substantially longer.

Following internal agency review, these ERSS products are posted online as publicly available watch lists (see Reaser et al. 2019c, this issue for discussion of watch lists in EDRR context). USFWS noted, in its response to the NISC data call, that ERSS-determined high-priority watch list species are identified at national, regional, and state scales, while other watch list species are identified by a number of states as part of their state aquatic nuisance species initiatives (Reaser et al. 2019c, this issue). A central clearinghouse of watch lists is needed to support rapid response actions; a clearinghouse would make watch lists more readily accessible, facilitate survey prioritization, and, if the watch lists were standardized, enable spatio-temporal risk comparison.

### APHIS-PPQ tiered weed risk evaluation

Plant Protection and Quarantine (PPQ), a program within the USDA's Animal and Plant Health Inspection Service (APHIS), is responsible for safeguarding American agriculture and natural resources from the introduction and spread of plant pests, including weeds and invasive plants (Groves et al. 2001; Magarey et al. 2017). PPQ regulates plants that may become invasive in two primary ways. Plants that have been shown to present a significant risk of becoming noxious weeds are prohibited from entering the US under the Plant Protection Act, and are listed under 7 CFR § 360 of the Code of Federal Regulations. Plants that have demonstrated a potential of becoming noxious weeds in the United States are regulated under APHIS' Not Authorized Pending Pest Risk Analysis (NAPPRA) regulations (7 CFR § 319.37-4).

To determine whether a plant species poses a noxious weed risk, PPQ evaluates weeds using a tiered approach (A. Koop, pers. comm). PPQ may initiate an evaluation for a variety of reasons, including (1) detection of a species that is new to the United States, (2) change in the invasive status of a species present in the United States or elsewhere in the world, (3) evaluation of a market access request for a plant for planting, or (4) evaluation of a pathway that may allow the entry of a potential weed (USDA 2016). Plants are initially screened to determine if they pose a potential threat and that they are not yet present in the US, or if present, are not widely established there. These plants then undergo a weed characterization evaluation, which is based on basic biological information about the species' identity, distribution, invasive status, and impacts. PPQ policy managers use this information to determine whether the plants are potential targets for exclusion from importation. Plants that are potential candidates for regulation under NAPPRA are formally evaluated through the NAPPRA process (7 CFR § 319.37-4), whereas plants that are potential candidates for regulation as a federal noxious weed are evaluated under PPQ's weed risk assessment (WRA) process (USDA 2016; see Fig. 2).

PPQ's WRA process is the agency's most detailed weed evaluation tool (USDA 2016). It consists of approximately 90 questions that address a species' ability to enter, establish, spread, and harm US agricultural and natural resources. The assessment includes three major analytical components. The first component is a predictive tool that uses a logistic-regression model, which was validated with 204 known US noninvaders, minor-invaders, and major-invaders (Koop et al. 2012). The outcome of the model is expressed in qualitative terms such as low risk, high risk, and evaluate further. It also expresses probabilities that a plant will become an invader. The second component of the WRA process evaluates the sensitivity of the predicted risk scores to uncertainty through

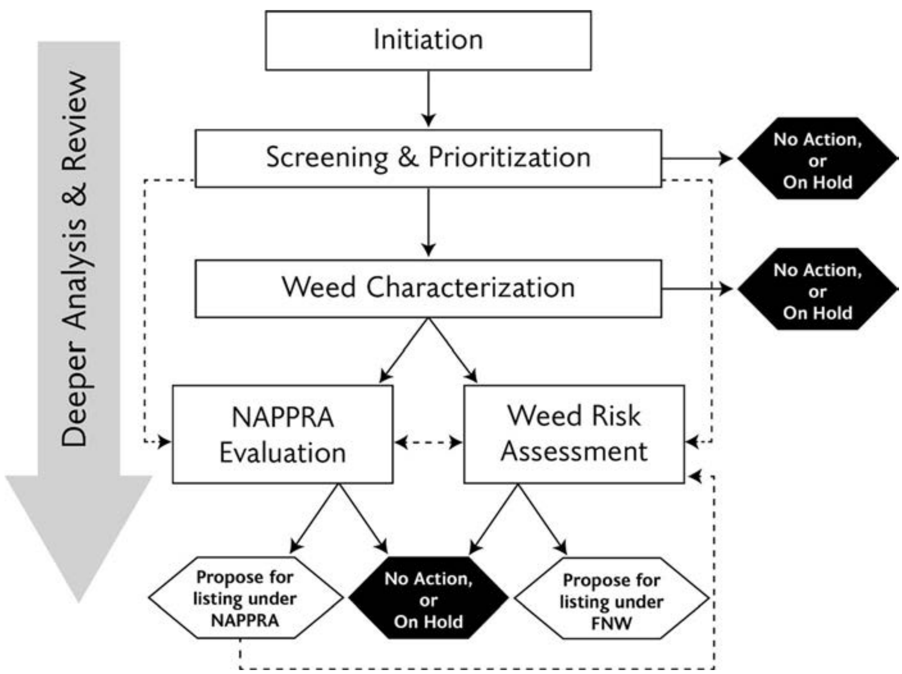


**Fig. 2** This figure (A. Koop, pers. comm) illustrates the flow of information from process initiation to management decision (output). Species classified for "No Action" either widely naturalized, widely cultivated and economically beneficial, or are native to a wide region of the United States. These species do not meet the criteria of being a quarantine pest. Species that are placed "On Hold" could be quarantine pests, but without enough evidence to confirm invasiveness or potential to cause harm. Assessed species that obtain a high risk result (or at times moderate) during characterization are evaluated further and are potential candidates for regulatory action. Depending on the outcome of these evaluations, these species may be considered for regulation as a Federal Noxious Weed (FNW) or under the Not Authorized Pending Pest Risk Analysis (NAPPRA) category. For additional information on the weed risk assessment or NAPPRA processes, go to www.aphis.usda.gov

an analysis, which generates a range of other possible scores if some of the answers in the WRA were to change slightly. The higher the uncertainty surrounding the evidence considered in the WRA, the more likely the answers to the individual questions will vary (Caton et al. 2018). The third component of the WRA process incorporates a climate-matching analysis to determine which US areas are suitable for species establishment (Magarey et al. 2017). PPQ developed detailed guidelines to allow anyone to conduct a WRA using its process (USDA 2016). By design, PPQ WRAs do not include any policy decisions, which allows any US stakeholder to use them as a resource for their own decision-making processes (A. Koop, pers. comm).

Prior to PPQ's adoption of its predictive model in 2012 (Koop et al. 2012), a WRA using the previous, narrative-based process (Lehtonen 2001) took 2–8 weeks to complete (Parker et al. 2007). With the 2012 WRA model, which is compliant with PPQ's analytical, regulatory, and management requirements, an analyst may complete an evaluation in 1–2 weeks depending on the species and the assessor's expertise (A. Koop, pers. comm). Additional time is needed for internal review of the assessment. Despite the relative efficiency of the WRA and NAPPRA processes, decisions to add a species to one or more regulatory lists may take years due to required compliance with other processes mandated by federal statutes and regulations, including economic impact assessment, NEPA compliance, and public comment periods. For example, it took 4 years to add 22 species of plants, which are potentially invasive, under the NAPPRA regulations (82 Fed Reg 116: 22786-77792, June 19, 2017). PPQ publishes on its website all NAPPRA evaluations used to support rulemaking (https://www.aphis.usda.gov/aphis/ourfocus/planthealth/import-information/permits/plants-and-plant-products-permits/plants-for-planting/CT_NAPPRA, accessed 27 September 2019) and all weed risk assessments it conducts (https://www.aphis.usda.gov/aphis/ourfocus/planthealth/plant-pest-and-disease-programs/pests-and-diseases/sa_weeds/sa_noxious_weeds_program/ct_riskassessments, accessed 27 September 2019).

## Key findings and conclusion

The need for the United States to develop a fair, feasible, science-based risk screening framework has been recognized for decades. Our findings indicate that the US approach to risk evaluation across the federal government remains largely ad hoc and under-resourced, particularly with regard to meeting staffing needs. The demand for risk evaluation exceeds current agency capacities (as also noted by Reaser and Waugh 2007), resulting in a backlog of risk assessment and reporting. In the context of risk screening for EDRR, time is of the essence. Some combination of staff expansion and technology application (e.g., developing machine learning tools; Martinez et al. 2019, this issue) will likely be necessary to support risk screening.

Risk screening capacity is also limited by information system capacity. Reaser et al. (2019b, this issue) explicitly address federal information system needs in the EDRR context. From a risk screening perspective, there is a clear need to incorporate wildlife and plant import data into open-access information systems so that species, quantities of imports, and country of origin data are readily available. Federal prioritization of risk screening for species new to trade or increasing in trade popularity could help reduce propagule pressure. Priorization could be accomplished through new or component databases that curate species-in-trade data that is contributed by industries or by harvesting non-native species trade data from social media via webcrawling tools (Reaser et al. 2008).

Poorly coordinated efforts can facilitate duplication of programs and processes, policy and programmatic confusion, inefficient use of limited resources, gaps in information sharing, and inconsistencies in regulatory enforcement. Barriers to the development of a federal-wide risk screening framework have included differences in agency missions and cultures, as well as a lack of funding and personnel. Any effort to build a multi-agency information framework to serve EDRR nationwide will need to carefully consider the differences in agency culture and how to foster a unified mission (Reaser et al. 2019a, this issue). Agency responses also suggest there is a lingering need to enhance collaborative, voluntary partnerships with states, tribes, industries, and other stakeholders that need to utilize risk screening frameworks and tools.

Our assessment also reveals that there are at least two US-developed risk screening tools available on which to build future efforts. Although, these tools are relatively new and thus have not yet been used widely for EDRR decision support, they show promise for broad application. They also demonstrate the need for the United States to focus on the development of a flexible, risk screening toolkit to support a standardized, transparent risk screening framework consistent with regulatory requirements (e.g., trade rule compliance). Other governments have come to similar conclusions; different taxonomic groups may require individualized, yet complementary variations in risk evaluation strategy (e.g., D'hondt et al. 2015; Mumford et al. 2010; Baker et al. 2008). Risk screening of pathogens and parasites may be particularly challenging, but the Belgian *Pandora* system provides a useful reference point for US consideration (https://ias.biodiversity.be/harmoniaplus, accessed 30 October 2019).

As the high-level policy and planning body with a "whole of government" mandate, NISC has the role and responsibility to facilitate the development of federal risk screening protocols and associated tools. Ideally, such work would proceed with strong input and cooperation from other government entities, the private sector, and technical experts from various scientific disciplines. In addition to the priorities already set forth in NISC management plans, our assessment indicates that the following actions would advance federal risk screening capacities, particularly within the EDRR context:

1. Creation of a user-friendly, open access, centralized, searchable clearinghouse of risk evaluation protocols, tools, and completed assessments available in the United States, with links to those produced elsewhere (e.g., D'hondt et al. 2015). The clearinghouse should incorporate and/or interface with similarly intended projects at the subnational and multi-national level, as discussed previously in this paper.
2. Timely, ongoing submission of information on risk evalution approaches and outputs into the clearinghouse. Ideally, contributions would not be limited to federal agencies, but be open to all parties conducting invasive species risk evaluation.
3. Development of performance metrics (e.g., reliability/verifiability, timeliness, transparency, replicability, accessability, cost effectiveness) for the risk screening capacities needed to support a national EDRR program and evaluation of the risk screening protocols and tools in the clearinghouse according to these metrics, with the findings, including data relied upon, made publicly available.
4. Based on the findings of (3), development of one or more invasive species risk screening protocols and associated tools for standardized use by federal agencies and their partners, keeping in mind that protocols and tools may need to be delineated by taxonomic group, as discussed previously in this paper. Where a rapid screening process characterizes a species risk as uncertain, supplemental tools may be needed to better evaluate that risk (e.g., FISRAM).
5. Development of complementary, science-based risk analytical protocols and tools (e.g., pathway-oriented risk screening, habitat-matching, climate-matching, horizon scanning) to facilitate and validate risk screening, as well as to assist with EDRR target analysis (per Morisette et al. 2019, this issue). A useful resource could include a model currently under development by the USFWS Midwest Region that promotes an integrated approach to species, pathways, and habitat/locational risk analyses for Asian carp in the Great Lakes.

Risk screening should be considered a key component of any EDRR program. Review articles indicate that an increasing number of evidence-based risk analyses are available for potential uses in the United States and abroad (e.g., Lodge et al. 2016). Although these tools can provide a useful conceptual framework for decisionmaking, they are not designed as an initial filter or risk screen and may necessitate significant resources (training, time, staffing, funding, data) that make them impractical for broad application.

There are clear benefits to ensuring that risk screening tools are standardized (such as those within the USFWS and APHIS systems, allowing for consistent and comparable outcomes) and made available through an open-access information system for reference. In building a national EDRR program, improved coordination and collaboration among relevant government agencies is essential for identifying programmatic challenges, developing minimum standards, publishing SOPs for risk screening protocols and tools, and launching a user-friendly, open access clearinghouse. A lack of sufficient data, including empirical evidence of harm, may be the greatest constraint to risk screening (as well as robust risk analyses; Roy et al. 2018). More studies that focus on evaluating impacts of non-native species established in the United States will provide evidence of harm for some species that have been screened and assessed as uncertain risk by one or more scientific tools. Federal capacities to enact sufficient risk screening capacities are thus also inextricably linked to federal support of a national invasive species information infrastructure (Reaser et al. 2019b, this issue).

Effective implementation of the recommendations contained herein will significantly improve coordination, cost-efficiencies, and collaboration across agencies with responsibilities for the detection and/or management of invasive species. Ultimately, this will improve the US government's ability to prevent the further introduction and spread of invasive species, thus protecting national assets.

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REVIEW

# Right place. Right time. Right tool: guidance for using target analysis to increase the likelihood of invasive species detection

**Jeffrey T. Morisette · Jamie K. Reaser · Gericke L. Cook · Kathryn M. Irvine · Helen E. Roy**

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**Abstract** In response to the *National Invasive Species Council's 2016–2018 Management Plan*, this paper provides guidance on applying target analysis as part of a comprehensive framework for the early detection of and rapid response to invasive species (EDRR). Target analysis is a strategic approach for detecting one or more invasive species at a specific locality and time, using a particular method and/or technology(ies). Target analyses, which are employed across a wide range of disciplines, are intended to increase the likelihood of detection of a known target in order to maximize survey effectiveness and cost-efficiency. Although target analyses are not yet a standard approach to invasive species management, some federal agencies are employing target analyses in principle and/or in part to improve EDRR capacities. These initiatives can provide a foundation for a more standardized and comprehensive approach to target analyses. Guidance is provided for improving computational information. Federal agencies and their partners would benefit from a concerted effort to collect the information necessary to perform rigorous target analyses and make it available through open access platforms.

**Keywords** Detection · Early detection and rapid response (EDRR) · Invasive species · Target analysis

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## Introduction

An invasive species is, "with regard to a particular ecosystem, a non-native organism whose introduction causes or is likely to cause economic or environmental harm, or harm to human, animal, or plant health" (Executive Office of the President 2016). The early detection of and rapid response to invasive species (EDRR) is a guiding principle for addressing invasive species in an effective and cost-efficient manner (Reaser et al. 2019a). In order to detect invasive species early in the invasion process, surveyors (including inspectors at points of entry and field-based personnel) need to know the characteristics of the species of interest and be in the right place, at the right time, and with the right tool(s). If these criteria are not met, invasive species may bypass prevention measures, establish, spread, and cause adverse impacts to valued assets.

The *2016–2018 National Invasive Species Council (NISC) Management Plan* calls for an assessment of the capacity of federal inventory and monitoring programs to detect invasive species (NISC 2016). Reaser et al. (2019a) provide a general overview of the assessment findings and identify capacity building needs. In this complementary paper, we provide guidance for using target analysis as a tool to maximize the likelihood of invasive species detection through inventory and monitoring programs (collectively referred to as surveillance herein). We define target analysis as a strategic approach for detecting one or more invasive species at a specific locality and time, using a particular method and/or technology(ies). Target analysis is a key component of a holistic EDRR framework, as described by Reaser et al. (2019a, b, c).

Invasive species can be detected incidentally through opportunistic identification (Morrisseau and Voyer 2014) such as citizen science programs (Waugh 2009). However, the implementation of proactive prevention measures, including surveillance, is considered the most cost-effective approach to addressing invasive species (Lodge et al. 2006; Leung et al. 2002; McNeely et al. 2001). By enabling the development of robust and efficient statistical sampling designs, target analyses can maximize the effectiveness and cost-efficiency of invasive species detection when the target is known (i.e., a decision has been made to survey for specific invasive species) (Chin et al. 2018; Berec et al. 2015; Hoffman et al. 2016; Wang et al. 2014; US Forest Service n.d.; http://www.landscapetoolbox.org, accessed 24 September 2018). Target analysis is particularly advantageous for "finding the needle in the haystack" when the target is (1) a high risk to valued assets if it goes undetected, (2) mobile, (3) self-perpetuating, (4) rare (e.g., introduced population size is small), (5) a novel species that can have unpredictable behavior (such as dispersal or competition), and (6) subject to response measures that are substantially constrained with respect to time, funding, and other resources.

Target analysis, in various forms, is applied across a wide range of technical fields where the criteria listed above are applicable. Examples include sampling design and theory, particularly for high-risk contexts (De Gruijter et al. 2006); probabilistic risk analysis in bioterrorism (Ezell and Winterfeldt 2009); pandemic prediction surveillance and modeling (Watters and Biernacki 1989); and wildfire management (Schroeder et al. 2016; Khamukhin and Bertoldo 2016). Lessons learned from the use of target analysis components within these contexts could help advance invasive species applications.

Taleb (2007) regards rarity, extreme impact, and retrospective predictability as attributes of a "Black Swan," a theory he developed to explain the disproportional role of high-profile, hard-to-predict, rare events in human history. Related to the Black Swan concept, Lindenmayer et al. (2010) describe "ecological surprises" as events beyond either expected or unexpected results. Because the management of established and potential invasive species constitutes planning in light of uncertainty (Cook et al. 2014), applying target analyses to invasive species management may also benefit from applying event-prediction theory and associated models. For example, the arrival of invasive dreissenid mussels in Lake Powell (Colorado) and Lake Mead (Nevada/Arizona) is a Black Swan scenario. Although we now know that invasive mussels can thrive throughout the western US (Wong and Gerstenberger 2015), previous guidance (which had gone through rigorous peer review) on where to monitor for mussel introductions indicated very little to no risk in areas that later became heavily invaded (Drake and Bossenbroek 2004). This was an "ecological surprise" (Lindenmayer et al. 2010). Given the uncertainties inherent to any biological model, practitioners need to apply new information as it becomes available to better inform both iterative modeling and adaptive management decisions. This principle is reflected in arrows indicating information iteration in Fig. 1.

Drawing from the aforementioned fields of application, we regard target analyses as meta-analyses that integrate raw data, as well as information generated for and from other analytical components of a comprehensive EDRR system. Figure 1 depicts target analysis as generating information on when, where, and how to look for a given species or set of species based on the evaluation of key information inputs. It

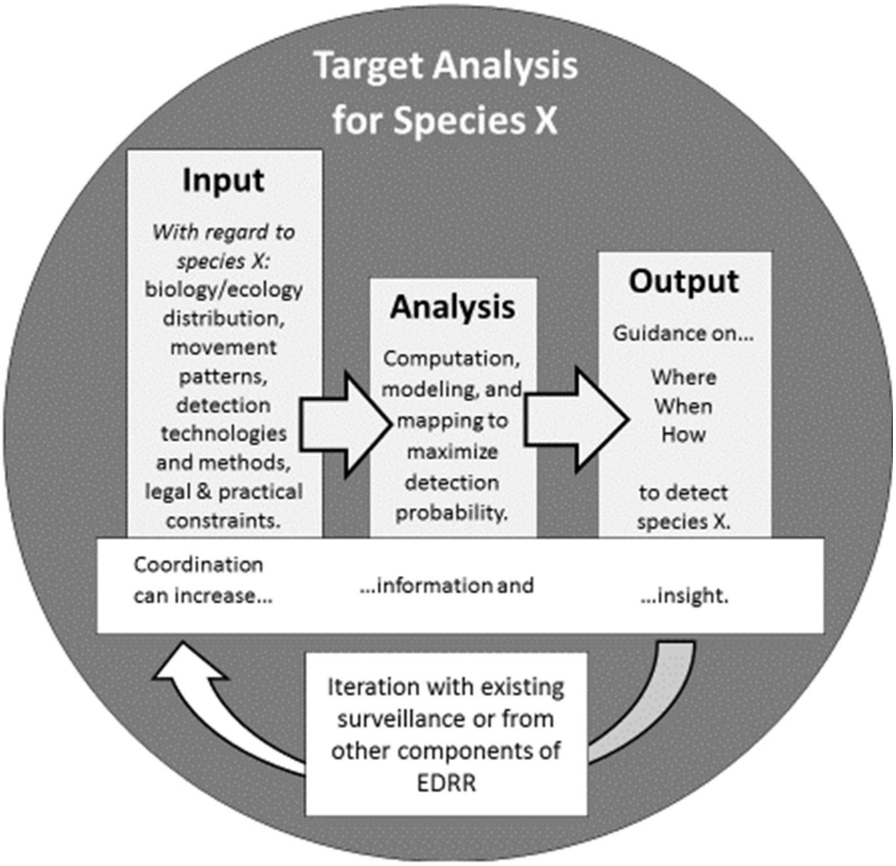


**Fig. 1** Target analysis: a conceptual framework. The figure depicts the input parameters, analytical approaches, and results (output) that can be used to guide a sampling strategy for specific species or groups of species in order to maximize the likelihood of their detection. Input data quantitatively characterize the biology and ecology of the target species, its distribution and movement patterns, as well as the methods and technologies used to detect the species in a context similar to the recipient ecosystem(s) of concern. The data analysis includes computations that use robust statistical sample survey design, modeling to forecast in space and time, and mapping to provide a spatial–temporal representation of locations for strategic sampling

provides a conceptual framework for target analysis, depicting the input parameters, analytical approaches, and results (output) that can be used to guide a sampling strategy for specific invasive species or groups of invasive species in order to maximize the likelihood of detection. The essence of target analysis is to use the best available information, integrated through computation, modeling, and mapping to answer key questions pertaining to when, where, and how to most effectively and cost-efficiently detect invasive species. The data inputs must be as reliable (authoritatively verified) and as up-to-date as possible.

Currently, no standardized approach to target analysis exists. Those conducting target analyses optimally use the most robust analytical approaches and tools available to them and report their methods. Russell et al. (2017) provide a practical example of target analysis computations. They consider the characteristics of the species of interest, multiple devices/technique being used, and the time frame to optimize surveillance for invasive rodents on islands after an eradication has been attempted. Although they do not include spatial variables in their formula, they do recognize the importance of spatial considerations by noting that the parameters in their calculations will differ between sites and in different climates.

The computations that constitute target analysis are largely built on existing information and use statistical sampling theory (Russell et al. 2017; Berec et al. 2015; Hoffman et al. 2016; US Forest Service n.d.; http://www.landscapetoolbox.org, accessed 24 September 2018). Modeling helps extend estimates about the invasive species in space and/or time (Cook et al. 2019; Wang et al. 2014). Mapping is used to consider important geospatial information, jurisdictional boundaries, and logistical aspects of surveillance strategy. In addition to highlighting the flow of input, analysis, and output, Fig. 1 also emphasizes coordination and iteration for conducting target analysis.

The following are questions to consider when one conducts a target analysis. These questions are intended to help identify the data to be processed through computational, mapping, and/or modeling approaches available to the analyst. For regulated species, analytical approaches must be consistent with the directives of relevant legal frameworks (Burgos-Rodríguez and Burgiel 2019).

Where?

1. What habitat(s) does the species occupy in its native range?
2. What resources (food, shelter, reproductive sites, etc.) is it attracted to?
3. What conditions and features (natural and human-constructed) promote or deter the invasive species?
4. How does the species spread by its own volition and in what territory/range size?
5. How can the species be transported, and what are the patterns associated with this mode of transport (i.e., what are the known, existing, or potential pathways)?
6. What are the most feasible interception points along this pathway?
7. How do 1-6 change through time (see When list)?

When?

1. What are the daily activity patterns of the species (diurnal, nocturnal, crepuscular)?
2. What are the weather-associated activity patterns for the species (temperature, moisture, etc.)?
3. What are the activity patterns of the species with regard to patterns in the availability of food, shelter, and other resources?
4. What are the activity patterns of the species with regard to the presence or absence of other species (predators, competitors, parasites, etc.)?
5. What are the seasonal activity patterns of the species (phenology, migratory patterns, population periodicity over years, etc.)?
6. When are the species most prevalent or likely to occur at the various steps of the invasion pathway?

How?

1. What visual, auditory, or other characteristics of the species facilitate detection?
2. What detection methods have been effective/ineffective in similar contexts?
3. What detection technologies have been effective/ineffective in similar contexts?
4. What are the most feasible detection points along the pathway?
5. How do the above (1–5) change according to time and location (see Where and When lists)?
6. How do authorities, policies, feasibility, and cost effectiveness influence application of the above (1–5)?

Federal agencies employing target analysis for invasive species EDRR, whether in name or principle, are largely doing so to increase detection rates at points of entry (pathway interception) and/or in known, potentially recipient ecosystems. In the points-of-entry context, special considerations for target analysis include (1) regulatory and policy directives that could influence method options, such as the Security and Accountability for Every Port Act (2006) and the US Department of Agriculture's (USDA) Agricultural Quarantine Inspection Monitoring program (USDA 2011) (see also Burgos-Rodríguez and Burgiel 2019); (2) the high volume of a wide diversity of conveyances and containers that could be moving invasive species as commodities or hitchhikers; (3) the dynamic nature of trade and travel patterns (Haack et al. 2014); (4) the advantage (over the broader spatial domain of recipient ecosystems) of very specific, known locations from which to monitor (US Department of Homeland Security and USDA 2003); and (5) the ability to include reliable information on the type, source, and movement history of the potential conveyance (e.g., baggage, cargo, trailered watercraft; USDA 2011). With regard to recipient ecosystems, special considerations for target analysis include the need to understand (1) pathway patterns and trends (i.e., how invasive species are entering and moving through the ecosystem) (USDA 2018); (2) how ecosystem characteristics vary over time and space; and (3) how species traits relate to these ecological patterns and trends (Brooks and Klinger 2012; Stohlgren and Schnase 2006).

To the best of our knowledge, no federal agency is *explicitly* conducting *comprehensive* target analysis for invasive species, and there is no overarching federal focus on target analysis as part of an invasive species EDRR framework. However, several agencies use components of target analysis and analytical approaches to develop invasive species sampling strategies. These could be considered target analyses in concept, or aspects of target analyses. We provide five examples below:

*Department of Homeland Security* The National Agriculture Cargo Targeting Unit (NACTU) is an operational arm of the Agriculture Programs and Trade Liaison (APTL) co-located at the National Targeting Center. Under the Department of Homeland Security, US Customs and Border Protection (CBP) Office of Field Operation, APTL has established NACTU to improved CBP's agriculture quarantine targeting through multiple pathways to include cargo and passengers. NACTU operations analyze national quarantine activities and apply resulting trends to importation practices in multiple pathways in order to identify quarantine risks before they arrive. With a strong focus on pest exclusion and trade, NACTU identifies inconsistencies in importation trends and applies risk-based criteria to identify repeat violators and high-risk pathways. This makes agriculture exams more efficient, thereby acting as a force multiplier towards CBP's agriculture mission.

*Department of Agriculture* On an annual basis, USDA's Animal and Plant Health Inspection Service (APHIS) has been using aspects of target analyses to forecast the likelihood of detecting European gypsy moth (*Lymantria dispar dispar*) outside of the existing federal quarantine area. Because pathways for spread differ across space (from natural spread over relatively short distances to human-assisted spread over long distances), the gypsy moth model is regionalized to capture these different pathways (Cook et al. 2019). The resulting model output is used to guide sampling, directing more effort to high-probability locations (USDA 2014). Using measurements of heat accumulation (such as growing degree days) in phenology models that predict the emergence of the adult flying stage, APHIS targets trap placement for optimal pest detection across space and time (Sheehan 1992; Régnière and Nealis 2002).

*Department of the Interior* The US Geological Survey (USGS) is considering a target analysis approach to enhance detection of the invasive fungus (*Pseudogymnoascus destructans*; Pd) that is commonly known to cause white-nose syndrome when infecting bats (Jachowski et al. 2014; Rodhouse et al. 2012). The analytical approach leverages monitoring data to project the likelihood of at-risk bat species occurrence at unsurveyed locations and to inform the timing of capturing bats in order to increase the chances of detecting Pd on susceptible bats.

The US National Park Service (NPS) has an extensive biodiversity inventory and monitoring program (Fancy et al. 2009). Invasive plant surveys and response are coordinated through their Exotic Plant Management Team (EPMTs). The Mid-Atlantic Inventory and Monitoring Network established a single platform where resource managers and support staff could access baseline information on natural resource inventory and monitoring, as well as information on observations and management actions from the EPMT and fire management staff (Dammeyer and Shedd 2017). The system can improve surveillance by providing documentation and maps of what has already been detected and treated as well as baseline ecological and disturbance information that can help inform future surveillance.

*Inter-agency* Together, the US Environmental Protection Agency (EPA) and US Fish and Wildlife Service (USFWS) are working with state agencies to evaluate approaches to the early detection of aquatic invasive species with the intent of establishing survey protocols and designing a process for routine evaluation of survey performance (Hoffman et al. 2016).

These exemplary programs can serve as a foundation on which to build a more holistic approach to target analysis within the US federal government and elsewhere. Agencies with responsibilities for invasive species detection could benefit from a standard approach to surveillance (intercept) data management and target analysis protocols. In keeping with the tenets of adaptive management (Buckley 2008), this would enable target analyses to be refined over time. By comparing targeted detections against baseline expectations, surveyors can determine if they are appropriately targeting the selected samples (Jarrad et al. 2015). The outcome of these analyses can be used to improve the quality of the target analysis and better optimize detection strategies (Hulme 2009). Artificial intelligence (machine learning) could also be used to identify detection patterns and trends and "train" target analyses to become more sophisticated for certain contexts and species (see Martinez et al. 2019).

Overall, the capacity for conducting target analyses can be improved through advancements in the quantity and quality of the information required for the analyses. In particular, this includes

1. Improvements in collection of and access to non-native species occurrence data (Reaser et al. 2019c),
2. Increasing our knowledge of species biology and ecology (Reaser et al. 2019b; Meyers et al. 2019),
3. Advances in invasive species detection technologies and data on their efficacy (Martinez et al. 2019; Kamenova et al. 2017; Lodge et al. 2006),
4. Standardization and expansion of other decision support tools, such as risk screening (Meyers et al. 2019), horizon scanning for strategic planning (Roy et al. 2015; Sutherland and Woodroof 2009), and dashboards for operational reporting [e.g., from business (Eckerson 2010) or human health contexts (Kunjan et al. 2018)] and
5. Increased awareness, communication, and coordination across agencies and with other monitoring programs [e.g., citizen science (Kamenova et al. 2017; Tulloch et al. 2013; Roy et al. 2012)].

## Conclusion

Executive Orders 13112 (Executive Office of the President 1999) and 13751 (Executive Office of the President 2016) charge federal agencies with taking a cooperative, cost-efficient approach to addressing invasive species. They underscore the need to apply the best-available data, analytical models, and technologies to support decision-making. Target analysis is an underused, yet vital tool for preventing the introduction and spread of invasive species. The broader application of target analysis could improve collaboration in species surveillance (especially across jurisdictions), information sharing, analytical tool development, and technology advancement.

The guidance provided here is not meant to be prescriptive or comprehensive; it provides a starting point for advancing the development and application of target analysis for invasive species EDRR with a view towards more integrated and comprehensive EDDR efforts. Federal agencies and their partners would benefit from greater awareness of target analysis as addressed in theory and by other fields of practice. This could include an assessment of opportunities for strengthening and expanding use of target analysis within their EDRR programs (e.g., watercraft inspection stations), a concerted effort to expand target analysis application where needed/warranted, ongoing improvements in the quantity and quality of information drawn upon for target analyses, and the communication of target analysis reports into an open-access clearinghouse for future reference. Collectively, these efforts could help increase early detection while maximizing the efficiency of existing or future invasive species surveillance efforts.

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REVIEW

# Technology innovation: advancing capacities for the early detection of and rapid response to invasive species

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**Abstract** The *2016–2018 National Invasive Species Council* (*NISC*) *Management Plan* and Executive Order 13751 call for US federal agencies to foster technology development and application to address invasive species and their impacts. This paper complements and draws on an Innovation Summit, review of advanced biotechnologies applicable to invasive species management, and a survey of federal agencies that respond to these high-level directives. We provide an assessment of federal government capacities for the early detection of and rapid response to invasive species (EDRR) through advances in technology application; examples of emerging technologies for the detection, identification, reporting, and response to invasive species; and guidance for fostering further advancements in applicable technologies. Throughout the paper, we provide examples of how federal agencies are applying technologies to improve programmatic effectiveness and cost-efficiencies. We also highlight the outstanding technology-related needs identified by federal agencies to overcome barriers to enacting EDRR. Examples include improvements in research facility infrastructure, data mobilization across a wide range of invasive species parameters (from genetic to landscape scales), promotion of and support for filling key gaps in technological capacity (e.g., portable, field-ready devices with automated capacities), and greater investments in technology prizes and challenge competitions.

**Keywords** Control · Detection · Early detection and rapid response (EDRR) · Eradication · Information management · Innovation · Invasive species · Technology

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## Introduction

Invasive species are a major threat to biosecurity (Meyerson and Reaser 2003), adversely impacting the economy (Bradshaw et al. 2016), natural and cultural resources (Simberloff et al. 2013; Drake et al. 2016;

Young et al. 2017), infrastructure (Invasive Species Advisory Committee 2016; Connelly et al. 2007), agricultural production (Bradshaw et al. 2016), and human health (Bradshaw et al. 2016; Young et al. 2017). In the United States, the economic damages and control costs of invasive species have been estimated to total more than $100 billion per year (Pimentel et al. 2005). Unless we are able to develop and apply more effective solutions, biological invasions and their impacts are expected to increase concurrently with growth in trade, travel, and transport (Mack et al. 2000; Reaser and Waugh 2007; Seebens et al. 2017).

Recognizing the need to innovate solutions to seemingly intractable invasive species problems, the US government's *2016–2018 National Invasive Species Council (NISC) Management Plan* (NISC 2016) and Executive Order 13751 (Executive Office of the President 2016) call for federal agencies to foster technology development and application. Responses to these directives have included an Innovation Summit (Conservation X Labs 2017a, b) and a review of advanced biotechnologies (Invasive Species Advisory Committee 2017). This paper is the response to the management plan goal to assess the capacity of the federal government to improve the early detection of and rapid response to invasive species (EDRR) through advances in technology application (NISC 2016).

Reaser et al. (2019a, this issue) define EDRR as a guiding principle for minimizing the impact of invasive species in an expedited yet effective and cost-efficient manner, where "detection" is the process of observing and documenting an invasive species and "response" is the process of reacting to the detection once the organism has been authoritatively identified and response options assessed. Eradication is the ideal outcome of invasive species detection and, due to the self-perpetuating nature of invasive species, there is a narrow window of opportunity for success. The larger the population and area it covers, the greater the likelihood that response options will no longer be feasible (Simberloff 2003).

Consistent with the management plan directive, the information presented in this paper reflects the findings of a survey of US government capacity for EDRR implementation (Reaser et al. 2019a and associated supplemental information, this issue), outputs of the Innovation Summit (Conservation X Labs 2017a, b), a review of recent literature on technology advancement for invasive species applications (e.g., Kamenova et al. 2017), and our direct experience working with technology innovators. We focus on emerging technologies and their applications that, if adapted and scaled as needed to specific contexts, could enhance national EDRR capacity.

Although much of the assessment addresses technologies already or soon to be available, we also explore opportunities to improve technological effectiveness and cost-efficiencies. We conclude the paper with key findings relevant to improving EDRR technological capacities with a view toward building national EDRR capacity. The terminology used and the organization of the paper is consistent with the EDRR framework presented by Reaser et al. (2019a, this issue), where technology is defined as the outputs of mental and physical effort, including tools and machines, intended to serve a societal value. Given limited budgets and other constraints, there is a need to use technologies to improve the effectiveness and cost-efficiency of actions taken at any point in the EDRR process. We focus on technological needs and approaches to improving information support, detection, identification, and response options.

## Technology advancement

Investments in technology innovation are demonstrating that seemingly insurmountable invasive species challenges can be overcome with substantial returns on investment. Although the current toolbox for addressing invasive species is incomplete and inadequate in many cases, new technologies are emerging, cross-over applications are being found for existing technologies (hereafter referred to as dual-use technologies), and multi-technology approaches are proving effective for particularly complicated and large-scale problems (Conservation X Labs 2017a).

There are clear opportunities for government leadership in technology innovation. Speakers at the Innovation Summit identified the following as federal agency roles and responsibilities for advancing technologies to improve invasive species prevention, eradication, and control (Conservation X Labs 2017a):

- Communicating the severity of the invasive species issue and the need for technology

innovation to address pressing invasive species challenges.
- Undertaking the scientific research necessary for technology advancement.
- Catalyzing and incentivizing technology innovation and dual-use technology.
- Enabling innovators to reach proof of concept and implement projects on meaningful scales, potentially producing new industries and jobs in the process.
- Creating, advancing, and maintaining the regulatory frameworks necessary for technology development and application.
- Facilitating international cooperation and development assistance, particularly in the areas of information and technology sharing, technology research and application, and the development of relevant legal frameworks.
- Applying technologies to prevent entry, increase detection, improve response to potential invasive species before they have a chance to cause harm, and to eradicate and control those invasive species that have already established.

In the context of EDRR, federal agencies and their partners need to develop or adapt technologies to be applicable in diverse contexts at varying scales while being time efficient and cost-effective. This will require better incentives for technological innovation and building support within broader social and regulatory frameworks. When applying any technology in the context of EDRR, decision makers and invasive species practitioners need to take the following points into consideration: (1) technology development and application is governed by policies and regulations that may foster or hinder EDRR efforts (Burgos-Rodríguez and Burgiel 2019, this issue) and (2) social acceptance ("social license") of technologies changes with time and locality and is necessary for enacting EDRR (Kendal and Ford 2017, 2018; van Putten et al. 2018). Privacy and private property rights are of increasing concern for surveillance (Takahashi 2012; McNeal 2016), while advances in genetic technologies as response measures have raised concerns from the public and professional scientists (http://www.synbiowatch.org/gene-drives, accessed 14 February 2019).

Kamenova et al. (2017) provided a comprehensive overview of traditional and emerging technologies for addressing invasive species. Below we build on this review by highlighting technologies and technological needs that are particularly important to US government agencies, as identified through the Innovation Summit (Conservation X Labs 2017a, b) and our assessment of federal capacities for implementing EDRR. Examples of federal agency initiatives to develop, test, and apply emerging technologies to address invasive species are provided throughout this paper. Some of the most promising opportunities for advancing the federal EDRR toolkit may come from agencies that do not have programs focused on invasive species; technologies originally developed for military, intelligence, and human health applications may have dual-use applications for invasive species detection or response. Further information on these federal roles and associated programs is available in the Innovation Summit reports (Conservation X Labs 2017a, b).

## Information Inputs

Accurate, accessible, up-to-date information is necessary to support every aspect of EDRR. Reaser et al. (2019b, this issue) and Wallace et al. (2019, this issue) broadly focus on federal capacities for information management in the EDRR context. We thus limit our presentation to technologies for enhancing information management.

Referring to the EDRR system outlined in Reaser et al. (2019a), target analysis is a strategic approach to evaluating the likelihood of detecting invasive species at a specific locality and time, using a particular method and/or technologies (Morisette et al. 2019, this issue), and risk screening is the rapid characterization of the types and degree of risks posed by a population of non-native species in a particular spatio-temporal context (Meyers et al. 2019, this issue). Both of these EDRR components draw information from other analytical approaches (e.g., horizon scanning; Sutherland et al. 2011; 2013; Roy et al. 2014b) which benefit from sufficient quantitative data. Thus, there is a substantial need for the increased collection of and access to non-native species data, as well as automated approaches to managing and analyzing big datasets (Reaser et al. 2019b, this issue).

Artificial intelligence (AI) is the ability of machines to acquire and apply information, in contrast to the intellectual capacity of humans and other animals.

Machine learning, an aspect of AI, is a process in which computers can be programmed to apply statistical techniques that enable them to become "self-taught" as they analyze data. This creates a self-improving analytical platform that increases in reliability over time. Machine learning can be used to verify the accuracy of species occurrence data (e.g., identifying data points outside the norm which may be errors), resulting in more cost-efficient data management and accurate information going into decision support tools (e.g., detecting crop pests; Behmann et al. 2015). The Western Governors Association is currently working with Google and other partners to develop an AI-based tool for cleaning non-native species occurrence datasets (B. Whitacre, pers. comm).

Social media, a set of cost-efficient and readily accessible technology platforms, can be used to augment the invasive species biology and occurrence data necessary to inform detection and response strategies. 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 [*Agrilus planipennis*]), as well as a method of assessing 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 and Tang 2017).These datasets could also provide additional geographic granularity for some invasive species.

Because geographic information systems (GIS) have the ability to gather, manage, analyze, and enable visualization of many types of spatio-temporal data, they are now a standard technology for natural resource managers (Wing and Bettinger 2008). In the context of EDRR, they provide a means of mapping species occurrence data in conjunction with a wide variety of environmental parameters (e.g., vegetation, moisture, temperature) so that relationships can be evaluated, and species distribution models developed (Guisan and Thuiller 2005; Gallo and Waitt 2011). In response to our survey of federal needs, the Department of the Interior's (DOI) US Fish and Wildlife Service (USFWS) indicated the need for a GIS database to support EDRR. The database would include multiple layers of information relevant to the detection of invasive species (e.g., biological parameters), as well as relevant information on potential recipient ecosystems (e.g., habitat suitability or disturbance parameters). The DOI National Park Service (NPS) acknowledged a similar need, suggesting that GIS systems have the ability to distribute alerts when invasive species are detected, update maps in a timely manner, and show the distribution of invasive species relative to federal resources (e.g., National Parks) so that surveys can be prioritized.

Complementary to GIS, remote sensing and satellite imagery can contribute to invasive species management. The National Aeronautics and Space Administration (NASA) responded to the survey to highlight how satellite products are used to document invasive species distributions (e.g., via habitat classification and species distribution modelling), spread (e.g., through time-series analysis), and ecology (e.g., distributional associations between species or environment). In addition, satellite products can be used to predict how invasive species will be impacted by future conditions by analyzing current distributional associations with climate or environment variables and applying those relationships to projected future models. Such tools can be combined with high temporal and spatial resolution information from the unmanned aerial vehicles, remotely operated vehicles, and nanosatellites described below.

## Detection and identification

Invasive species may be difficult to detect, especially when first introduced because the founding population size and density are often low or the organisms may be small bodied and/or cryptic, enter landscapes that are complex and/or remote, and be unknown to observers (Morisette et al. 2019, this issue). In this section we provide an overview of technologies that can be used to increase the likelihood and efficiency of invasive species detection, as well as the rate and accuracy of invasive species identification. In the context of EDRR, the ability to detect and identify organisms in a near-simultaneous manner is ideal, although identification should also be considered tentative until confirmed by a taxonomic expert (authoritative identifier). Additional discussion on federal needs for taxonomic capacity, as well as examples of identification technologies are provided in Lyal and Miller (2019, this issue).

## Internet-based detection

Internet commerce (hereafter e-commerce) is a vital part of the US economy that has experienced substantial growth in recent years. A portion of this activity includes the sale and trade of living organisms, some of them are invasive species or organisms associated with invasive species. A number of federal entities have jurisdiction over aspects of e-commerce and, in 2014, the National Invasive Species Council's Invasive Species Advisory Committee (ISAC) recommended these agencies (esp. US Department of Agriculture [USDA], USFWS, and the Department of Homeland Security [DHS]) expand the use of web crawlers to detect invasive species moving through e-commerce (ISAC 2014). A "web crawler" is a program or automated script which "scrapes" the World Wide Web for specific information (based on keywords or codes) in a methodical, automated manner. Suiter and Sferrazza (2007) reported on an Invasive Species Internet Monitoring System (ISIMS) being used by USDA's Animal and Plant Health Inspection Service [APHIS], Plant Protection and Quarantine [PPQ] and the Smuggling, Interdiction and Trade Compliance [SITC] program to search for websites selling regulated insects, weeds, mollusks, fruits and vegetables, and for animals and animal products that have the potential to carry highly pathogenic avian influenza. To the best of our knowledge, ISIMS is now focused on a limited number of plant pests affecting major agricultural commodity crops. Coupling web crawler and machine learning technologies could produce powerful tools for detecting invasive species prior to their potential entry into natural or agricultural environments.

The Internet of Things (IoT) phenomenon refers to the use of internet-connected sensors (visual, chemical, acoustic, and biological) to help 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, Raspberry Pi) are improving and expanding invasive species detection capacities. For example, a Montana-based company, AIS Solutions, is testing a "geo-fencing" technology for more accurate monitoring and tracking of watercraft to prevent the spread of zebra and quagga mussels. The technology includes relatively inexpensive electronics outfitted on recreational watercraft, including a small, waterproof battery, and solar-powered geographic positioning system (GPS) or electronic logging device (ELD). The winning entry in the US Department of State's (DOS) 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.

There are online communities and open innovation sites dedicated to facilitating the merger of AI and big data analytics (e.g., Banerji et al. 2010; Beaumont et al. 2014; Swanson et al. 2016). Crowdsourcing through platforms like eBird (Sullivan et al. 2014) and iNaturalist (Van Horn et al. 2018) can also accelerate the identification of large numbers of complex images (Santana et al. 2014) that may contain invasive species. At the time of writing, iNaturalist has used its global set of identified photos of biodiversity to train computer vision to suggest identifications for more than 24,000 species (C. Seltzer, pers. comm). Because most invasive species originate outside of the United States, incorporation of a global dataset offers clear advantages; species that are common elsewhere in the world may be detected more readily in new areas if they are suggested by the computer vision model. An example of this recently occurred in Ontario where the invasive box tree moth (*Cydalima perspectalis*) appears to have been recorded for the first time in North America (https://www.inaturalist.org/blog/18683-an-invasive-moth-is-recorded-in-ontario-canada-for-the-first-time-observation-of-the-week-9-9-18, accessed 30 October 2019).

## Visual detection

Traditional approaches to the visual detection of invasive species include observation with the naked eye, binoculars, spotting scopes, and microscopes. The effectiveness of these relatively low tech and low-cost approaches could be improved using advanced analytical tools for target analysis (Morisette et al. 2019, this issue). For example, DOI's US Geological Survey (USGS) Fort Collins Science Center (FORT) is optimizing search efforts for the invasive brown tree snake (*Boiga irregularis;* Klein et al. 2015) in Guam by evaluating the pace that transects are searched. Preliminary findings indicate that visual searches walked at a faster pace (1.32 km/h) than current pace (0.44 km/h) yield 63% more snakes per unit time.

There are more than 7.5 billion mobile phone 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. Smartphones are thus enabling real-time linkages between field-based visual observations and internet-based identification, reporting, and mapping. In addition to the iNaturalist program described in the previous section, federal agencies and others are using the Early Detection and Distribution Mapping System (EDDMapS; https://www.eddmaps.org, accessed 30 October 2019) to identify and report the locality of invasive species from the field. For example, the USGS Great Lakes Science Center is developing a *Phragmities* Adaptive Management Framework that includes EDDMapS integration (http://greatlakesphragmites.net/pamf, accessed 30 October 2019).

Advances in the application of light-based technologies are also making some invasive species more readily detectable and identifiable. For example, USGS FORT and the National Wildlife Health Center (NWHC) have developed an ultraviolet light to detect an invasive microscopic fungi (*Pseudogymnoascus destructans*) that causes the devastating white-nose syndrome in hibernating bats. Similarly, the US Environmental Protection Agency (EPA) has worked with various partners to develop approaches to visually distinguish between algae, cyanobacteria, and golden algae (*Prymnesium parvum*). Researchers use a blue fluorescent light (around 480 nm) and green fluorescent light (around 545 nm) to excite organisms and distinguish between algae and cyanobacterial based on the specific autofluorescence of their photosynthetic pigments. The presence of the organism is then confirmed using the Prism and Reflector Imaging Spectroscopy System.

Opportunities for visual detection can also be enhanced through the use of traps, attractants, algorithms, and various sensors. Traditional trapping approaches are discussed later under the Response Technologies section. Here we focus on camera traps, small devices that utilize motion sensors to remotely capture digital images (photo or video) (Swann et al. 2010; Burton et al. 2015). Camera traps work particularly well for detecting large-bodied, mobile, and cryptic species that are otherwise challenging to detect in remote or rough terrain (Linkie et al. 2013; Sollmann et al. 2014). Technological advances in camera trap technology include "smart" capabilities, such as 360 degrees image capture, machine vision (see Martinez et al. 2018), sensors that facilitate automatic object tracking once a species is recognized, and the ability to report species in real-time. Some of these functions already exist in consumer drones and camera traps (Ramsey 2012) and are being applied in federal programs. For example, the USGS is working with Conservation Metrics, Inc. to develop machine vision algorithms from existing camera trap images of brown tree snakes.

With support from the Department of Energy [DOE], Whooshh Innovations has developed a dual-use fish passage technology that employs real time electronic scanning to identify and manually extract invasive fish when they try to pass a fish barrier. The system is trained to distinguish invasive fish from native fish and direct them into separate tubes; native fish pass through the system into spawning groups and invasive fish are removed from the waterway. It's hoped that advances in machine vision will eventually allow full automation of the system (Conservation X Labs 2017b).

### Acoustic detection

Non-native species that vocalize or otherwise make sound (e.g., chewing) can be detected through environmental audio recordings (Servick 2014). Acoustic detection approaches for birds (Dawson and Efford 2009), bats (O'Farrell et al. 1999), and other animals are well-established (e.g., for aquatic animals see Kessel et al. 2014). However, process efficiencies (cost and time) and identification accuracies would likely be improved by applying AI approaches to information management and data analysis (e.g., for AI applied to bird detection see Stowell et al. 2018 and for bat detection see Mac Aodha et al. 2018).

Technology advancements are enabling acoustic detection of organisms that are far less audible to the human ear. For example, the Stevens Institute of

Technology, working with DHS Customs and Border Protection (CBP), has used 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), as well as adult and larval Dermestid beetles (*Trogoderma inclusum*) and mealworms (*Tenebrio molitor*) in rice samples (Flynn et al. 2016). Based on these successes, DHS is developing detection tools for use at ports of entry that include both microwave and acoustic sensors (Flynn et al. 2016).

Mosquito detection is another emerging application of acoustic sensors. For example, a program called HumBug is collecting audio recordings of mosquitos to train machine learning algorithms to identify the 3,600 known species of mosquitos based on sound. The goal is to create a program that will notify users (e.g., via smartphones) about the presence of mosquito species in a user's proximity. Alerts such as these could be incorporated into national EDRR programs to enable the rapid detection of invasive mosquitoes and/or invasive pathogens (e.g., Zika virus) transmitted by mosquito vectors.

Smartphones, which contain microphones and sufficient computational power for acoustic monitoring (Lane et al. 2010), are enabling rapid growth in the population of acoustic detectors. This is particularly true for taxonomic groups (esp. birds) that already garner substantial attention from naturalists and citizen scientists (e.g., bats and loons in Maine; Stockwell and Gallo 2017).

Examples of other federal agency applications of acoustic technologies to detect invasive species include the USGS Great Lakes Science Center (GLSC)'s use of Dual Frequency Identification Sonar (DIDSON) to assess the abundance and migration timing of sea lamprey (*Petromyzon marinus*) and common carp (*Cyprinus carpio*) in Great Lakes tributaries. Collaborators at Central Michigan University are developing an automated data processing program. USGS also operates adaptive resolution imaging sonar (ARIS), the next generation of DIDSON, in wetland and other habitats to characterize fish movement and habitat (http://www.soundmetric.som/products/aris-sonars, accessed 30 October 2019).

## Chemical detection

Dogs can provide a "low-tech" yet sophisticated approach to the chemical detection of invasive species. Initially used to detect scat and other signs of cryptic endangered species (Reindl-Thompson et al. 2006), detector dogs are now accomplishing numerous other conservation tasks, including detection of birds killed by striking windows and other infrastructure (Homan et al. 2001), illegally trafficked animal parts, and invasive species. Not surprisingly, dogs have been used most frequently and successfully to detect invasive mammals, including feral cats (*Felis catus*), nutria (*Myocastor coypus*), and the small Indian mongoose (*Herpestes javanicus*) (Fukuhara et al. 2010; Kendrot 2011; Glen et al. 2016). Detector dogs have also successfully located a variety of other invasive taxa, including Dreissenid mussels (see http://www.musseldogs.info, accessed 30 October 2019), brown tree snakes, Burmese pythons (*Python bivittatus*) (Savidge et al. 2011; Avery et al. 2014), insects (Lin et al. 2011; Lee et al. 2014), and even invasive plants (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 of entry (Vice and Vice 2004).

E-nose devices, engineered biomimics of a dog's nose, are currently used in laboratory settings within the agricultural industry to detect the presence of invasive microbes on crops and other plants, for example (Baietto et al. 2015; Wilson 2013; Jansen et al. 2011; Wilson et al. 2004). There is at least one portable e-nose device on the market (Sensigent's Cyranose e-nose), and a research team at the Swiss Federal Institute of Technology in Zurich (ETH Zurich) is working on a small, low-cost version. Lower 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, at a port of entry) to detect the volatile organic compounds (VOCs) emitted by plants when vegetative tissues are damaged by invasive species (Unsicker et al. 2009).

Advances in nanofabrication (design and manufacture of devices with dimensions measured per nanometer) have permitted the manufacture of highly sensitive nanobiosensors in large volumes at relatively low cost. A nanobiosensor is made of nanomaterials that assess biological interactions and translate the output into a readable form using transduction and electromechanical interpretation (Malik et al. 2013). They can act as accurate chemical sensors (Chikkadi et al. 2012). Nanobiosensors have already been developed for the agricultural and veterinary sectors to detect invasive pathogens (fungal, viral, and bacterial) in crops and animals (Lambe et al. 2016; Handford et al. 2014; Chen and Yada 2011). If networked and scaled, nanobiosensors may be able to detect the VOCs emitted by invasive plants, insects, and pathogens over a large area (Afsharinejad et al. 2016). These and other advances in development may provide tools for detecting a wide range of invasive species at ports of entry or in recipient ecosystems.

USGS GLSC researchers are studying sea lamprey pheromones and alarm cues that could be used in a "push–pull" technique to (1) attract sea lampreys to traps, unsuitable spawning habitat, or areas that can be treated with lampricides and (2) deter sea lampreys from entering areas that have optimal spawning habitat or are difficult to treat with lampricides. USGS FORT scientists are experimenting with novel scents sprayed along transects with the goals of drawing brown tree snakes near to increase detection rates and enable more effective response.

## Genetic detection

Numerous molecular diagnostic tools have been developed in recent years for use in clinical settings, and there has been a push to apply similar tools to invasive species management. In particular, there are opportunities to use genomic tools for invasive species biosurveillance (e.g., for managing forest pests; Bilodeau et al. 2018; Roe et al. 2018). The use of deoxyribonucleic acid (DNA) for invasive species identification is well-established (Lyal and Miller 2019, this issue), but limited in application because relatively few species have been genetically sequenced and profiled in open access information systems, including GenBank, the National Institute of Health (NIH) annotated collection of all publicly available gene sequences (Benson et al. 2013), or the other international databases with which GenBank interfaces (https://www.ncbi.nlm.nih.gov/genbank, accessed 30 October 2019). Examples of current and emerging tools for the genetic-based detection and identification of invasive species follow. Those drawn from the federal agencies indicate that applicable research, information management, and technology advances are scattered across numerous programs, some of which may be duplicative with regard to species and approaches being addressed. There are clear opportunities and needs to provide a unified vision for these efforts, establish standards to make research outputs repeatable and readily comparable, and develop a government-wide repository for genomic information on non-native species. The USFS National Genomics Center for Fish and Wildlife Conservation (https://www.fs.fed.us/research/genomics-center/species-profiles, accessed 30 October 2019) may be appropriate for such a role. Since there are indications that genome size tends to be small for invasive species and measuring genome size is well established and inexpensive (Suda et al. 2014), the repository would ideally facilitate additional analysis of genomic size implications for invasiveness risk by filling data gaps and linking with other relevant information systems (Garcia et al. 2014).

With funding from the USFWS, researchers from Jacksonville State University and King's College London are developing rapid detection protocols and refining molecular techniques for the identification of an invasive freshwater snail, red-rimmed melania (*Melanoides tuberculata*) and associated trematodes using DNA barcoding, a method of using a short genetic marker in an organism's DNA to identify it as belonging to a particular species. Ultimately, they hope to be able to evaluate the genetic relatedness of populations to determine pathways and dispersion patterns. DNA barcoding has also been used to identify invasive wood-boring beetles in solid wood packaging, thus creating an opportunity to improve the rates of invasive species interception at ports of entry (Wu et al. 2017). Armstrong and Ball (2005) discuss the application of DNA barcodes to biosecurity.

Unfortunately, the current approaches to DNA barcoding are costly, require laboratory analysis, and need substantial time and expertise to analyze samples. The development of portable, field-ready DNA sequencing systems could reduce the costs, training, equipment, and time required for barcode analysis. These systems are becoming increasingly feasible, enabled in part by new devices such as the Oxford Nanopore MinION and nextGen Smidgion and by the International DNA Barcode of Life Library database (http://ibol.org, accessed 30 October 2019; Jain et al.

2015). Conservation X Labs is developing a low-cost, modular, battery-powered, field-ready device to extract, amplify, and identify DNA barcodes from biological samples (John 2016). The product would make it feasible to use DNA barcoding as a standard tool for the detection of species for which the relevant genetic information had already been catalogued.

Environmental DNA (eDNA) is the DNA of organisms secreted into the environment via feces, mucus, and gametes (an organism's reproductive cells), as well as through shed cells, skin, hair, and decomposing carcasses (Thomsen and Willerslev 2015). It is readily detectable in soil and water samples and can bypass many of the issues inherent in observing or capturing an organism (Foote et al. 2012; Jerde et al. 2011). The specificity and broad contextual application of eDNA makes the approach attractive as an invasive species detection tool (Hinlo et al. 2018; Kamenova et al. 2017).

Multiple US agencies are funding, developing, testing, and applying eDNA techniques to rapidly detect and identify invasive species. For example, the USFWS Conservation Genetics Laboratory in Anchorage, Alaska has developed a species-specific eDNA assay that is being used to test water samples collected by the Alaska Department of Fish and Game for evidence of northern pike (*Esox lucius*). USFWS Warm Springs, Fish Technology Center is developing and refining eDNA techniques for detection of numerous species, including the crayfish plague agent (*Aphanomyces astaci*), African jewelfish (*Hemichromis bimaculatus*), and Asian swamp eel (*Monopterus albus*). The USFWS has provided funding to the California University of Pennsylvania to develop eDNA protocols for the detection of the rusty crayfish (*Orconectes rusticus*) in lotic streams. As part of the Great Lakes Restoration Initiative (GLRI) the EPA Cincinnati lab is working with The Nature Conservancy and Hawaii Pacific University to evaluate the applicability of incorporating eDNA metabarcoding into detection programs as a taxonomic identification tool for multiple species simultaneously. Work by the NPS suggests that eDNA analysis may improve our ability to detect invasive species earlier in the invasion process than previously feasible.

Advances in the capacity of systems to sequence eDNA rapidly at high volume could radically advance detection-identification-reporting speeds while reducing labor costs (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 point of origin of the DNA (Roussel et al. 2015). eDNA has been detected from fish removed from an ecosystem up to 35 days after elimination (Dunker et al. 2016), which makes the assay's high sensitivity a potential limitation due to sample contamination or the removal (or departure) of the organism from the site prior to testing. Traditional detection methods can, and ideally should, be combined with eDNA for results verification (Kamenova et al. 2017).

Field-based biological assays designed to identify species in a short period of time based on genetic material are also showing promise as scalable technologies for invasive species detection and identification. For example, USGS is creating an assay to detect invasive carp based on eDNA via loop-mediated isothermal amplification (LAMP; https://www.usgs.gov/centers/umesc/science/developing-a-portable-lamp-assay-detecting-grass-and-black-carp, accessed 30 October 2019). Microsoft's Project Premonition (https://www.microsoft.com/en-us/research/project/project-premonition/, accessed 30 October 2019), an effort funded by the Department of Defense's Intelligence Advanced Research Projects Activity (IARPA) program, developed AI-based traps to identify and selectively capture mosquitoes. The next step is to remotely detect pathogens carried by the trapped mosquitoes through gene sequencing.

## Unmanned aerial vehicles and remotely operated vehicles

Unmanned aerial vehicles (UAVs) and underwater remotely operated vehicles (ROVs) can provide cost-efficient detection of some invasive species. They are particularly useful for species that are readily detected by sight (e.g., large bodies, distinctive vegetative patterns) and the search needs to proceed over large areas and/or rough terrain that is difficult for humans to directly access. Despite the regulatory and licensing barriers to deploying drones in the United States (Burgos-Rodríguez and Burgiel 2019, this issue; Werden et al. 2015), they are rapidly becoming standard equipment in conservation toolkits.

UAVs and ROVs can be outfitted to carry a variety of cameras and sensors designed to maximize the likelihood of detection (Harwin and Lucieer 2012).

Some systems are able to collect biological specimens for species analysis. Examples of invasive species detected through the use of drones in combination with image processing include: yellow flag iris (*Iris pseudacorus*; Baron et al. 2018), invasive grasses (*Cenchrus ciliaris* and *Triodia* spp.; Sandino et al. 2018), Burmese pythons (*Python bivittatus;* Gomes 2017), and silk oak trees (*Grevillea robusta*; Strohecker 2017).

Drones can also replace aircraft and other vehicles in carrying advanced sensor packages like a laser-based light detection and ranging system similar to radar, known as LiDAR, which have been used to detect invasive plants (Asner et al. 2008; Barbosa et al. 2016) and fish (TerraDaily 2018). Lightweight LiDAR sensors for drones are either already on the market or under development (e.g., LeddarTech and Luminar). In Florida, the Army Corps of Engineers (USACE) is currently using a NOVA/NOVA Block II UAV system, which can carry 15 lb, cover 750 acres, and take images at a 3.5 cm resolution. Geomatics experts have been engaged to help with auto-classification of the aerial imagery collected from UAVs to automatically identify specific objects of interest. For instance, USACE uses auto-classification algorithms to identify invasive grasses.

Although not as readily controlled over large areas, Do-it-Yourself (DIY) kite or balloon mapping can also provide inexpensive site access and high-resolution sensor transport to support invasive species detection via remote imaging. Public Lab has pioneered the use of kite and balloon mapping and created open source software, MapKnitter, to combine aerial images into a georeferenced mosaic (Delord et al. 2015). Because kite and balloon mapping equipment is inexpensive and readily available to the public citizenry, these approaches could greatly facilitate the detection and reporting of invasive species over large areas of private land. They are well suited for EDRR initiatives led by citizen scientists.

### Nanosatellites

Traditional earth observation satellites are costly (e.g., Landsat 8 cost approximately $900 million), non-adaptable once constructed, and require a decades-long development time. More technologically flexible, low-cost nanosatellites (satellites of low mass and size, usually under 500 kg) may be useful for detecting invasive species via remote-sensing data in situations in which larger satellites are limited by cost, spatial and/or temporal resolution, and orbital parameters, and drones are limited by battery power, payload, and social acceptance (Selva and Krejci 2012; see Table 4 in Martinez et al. 2018). Nanosatellite constellations can leverage the low costs of the satellites and their launch, coupled with a rapid launch cycle, to allow for rapid evolution of the constellation capacity. One company, Planet, operates a constellation of 149 nanosatellites, enabling three-meter-resolution imagery of the Earth every day (https://www.planet.com, accessed 30 October 2019). By comparison, Landsat 8 provides 30 m resolution (15 m panchromatic) of the entire planet every 16 days (Roy et al. 2014a). Nanosatellites also have the capacity to harness the rapid evolution of consumer electronics. EarthNow is developing a constellation of satellites to provide real-time on-demand pictures and video of anywhere on the planet (https://earthnow.com, accessed 30 October 2019).

There are some drawbacks to nanosatellite constellations, including small platform size, lower operational powers, and larger data analysis challenges (e.g., calibrating sensors across many individual satellites, ground truthing, and data integration) (Dash and Ogutu 2016). However, well-calibrated instruments managed by federal agencies, like Landsat and MODIS, 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. Furthermore, NASA's venture class missions, such as Global Ecosystem Dynamics Investigation (GEDI) (https://gedi.umd.edu/, accessed 30 October 2019) and ECOsystem Spaceborne Thermal Radiometer Experiment on Space Station (ECOSTRESS) (https://eospso.nasa.gov/mission-category/13, accessed 30 October 2019) demonstrate quicker and more nimble federal space-borne programs that can bridge between traditional satellite sensors and nanosatellites. EDRR programs should have access to up-to-date, 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).

### Response technologies

In the context of EDRR, response technologies are needed to facilitate the speed at which eradication and containment can be initiated and fully enacted. They are also needed to broaden the response toolkit, enabling effective and cost-efficient responses to species and in localities that have thus far proven too challenging to address with current approaches.

Many of the technologies discussed in the context of invasive species detection can also facilitate invasive species eradication and containment when used individually or in combination. For example, researchers at the University of Alberta used machine learning to analyze the factors that led to success or failure in 143 attempts to eradicate aquatic invasive species and developed a decision tree for responders in the field to guide their choice of response strategy (Xiao et al. 2018). Campbell et al. (2015) predict that drones, in combination with infrared cameras, pre-programmed night flights, bait delivery mechanisms, and AI data processing, will be widely adopted for invasive rodent eradication programs within the next five years (see also Sandino et al. 2018). Below we provide a brief overview of response tools not previously discussed in this paper.

### Mechanical advancements

Federal agencies and their partners are working to improve traditional approaches to the capture, removal, and exclusion (containment) of invasive animals. Goals include increasing system effectiveness, cost-efficiency, portability, and deployment speed, while minimizing impacts on non-target species. For example, USGS researchers have developed and enhanced traps for brown tree snakes, developed traps for Burmese pythons, designed multi-capture traps for tegu lizards (*Salvator merianae*), improved capture rates and efficiency for the sea lamprey, and developed attractants that improve Asian carp net captures. Frequently, this work involves a combination of behavior research, modeling, and engineering. Studies of brown tree snake behavior at traps, combined with analytical modeling using a program known as SLITHER, contributed to advances in trap design and strategy for brown tree snakes (Lardner et al. 2017). The National Oceanic and Atmospheric Administration (NOAA) and two non-profit organizations have supported multi-faceted research on a modified lionfish (*Pterois* spp.) trap that uses a fish-attraction device, allows for deep water control of lionfish, minimizes bycatch, and is easy to transport, deploy, and retrieve. In initial tests, the trap caught more than 75% of the lionfish it attracted during an 18-day "soak time." Further advancements are in progress (Conservation X Labs 2017b; Lieber-Kotz 2017; Yuzvik et al. 2018).

Fencing can be used to create barriers that limit and/or direct invasive species movement to increase capture rates. Fences have long been used to successfully control feral pigs and goats. Recently, lessons learned from that work, aided in the construction and operation of the longest cat-proof fence (five miles) in the United States at Hawaii Volcanoes National Park. It is hoped that the fence will prevent cats from accessing the main nesting area of the federally endangered native seabird 'ua'u, or Hawaiian petrel (Ferracane 2016). Virtual fencing can also be created using various non-physical barriers to animal movement. For example, studies of fish sensitivities to electric fields have enabled the USGS GLSC to employ a stream-wide field of pulsed direct current (electric lead) to guide sea lamprey into an underwater trap, enabling the removal of up to 80% of the animals from free-flowing streams in the Great Lakes Basin.

In the Midwest, the USFWS has innovated a new approach to electro-fishing, a technique developed in the 1930s that delivers underwater electric current that shocks fish (like a stun gun), causing them to float to the surface where they can be readily netted. A specially designed boat—the Magna Carpa—with giant wing-like nets protruding from its sides, cruises large water bodies for Asian carp. Using a higher charge, they can kill and cull the fish. In approximately five minutes, they are able to collect as many as 500 carp, which are later processed into fertilizer (Fronte and Garth 2015).

Robotics, alone or in combination with other technologies, can increase the timeliness and cost-efficiency of various response measures (Cantrell et al. 2017). Robots provide additional labor for long hours in challenging conditions (e.g., underwater, during inclement weather, at night). Researchers at the Queensland University of Technology created the COTSbot (crown-of-thorns starfish robot), an autonomous robot equipped with machine vision, stereoscopic cameras, and a pneumatic injection arm, to identify and kill crown-of-thorns starfish (*Acanthaster planci*) in the Great Barrier Reef. Envirocart created a diver-assisted technology that cleans invasive species and other debris off the hulls of large vessels in the water and is working on a version that does not require human assistance. These innovations suggest that investments in robotic technology could substantially increase rapid response capacities in a wide range of contexts.

Chemical advancements

*Toxicants* Pesticides are one of the most commonly used tools in the invasive species toolkit (Wittenberg and Cock 2001). The need to protect agricultural products has led to the development of numerous toxicants for terrestrial plants and animals, some broad-spectrum, others target-specific. In responding to the federal survey (Reaser 2019, this issue), federal agencies noted that there are substantially fewer pesticides available to address aquatic invasive species and they tend to have substantial shortcomings, including lack of ability to target specific taxonomic groups and the need to apply chemicals throughout the entire water-column, resulting in equal exposures of native and invasive species.

Federal agencies are funding, developing, testing, and applying new toxicants for aquatic invasive species. For example, the USGS Upper Midwest Environmental Research Center (UMESC) is developing a system that allows for targeted delivery of pesticides to kill silver carp (*Hypophthalmichthys molitrix*) and bighead carp (*Hypophthalmichthys nobilis*). They are also experimenting with carbon dioxide as a non-selective deterrent to invasive fish passage and for lethal control. The initial work has demonstrated 100% mortality of silver carp when $CO_2$ is injected under ice. The USGS Columbia Environmental Research Center (CERC) is beginning to develop a piscicide that would affect only black carp (*Mylopharyngodon piceus*); the work takes advantage of the species' unique feeding behavior and properties of the toxicant.

Marrone Bio Innovations' development of Zequanox, the only selective and environmentally compatible molluscicide commercially available for killing zebra (*Dreissena polymorpha*) and quagga mussels (*Dreissena bugensis*), inspired the USGS UMESC to organize an Invasive Mussels Collaborative (IMC; http://invasivemusselscollaborative.net, accessed 30 October 2019), hosted by the Great Lakes Commission. The IMC advances scientifically sound technologies for invasive mussel control. This initiative could serve as a model for managing the development and application of other emerging invasive species technologies.

Federal agencies have also been facilitating rapid advances in treatment technologies for hull fouling over the last decade. The US Coast Guard recently summarized vessel biofouling prevention and management options with an emphasis on technology advancement (US Coast Guard 2015). The current approach to addressing invasive hull fouling organisms is to apply anti-fouling and/or foul-release coatings that disrupt biofilm formation (i.e., attachment capacity). Anti-fouling coatings prevent or deter the settling of biofouling organisms on a surface by the use of leached pesticides, typically cuprous oxide or tributyltin, into the water. The pesticides are either tethered to the coated surface or are released from the surface into the surrounding environment. Foul release coatings present a hydrophobic, low surface energy that minimizes the adhesion of biofouling organisms. Additional work is needed for processes to treat submerged niche areas of ships (e.g., rudders, sea chests) where organisms can find shelter.

Not all of the toxicant advancements have been in the aquatic sector. For example, staff of USDA's National Wildlife Research Center (NWRC) and collaborators have been working together to develop Hog-Gone, a sodium nitrate bait for controlling feral pigs. At high doses, the product reduces the ability of red blood cells to release oxygen to tissues causing organs to fail. Swine are particularly sensitive to sodium nitrate and work is underway to evaluate and minimize non-target effects (Snow et al. 2018).

*Toxicant delivery* Technological advances are also being made to improve the delivery of existing toxicants. For example, the NPS successfully worked with partners to innovate the delivery of toxicants to black rats (*Rattus rattus*) via aerial broadcast on Anacapa Island in Channel Islands National Park (Howald et al. 2010). On nearby Santa Cruz Island, they are working with collaborators to eradicate argentine ants (*Linepithema humile*) using a pesticide delivered in hydrating beads (https://www.nps.gov/chis/learn/management/ants.htm, accessed 30 October 2019).

Researchers from USDA NWRC and their colleagues have been developing various approaches to deploying dead neonatal mice baits treated with acetaminophen, which is toxic to the snakes, to reduce brown tree snake populations in forested sites on Guam. The treated mice are individually attached to four-foot-long paper flag streamers and deployed by hand from helicopters or, in recent experimental trials, by a modified air gun. The streamers entangle the treated mice in vegetation above ground level, where they can be consumed by brown tree snakes and are less likely to be consumed by non-target species. The USDA Wildlife Services staff are also developing a Hog-Hopper bait dispenser that limits delivery of Hog-Gone to feral pigs.

*Signal disruption* Many invasive animals and parasites use chemical signaling to identify food and habitat resources, as well as communicate with others of their species (e.g., to attract mates). Highly targeted pesticides can be used to disrupt these processes. For example, researchers in New Zealand and with the USDA found that the application of multiple types of pheromones led to reproductive failure and the population decline of invasive light brown apple moths (*Epiphyas postvittana*), a significant agricultural pest (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). These findings could be used to develop new signal disrupting pesticides that reduce the risk of mosquito-borne diseases.

## Biocontrol advancements

Biological control (hereafter biocontrol) is the management of invasive species or other pests through the introduction of another organism that will limit its population growth and spread, typically through disease, parasitism, or predation. In 2015, ISAC published a white paper on enhancing the effectiveness of biological control programs targeting invasive species by utilizing integrated pest management, a combination of chemical, biological, and physical control (ISAC 2015). Federal agencies are working on a wide-range of other scientific and technical improvements to traditional biocontrol, much of which is coordinated through the Technical Advisory Group for Biological Control Agents of Weeds (https://www.aphis.usda.gov/aphis/ourfocus/planthealth/import-information/permits/regulated-organism-and-soil-permits/biological-control-organism-permits/sa_tag, accessed 30 October 2019). More specific examples include the USGS Forest and Rangeland Ecosystem Science Center collaborative efforts to test and assess the impact and efficacy of bacteria (ACK55, "black fingers of death") to control cheatgrass (*Bromus tectorum*), as well as USFWS support of Stephen F. Austin State University research on the use of giant salvinia (*Salvinia molesta*) extracts to manage the species, as well as other organisms, with few non-target impacts.

From ecological and human health perspectives, there is a strong interest in eradicating, or at least containing, invasive mosquitoes and the invasive pathogens vectored by mosquitoes. The US Agency for International Development (USAID), through its Zika Grand Challenge, recently funded research into the use the bacterium *Wolbachia pipientis* to combat Zika. *Wolbachia* plagues approximately 60% of insect species worldwide (Hilgenboecker et al. 2008) but doesn't naturally infect the yellow fever mosquito (*Aedes aegypti*). Infecting *A. aegypti* with *Wolbachia* hinders the mosquito's ability to transmit Zika, dengue, and chikungunya to humans; reduces the fertility of the mosquito hosts; and influences the sex ratio of offspring (Aliota et al. 2016; Molloy et al. 2016). Moreover, *A. aegypti* pass the bacteria intergenerationally (Walker et al. 2011; Ye et al. 2015). Verily Life Sciences, LLC created a program called Debug, through which it intends to raise and release sterile male mosquitoes infected with *Wolbachia* to eliminate disease-carrying mosquitoes. The approach is being explored as a tool to manage avian malaria in Hawaii, where the disease has decimated endemic avifauna (LaPointe et al. 2012).

## Genetic advancements

*Genome Engineering and Gene Editing* A modern synthesis of biology and technology has created the entirely new field of synthetic biology, a subdiscipline 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. For example, clustered regularly interspaced short palindromic repeats (CRISPR), CRISPR-associated protein 9 (Cas9) endonuclease, and other molecular tools enable precise genomic editing by allowing scientists to make specific base edits, delete or add a specific gene, and insert a large pieces of DNA at multiple positions within a genome (Cong et al. 2013; Barrangou and Doudna 2016; Rees and Liu 2018). These advances have the potential to create highly efficient tools to eradicate invasive species. ISAC recently reviewed the application of advanced genetic technologies to invasive species prevention and management and made recommendations to NISC for improving policy, research, and advisory frameworks (ISAC 2017).

Mosquitoes are among the first targets of gene editing for invasive species eradication. In Brazil, Oxitec has pioneered a new Friendly™ *A. aegypti* mosquito control approach by placing a self-limiting gene that causes offspring to die, and a marker gene that allows the organism to be monitored, into the *A. aegypti* mosquito. Males, which do not bite or transmit disease, are sorted and released. When a male mates a wild female it passes the self-limiting gene on to all its offspring, which die before reaching adulthood. Unlike other approaches, Friendly™ mosquitoes die along with their offspring, and therefore do not persist in the environment or leave any ecological footprint (Winskill et al. 2015). The technique 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 population growth (Piaggio et al. 2017).

Five efficacy trials showed greater than 90% suppression of *A. aegypti* in the Cayman Islands, Brazil, and Panama. These results compare favorably to conventional mosquito control methods that at best are only able to suppress *A. aegypti* populations by an estimated 30–50%. In Brazil and the Cayman Islands, the Oxitec approach is now in programmatic use, and currently being deployed in areas that cover over 65,000 people, thus demonstrating scalable capabilities for area-wide control of this disease-carrying mosquito. In 2016, Oxitec received a final finding of no significant impact and final environmental assessment from the US Food and Drug Administration (FDA) for an investigational trial in the Florida Keys. The FDA team, which consisted of experts from the Center for Veterinary Medicine (CVM), the Centers for Disease Control and Prevention (CDC), and the EPA, concluded that the reared mosquitoes will have no significant impact on human health, animal health, or the environment (Conservation X Labs 2017b). This approach is also being explored as an option for addressing avian malaria in Hawaii (Piaggio et al. 2017). While a promising technology, a recent study of the Oxitec release program in Jacobina, Brazil, detected portions of the transgenic mosquito strain's genome in the target mosquito population, which suggests the critical need for genetic monitoring programs to work in tandem with such releases (Evans et al. 2019).

*Gene silencing* USGS GLSC and partners are exploring the use of gene silencing as a means of managing *Phragmites australis* at a land-scape scale (https://www.usgs.gov/centers/glri/science/invasive-phragmites-science, accessed 30 October 2019). The genetic approach is seeking a species-specific control option for managers, which could be useful in sensitive areas or areas where conventional control efforts are not practical. RNA-based gene selecting disrupts the transmission of genetic information necessary for protein synthesis and train development. Thus, for example, if genes essential for photosynthesis are silenced, a plant will fail to produce energy for itself.

Ribonucleic acid interference (RNAi). RNAi is a biological process in which RNA molecules inhibit gene expression or translation by neutralizing targeted messenger RNA molecules through an increase or decrease in their activity. In the wild, this approach may protect species against viruses that insert parasitic nucleotide sequences. This approach has been used as a potential cure for cancer (Titze-de-Almeida et al. 2017) and in agriculture (Zotti et al. 2018). It may also be applicable for invasive species as a highly precise (taxa specific), efficient, and stable biopesticide, using prey species as vectors for transmission. Vertebrates may also digest RNA nanoparticles, which may serve as a delivery vehicle (Campbell et al. 2015).

*Gene drives* A gene drive is a naturally occurring mechanism that promotes the inheritance of a particular gene to increase its prevalence in a population (Burt 2003). In theory, gene drives could be used to push deleterious traits into an invasive population, thereby reducing the population's overall fitness (Esvelt et al. 2014). For example, it may be feasible to use the "sex ratio distortion" drive (Galizi et al. 2014; Hammond et al. 2016), which results in fertile offspring of only one sex, to be used to eradicate populations of invasive species by “breeding that population out of existence” (Piaggo et al. 2017). Scientists are also exploring gene drives to ameliorate insect- and animal-borne pathogens (Esvelt and Buchthal 2016; Esvelt et al. 2014; Sinkins and Gould 2006), eradicate invasive rodents in the island context (Campbell et al. 2015), and address a range of other species including cane toads (*Rhinella marina*), feral cats (*Felis catus*), and invasive mussels (Moro et al. 2018). The latter work is being conducted through a partnership that includes USDA scientists and is being partially funded by DOD’s Defense Advanced Research Projects Agency (DARPA).

Moro et al. (2018), Piaggio et al. (2017), and the National Academies of Sciences, Engineering, and Medicine (2016), among others, have explored issues with gene drive application, including the potential for gene transfer between modified individuals and related taxa, public opposition, and unanticipated ecosystem effects following successful eradication. 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. 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 limit the transfer of modified genes (Esvelt et al. 2014). However, recent mathematical models suggest that gene drives are best suited to applications where the impact is intended to affect *all* wild populations of the target species, like in malaria prevention (Noble et al. 2018). DARPA’s Safe Genes program is supporting advances in synthetic biology, as well as approaches to mitigate the risk of unintentional consequences or intentional misuse of these technologies (https://www.darpa.mil/program/safe-genes, accessed 30 October 2019).

## Fostering innovation

Although invasive species are having a substantial impact on highly valued assets and addressing the problem is fraught with challenges, those of us intent on solving the problem need to move away from a focus on “doom and gloom” and towards a perspective of optimism and innovation. Invasion biology, as a field, could benefit by becoming more solutions-oriented, open to novel ideas, engaging partners from other disciplines, and inviting new perspectives and models for technical application.

Federal agencies have important roles in incentivizing technology development and application. Attracting new solvers and potential paths forward is a critical element for stimulating the innovation pipeline. Prizes and challenges can bring in new solvers from new disciplines and are pay-for-performance mechanisms that do not prejudge the solution or influence the potential solution range. Mass collaboration, co-creation, and open source approaches also serve to encourage collaboration across non-traditional disciplines. This may include crowdsourcing data to increase the leverage of public sector actions. Expanding citizen science initiatives and public–private partnerships provide additional opportunities to call in and engage new solvers and solutions.

### Open source mass collaboration

Greater degrees of global connectivity have created a new paradigm of open source science, which is transforming how scientific discoveries are made and technological solutions are created. Open source approaches can help develop and/or source new ideas or products, distribute the burden for collecting and analyzing data, co-design new solutions, and share in the burdens of research, publication, and funding, while simultaneously engaging the public. Such innovation is useful for soliciting expertise and applications from other fields. Open innovation through mass collaboration, especially when combined with prizes and challenges, can transform how problems are solved by sourcing solutions from various disciplines around the world. 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 Creating Opportunities to Meaningfully Promote Excellence in Technology, Education, and Science Act (COMPETES), federal agencies can offer prizes and conduct competitions to encourage innovation, seek solutions to tough problems, and advance an agency’s core mission. Since the COMPETES Act was signed, the US 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 technologies to enhance EDRR capacities.

One example of a successful open mass collaboration is Open Source Drug Discovery (OSDD) (http://www.osdd.net/, accessed 30 October 2019), which used open mass collaboration to develop new drugs for neglected tropical diseases and made the resulting drug formulations 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.

Ideation, hackathons, and crisis mapping

Ideation events, hackathons, and crisis mapping are collaborative techniques to encourage interdisciplinary collaboration and innovation. Ideation events bring people together, usually from a range of disciplines, to innovate new solutions to societal problems. Conservation X Labs and the NISC Secretariat recently collaborated in multiple ideation events to harness new thinking for invasive species problem resolution. Teams at the 2017 Make for the Planet event hosted at the Smithsonian Institution's Earth Optimism Summit (https://www.makefortheplanet.com/home, accessed 30October 2019) generated ideas to detect invasive species in logistically-challenging landscapes, for example. At the 2018 Big Think for Water Conservation, participants proposed solutions to addressing aquatic invasive vegetation (https://conservationxlabs.com/water-challenge, accessed 30 October 2019).

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 context, hackathons can help engineer solutions to problems where, for example, there are large data sets or the need to create decision support systems. In 2017, NASA hosted Space Apps hackathon that included a tool for tracking invasive species in your neighborhood over time (https://2017.spaceappschallenge.org/challenges/our-ecological-neighborhood/trace-invaders/details, accessed 30 October 2019).

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). 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). Extreme weather events can spread invasive species into new water bodies through flooding and/or as hitchhikers on floating debris. USGS scientists have created online "storm tracker" maps to project the potential spread of non-native aquatic plant and animal species as a result of hurricane activity (Neilson et al. 2018).

Prizes and challenges

Prizes and challenges are competitive performance-based mechanisms that can draw upon novel disciplines, harness innovations from adjacent sectors, and attract innovators with the intent of inspiring new solutions to substantial problems. Prizes and challenges can "crowdsource" new solutions with the recognition that breakthroughs may not come from expected disciplines or institutions. A prize focuses on a single breakthrough, while a challenge helps create new communities of solutions and practice. Prizes and challenges focus on defining the issue and its constraints, rather than directing participants to a specific solution. Accordingly, such open innovation mechanisms can be much more efficient than traditional grants as they 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 inspire problem solvers to invest their expertise in developing a specific breakthrough. In contrast to a prize, a challenge provides grants or equity investments to multiple winners that meet the terms of the challenge.

The US Agency for International Development (USAID) started a Grand Challenges initiative through its Global Development Lab (https://www.usaid.gov/GlobalDevLab, accessed 30 October 2019) in an effort to catalyze solutions to sustainable development problems, which could include a wide range of invasive species impacts (e.g., food and water security, human health, human conflict). They have successfully used open innovation for responses to Ebola and Zika outbreaks.

The DOI Bureau of Reclamation has used prizes to inspire solutions to invasive quagga and zebra mussels (https://www.usbr.gov/mussels, accessed 30 October 2019), while the DOI Office of Native Hawaiian Relations sponsored a prize for technologies to detect and cure Rapid Ohi'a Death (https://conservationx.com/challenge/invasives/ohia, accessed 30 October 2019). Federal government challenges are posted on the Challenge.gov website (https://challenge.gov, accessed 30 October 2019).

The state of Michigan recently concluded the Great Lakes Invasive Carp Challenge (https://www.michigan.gov/dnr/0,4570,7-350-84430_84439—,00.html, accessed 30 October 2019) to source solutions that will stop invasive carp from reaching the Great Lakes. One of the winning ideas, "Cavitation Barrier to Deter Asian Carp," involves specially designed propellers that generate a wall of cavitation bubbles, which implode and cause high-speed jets of water to repel and prevent fish passage beyond the bubble barrier.

Recently, Conservation X Labs and the NISC Secretariat collaborated in the development of the Digital Makerspace (https://conservationx.com, accessed 30 October 2019) an online platform for community-based ideation, challenges, and prizes. The platform was launched in 2018 during National Invasive Species Awareness Week with a focus on three invasive species challenges: detection technologies for the chytrid fungi impacting amphibians worldwide (https://conservationx.com/challenge/invasives/chytrid, accessed 30 October 2019), detection technologies and a cure for the chytrid fungus attacking ohia trees in Hawaii (see above), and the detection of rodents on remote islands post eradication efforts (https://conservationx.com/challenge/invasives/zero, accessed 30 October 2019). The platform remains open to additional invasive species challenges and prizes.

## Making innovation applicable

### Taking technology to market and scale

Establishing a strategy for marketing and scaling up the application of a technology is just as important as the innovation itself. Scale and market sustainability as part of the core innovation design process is critical to achieving the greatest impact. Federal agencies are also contributing critical leadership roles in this regard.

The National Science Foundation's (NSF) Innovation Corps (I-Corps) program (https://www.nsf.gov/news/special_reports/i-corps/, accessed 30 October 2019) helps researchers translate discoveries into technologies and products with near-term benefits for the economy and society, and in the long term, into commercial enterprises. The program teaches NSF grantees to identify valuable product opportunities that can emerge from academic research and offers entrepreneurship training to participants.

The I-Corps program applies the scientific method to entrepreneurship by encouraging researchers to test their hypotheses about demand. In this process, it is critical for researchers, such as the creators of artificial coral reefs, to get out of their technical area of practice to determine whether there is broader market demand for a product, and if not, how a "product" should be redesigned in the face of that evidence. Although we are not aware of specific examples in the invasive species field to date, the potential certainly exists for the support of invasive species innovations emerging through the NSF granting and I-Corps programs.

Small businesses can be nimble catalysts for change and can commercialize solutions, and entrepreneurs need financing to capitalize on high-risk/high-reward approaches. The government has a role to play to incentivize innovation, which can help draw experts from other disciplines. Different types of supporting resources (e.g., mentorship networks) and forms of capital (e.g., intellectual, social, financial) can be offered to entrepreneurs, but strong motivators, such as love, pride, and fear are also important drivers.

The US Small Business Innovation Research (SBIR) program (https://www.sbir.gov, accessed 30 October 2019) is a highly competitive program that encourages domestic, small businesses to engage in research and development that have the potential for commercialization. Through a competitive awards-based program, SBIR enables small businesses to explore their technological potential and provides incentives to profit from commercialization. By including qualified small businesses in the nation's research and development arena, high-tech innovation is stimulated, and the US reinforces an entrepreneurial spirit as it meets specific research and development needs. Such programs are useful for taking research out of the lab and turning it into tangible products and services that are the basis for scalable enterprises.

A key lesson learned from experiences with the SBIR program is the importance of connecting a problem to an economic opportunity (e.g., an invasive species grand challenge) in order to create a demand for new innovation. In this regard, government agencies need to consider how they use these tools and levers to build private sector opportunities.

### Advancing regulatory frameworks

Federal rulemaking can have a profound influence on technology development and application; the nature of that influence can either facilitate or limit effective outcomes. Although many view federal regulations as suppressing commercialization or undermining innovation, the federal government's goal is to increase predictability for technology development and ensure public safety. Contrary to popular belief, the US government does not regulate technologies or processes (i.e., gene editing), rather it regulates products. New regulatory challenges are arising with the advent of new technologies (esp. biotechnologies) that do not fall clearly into existing areas of an agency's responsibility, or that cut across multiple agencies (ISAC 2017). In the case of advanced biotechnology applications for invasive species, the Coordinated Framework for the Products of Biotechnology provides an iterative mechanism for the relevant regulatory agencies to coordinate on how to address present and future technologies (Office of Science and Technology Policy 2016a, b; National Academies of Sciences, Engineering and Medicine 2017). Burgos-Rodriquez and Burgiel (2019, this issue) provide a broad overview of legal and policy matters influencing EDRR in the US context.

### Summary of needs and conclusion

Through the Innovation Summit and survey of federal capacities for applying technologies to EDRR federal agencies have identified a wide range of opportunities to advance technological innovation for and application to the invasive species issue. The Innovation Summit report includes a summary of actions needed to advance technologies for the prevention, eradication, and control of invasive species more broadly (Conservation X Labs 2017a). Below we provide an overview of the primary needs identified by the federal agencies to further their ability to increase technology effectiveness and cost-efficiency in the EDRR context. See Reaser (2019, this issue) for these recommendations in the context of a comprehensive blueprint for a national EDRR program.

1. Increase and modernize research facilities. Federal agencies need adequate facilities to conduct the research necessary to develop and test new technological solutions. This includes facilities for improving understanding of animal biology and behavior (e.g., what kind of bait they will eat, how they behave around certain traps), as well as sophisticated biosafety laboratories for handling risky organisms (e.g., pathogens) or toxins. Facilities need to enable operations consistent with changing regulations, new approaches, and study replication. Region-based facilities would enable prioritization of work on specific species of particular concern at that locality and thus foster greater opportunities for partnerships with other institutions with similar concerns.
2. Expand staff capacities. Federal agencies need a workforce of innovators that includes staff with particular expertise in emerging fields of application to the invasive species issue, especially genetics, engineering, and bioinformatics. Detailing staff between agencies (e.g., DOD intelligence or military technology staff to CBP or USGS) could substantially increase opportunities for identifying dual-use technologies that could meet federal needs with little additional investment. Research partnerships with non-federal institutions, particularly with the private sector or academia, could also increase the workforce focused on finding solutions to specific invasive species problems.

3. Improve information infrastructure. Federal agencies routinely cite limits in the availability of data and decision support tools as barriers to effectively addressing invasive species. Reaser et al. (2019b, this issue) and Wallace et al. (2019, this issue) broadly address information needs in the EDRR context as part of this Special Issue. In the context of technology advancement, agencies emphasized the need for:

   a. Genetic libraries (DNA fingerprinting) to enable identification tool development and cell lines of current and potential invaders to allow in vitro screening of potential control agents. Ideally, agencies would collaborate within the United States and with international partners in the development and operation of a functional genomics and metabolomics database of current and potential invaders;
   b. Biological data that will enable agencies to target technologies for use on specific invasive species in a wide-range of contexts with minimal impact on non-target organisms;
   c. Data on non-native species being imported into the United States and/or otherwise moving through US trade to enable horizon scanning and pathway analyses; and
   d. Spatial analysis data that are web-accessible, can be coupled with other datasets (e.g., species occurrence, pathways, biology), and are accessible by non-federal collaborators.

4. Advance priority technologies. Federal agencies identified the following technologies as needing greater support from financial, institutional, and/or regulatory perspectives:

   a. Surveillance technologies (from sonar to satellites) that will greatly facilitate non-native species detection at points of entry and in logistically challenging situations (e.g., underwater, in remote locations, at night);
   b. Identification tools, particularly devices that can be field-employed and allow for immediate recording of locality, data logging, and reporting to authoritative identifiers;
   c. Response tools that will be effective, socially acceptable, and cost-efficient, with an emphasis on increasing research and regulation to facilitate the use of genetic-based technologies and other alternatives to traditional pesticides that can be used in logistically challenging contexts. Partnerships among agencies and with non-federal institutions may be necessary to address registration and other regulatory requirements in a timely manner; and
   d. Drone technology enabling broad detection and response application on federal lands and lands managed by federal partners.

5. Use prizes and challenges to complement more traditional grants and agreements. Although some federal agencies are already employing prizes and challenges to encourage solutions to invasive species challenges that are undermining their mission capacity and endangering the assets they manage, there are substantial opportunities for expanding these programs more broadly across the federal government and providing resources to scale solutions.
6. Foster a thriving culture of innovation and community of practice. The Innovation Summit and Digital Makerspace, both responses to *2016–2018 NISC Management Plan* (NISC 2016) priorities, are platforms for fostering a community of solvers within and among federal agencies, as well as with federal partners. The expansion of these initiatives is needed, as well as a forum for ongoing interagency dialogue between federal agency staff faced with invasive species challenges and the government research and development experts who have problem-solving expertise (esp. in the fields of intelligence, engineering, and genetics).

Investments in technological innovation are rapidly advancing our ability to prevent, eradicate, and control invasive species. There is renewed hope that we can overcome the invasive species challenges that have thus far seemed insurmountable. The application of emerging and dual-use technologies can represent a long-term cost-savings compared to the existing, often inefficient and ineffective, practices currently in the invasive species toolbox. Prioritizing technology innovation can have substantial payoffs—potentially saving millions of dollars in costs posed by a single species. Federal agencies and their partners have a clear role in identifying challenges and opportunities, inspiring innovation, expand investment, and reducing barriers to the development and application of possible solutions.

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REVIEW

# Capacity of United States federal government and its partners to rapidly and accurately report the identity (taxonomy) of non-native organisms intercepted in early detection programs

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**Abstract** The early detection of and rapid response to invasive species (EDRR) depends on accurate and rapid identification of non-native species. The *2016–2018 National Invasive Species Council Management Plan* called for an assessment of US government (federal) capacity to report on the identity of non-native organisms intercepted through early detection programs. This paper serves as the response to that action item. Here we summarize survey-based findings and make recommendations for improving the federal government's capacity to identify non-native species authoritatively in a timely manner. We conclude with recommendations to improve accurate identification within the context of EDRR by increasing coordination, maintaining taxonomic expertise, creating an identification tools clearinghouse, developing and using taxonomic standards for naming and identification protocols, expanding the content of DNA and DNA Barcode libraries, ensuring long-term sustainability of biological collections, and engaging and empowering citizens and citizen science groups.

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**Keywords** Biosecurity · Diagnostics · Early detection and rapid response (EDRR) · Identification · Invasive species · Pests · Taxonomy

## Introduction

The United States government defines invasive species as, "with regard to a particular ecosystem, a non-native organism whose introduction causes, or is likely to cause, economic or environmental harm, or harm to human, animal, or plant health" and recognizes invasive species as a growing threat to a wide range of national values, including food and water security, infrastructure, and the environment, as well as plant, animal, and human health (Executive Office of the President 2016). The costs of these impacts to the US economy are already estimated in the tens to hundreds of billions of dollars per year and are expected to rise as new species are introduced and already established species continue to spread (Epanchin-Niell 2017; Pimentel et al. 2005). The implications are global; invasive species already in the United States pose risks to neighboring countries and trade partners (Paini et al. 2016; Reaser et al. 2003).

Minimizing invasive species impacts requires projecting and documenting non-native species occurrence (Reaser et al. 2019a, this issue), risk screening (Meyers et al. 2019, this issue), and timely and effective management responses. Reaser et al. (2019a, this issue) provide a systematic framework for the early detection of and rapid response to invasive species (EDRR), defining it as a guiding principle for minimizing the impact of invasive species in an expedited yet effective and cost-efficient manner, where detection is the process of observing and documenting an invasive species, and response is the process of reacting to the detection once the organism has been authoritatively identified and response options assessed. We adopt this approach and provide this paper as a component of the assessment of US capacities for enacting EDRR described by Reaser et al. (2019a, this issue). Here, we explicitly respond to the *2016–2018 National Invasive Species Council (NISC) Management Plan* directive to assess "the capacity of the federal government and its partners to rapidly and accurately report the identity (taxonomy) of non-native organisms intercepted in early detection programs" (NISC 2016). Our findings are drawn from responses to a survey distributed to the federal agencies (Reaser 2019a, this issue), online research, interviews with agency staff, government reports, and peer-reviewed literature. Throughout the paper, we provide recommendations to improve taxonomic capacity for EDRR applications.

## Assessment findings

Although there has been a culture of interagency support in the taxonomic identification of species and new technologies are speeding up taxonomic identification and making the overall process more cost-efficient, the federal government's capacity to identify non-native species in a timely and accurate manner needs substantial improvement. A complex set of federal, state, and other entities provide, or can potentially provide, taxonomic support for identifying invasive species and creating identification technologies, but discovering the identities and capacity of these entities is challenging. Many are collaborating at some level, but few clear Identification Process Chains (IPC; see below) exist, and some correspondents had problems locating these for reference. Developing a sustainable taxonomic/identification system to support a national EDRR program requires simplification, streamlining, greater collaboration, clarity on available capacity, and flexibility to adapt to changing pressures. Above all, it needs to provide relevant identification as soon as possible after the detection to enable proper reporting and appropriate responses, thus playing a critical role in the comprehensive EDRR framework described by Reaser et al. (2019a, this issue).

### The importance of identification and taxonomy for invasive species management

The importance of taxonomic support for invasive species identification has been emphasized globally (Davis Declaration 2001; Smith et al. 2008; Pyšek et al. 2013; Commission on Genetic Resources for Food and Agriculture 2019) and nationally (Meyerson and Reaser 2003; Chitwood et al. 2008; Diaz-Soltero and Rossman 2011; Buffington et al. 2018a, b). A general concern, also raised by federal agencies and individuals contacted in this study, is the diminishing availability of taxonomic expertise, arising from a decreasing number of scientists and changing priorities of laboratories (Meyerson and Reaser 2003; Stack et al. 2006).

The importance of correct, rapidly delivered identification cannot be overstated. The provision of a (scientific) name for an organism suspected to be invasive allows:

- clarity whether the organism is likely to be non-native;
- access to biological, ecological, pathway, and management information;
- determination of any county, state, or federally prescribed actions;
- unequivocal communication between stakeholders.

For example, in 2002 the "Rasberry crazy ant" (*Nylanderia fulva*) was reported in Houston, Texas. This proved to be very difficult to identify. Even getting specimens to taxonomists sufficiently expert in the group took too long. Identification was not confirmed until 2012 (Gotzek et al. 2012), by which time the species had spread considerably and caused massive damage.

#### *Key scenarios requiring identifications*

The circumstances in which a potential invasive species is detected have important implications for the problems faced in its identification and the personnel engaged in the Identification Process Chain (IPC; see below), and thus capacity requirements. Two non-exclusive axes can be used to explore this matter (Fig. 1).

*Axis 1: Targeted cf. General inspections*. Targeted inspections and monitoring activities focus on one or a few key species (e.g., Asian hornet [*Vespa velutina*] in the United Kingdom [Gov.uk 2017]). General inspections, such as BioBlitzes (Silvertown 2009; Looney et al. 2016; Doing it Together Science 2017), will expose the inspection team to a very large number of species, which may or may not be actually or potentially invasive.

*Axis 2: Pathway cf. Site inspections*. Pathway inspections screen for actual or potential invasive species in the context of a pathway (e.g., solid wood packaging at Ports of Entry [PoE], trailered boats through state-line inspections; see Liebhold et al. 2006, 2012; Jenkins et al. 2014) and site inspections survey the area within a larger recipient ecosystem where invasive species might be detected (e.g., National Parks, agricultural extension).

The two axes operate together, for example targeted inspections are most effectively carried out as a result of risk assessments that highlight particular pathways (European Environment Agency 2010; Poland and Rassati 2019). A strategic framework for surveillance

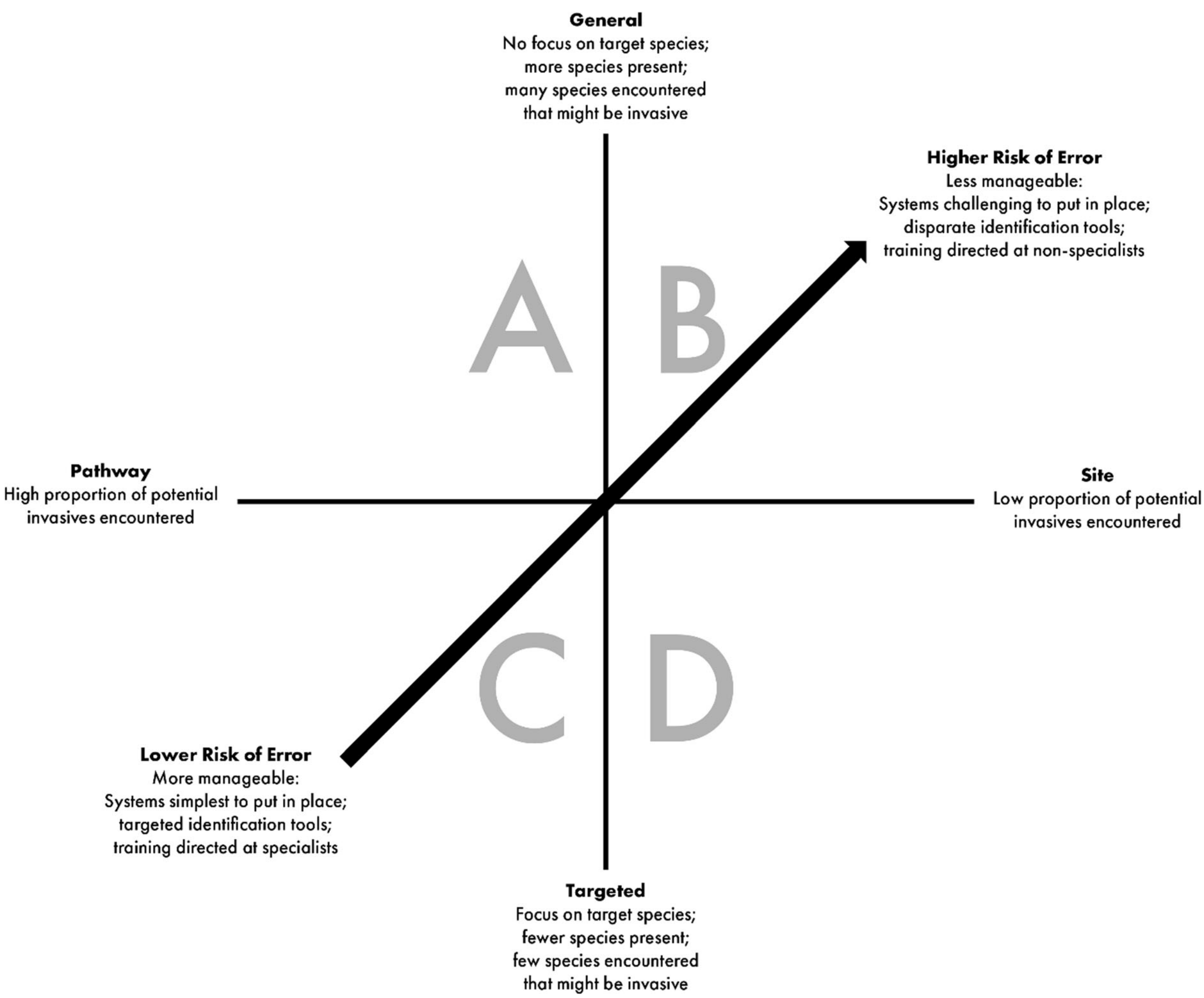


**Fig. 1** Identification scenarios. The greatest management challenges and highest risk of error are in the top right, the most sustainable management possibilities in the bottom left. The background letters are for reference in the text

can consider the nuances and caveats for PoE vs recipient ecosystems (Morisette et al. 2019, this issue).

*Targeted species (Fig. 1 quadrants C and D)*

Targeted species inspections are most likely to feature a relatively high proportion of target to non-target observations (non-invasive species that might be confused with invasive species), many repeat observations, a geographically fixed base, and long-term staff or citizen science engagement. These allow focused identification technologies; staff training and expertise build-up in the use of sampling equipment and identification technologies; sensitization to target species; strong, formalized and short Identification Process Chains with high potential for rapid response; and minimized risk of error. For example, the US Fish and Wildlife Service (USFWS) uses eDNA to detect invasive carp in the Great Lakes (Jerde et al. 2013; Mahon et al. 2013; falling in quadrant D), and the federal and state agencies have collaboratively developed methods to detect brown tree snakes at points of entries (Clark et al. 2018; falling in quadrant C).

*Pathway inspections (Fig. 1 quadrants A and C)*

PoE Pathway inspections feature trained staff and rapid IPCs, either through local Plant Inspection Stations (US Department of Agriculture 2017a), or through US Department of Agriculture's (USDA) Animal and Plant Health Inspection Service (APHIS) National Identification Service (APHIS 2015), Centers for Disease Control and Prevention (CDC 2013), or USFWS (USFWS Office of Law Enforcement 2017). US Customs and Border Protection (CBP) Agriculture Specialists are trained to identify pests and diseases, but their preliminary identification has to be confirmed by a USDA entomologist or plant pathologist. APHIS has a rapid (24 h) identification system in place (at least where taxon specialists are available). CBP Agriculture Specialists and others at PoE are supported by specialist identification technologies (USFWS 2010; APHIS 2017a).

State Line Pathway inspections are particularly important for states with significant agricultural industries such as California and Florida, where inspection agents can send interceptions or photographs to taxonomists in a formal system (California Department of Food and Agriculture 2018a). A special case is watercraft inspections, where detection of biological material alone may suffice to require decontamination and individual organisms may not need to be identified.

*General and site inspections (Fig. 1 quadrant B)*

General and site inspections pose the most challenging model for capacity. Often they are handled regionally, with variable integration between regions (e.g., USDA's National Institute of Food and Agriculture [NIFA]'s Crop Protection and Pest Management Program (CPPM) [NIFA n.d.], USFWS regions), or between sites (e.g., DOD lands, National Park Service [NPS]). DOD manages invasive species under local Integrated Natural Resources Management Plans (INRMP) liaising with the USFWS, but with no national coordination. The number of possible species and the larger areas involved pose a problem. Allen et al. (2009) report 3756 different non-native plants in US National Parks with a maximum of 483 non-native species from one park, and more than 120 National Parks contain 50 or more non-native species (Stohlgren et al. 2013). Agriculture is perhaps better served than natural areas, with the APHIS Cooperative Agricultural Pest Survey (CAPS) Program (NIFA n.d.), which carries out national and state surveys targeted at specific exotic plant pests, diseases, and weeds identified as threats to US agriculture and/or the environment, much of which operates at the state level through the Cooperative Extension System (CES).

General and site inspections are likely to feature an unknown and potentially large number of target species, a relatively low proportion of target to non-target observations; few repeat observations; intermittent inspections without a fixed base for staff; and short-term observer engagement with involvement of amateur and ad-hoc observations. These lead to employment of many identification technologies of mixed quality; fewer opportunities for staff training and building expertise; weak or ad-hoc IPCs; and higher risk of not identifying potential invasive species at low density. Rapidity in the flow of information is also more challenging. Strategic efforts on target analysis and detection (Morisette et al. 2019, this issue; Reaser et al. 2019a, this issue) can help address these challenges, but equally important is investing in proper taxonomic identification.

## Building a sustainable taxonomic resource to support EDRR

A sustainable taxonomic resource includes capacity both of people and the resources they use (Table 1). Crucially, all elements must be present and available; lack of taxonomists removes the most authoritative layer and precludes identifying many interceptions, while loss of citizen science input may make general site surveys impossible. Taxonomists and other identifiers require collections and identification technologies, and all stakeholders must have access to the same lists of species names. Not only must all of these elements be present, but the personnel (and those detecting possible invasive species and seeking identifications) must be efficiently connected through an IPC. Different aspects of a sustainable taxonomic resource may be preeminent in EDRR activities in different quadrants of Fig. 1, but the whole structure is required for any of it to be fully operational. For such a system to function there has to be some oversight and responsibility for maintenance, or at least a central resource or portal where information and contacts can be shared. This should be a facet of whatever coordination mechanism is implemented for any national EDRR framework.

This taxonomic resource capacity cannot exist in isolation, and it will operate in response to its users' requirements. Federal bodies and users of invasive species identification expertise or technologies should therefore consider their requirements and how they are met, and ask themselves:

1. Is the current expertise supply sufficient and subject to management? (Any expertise based on retired specialists or being provided on an ad hoc basis is not within the management capacity of the body.)
2. Are high-risk groups of organisms of key importance covered taxonomically (see Reaser et al. 2019b, this issue)?
3. Where will expertise and supply of identification technologies (see Martinez et al. 2019, this issue) come from in 5 years' time? (Taxonomists take time to train and recruit, and a succession plan is needed to ensure that at least high-priority groups are covered).

### Identification process chains

In the context of EDRR three key stages can be considered as forming an Identification Process Chain (IPC): detection (interception, screening, collection, etc.), identification, and reporting (receipt of identification by the management authority) (Fig. 2). Table 2 gives recommendations to establish and improve IPCs. The IPC described here provides additional details among the detection, identification, and reporting components of the EDRR framework from Reaser et al. (2019a, this issue).

Failure to have an authoritative IPC can have serious consequences, as with a case of *Drosophila suzukii*, the spotted wing *Drosophila.* Here, following an incomplete identification from local experts, a farm advisor used a web search engine to locate an expert. Unfortunately this person was not a taxonomist and the identification was incorrect, hindering response (Hauser et al. 2009; Hauser 2011). The IPC should be rapid and effective (Stack et al. 2006). It should be managed so that both specimens and necessary information are transmitted along it and all individuals know procedures to follow and the priority of the submission. The more complex the chain the longer the identification process (Smith et al. 2008), the greater the chance for miscommunication, and the less it is fit for EDRR.

IPCs differ between agencies and even different regions or staff within a single agency, and they may not be formalized or widely understood. Almost every agency responding to the NISC survey, and many individuals contacted, called for stronger linkages between those intercepting possible invasive species and sources of taxonomic expertise. Members of established networks, such as the National Plant Diagnostic Network (NPDN; Stack et al. 2006; https://www.npdn.org, accessed 12 March 2019), National Animal Health Laboratory Network (APHIS 2017b), and the Wildlife Health Information Sharing Partnership event reporting system (WHISPers) may, through their interactions, facilitate a sample reaching the appropriate expertise. However, unless this is built into a formal system of sample transfer, the potential of network membership may not be fully realized. Collaboration is an important component of invasive species management (Davis Declaration 2001) including EDRR, and may facilitate locating expertise. Collaboration between CBP, USDA, CDC and

**Table 1** Actors, their roles, and the resources necessary for the actors to carry out their tasks in a sustainable taxonomic framework

| Actors | Roles | | | | Key resources used | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Research—establishing species concepts; correct names to use | Generating identification technologies | Identifications | Compiling authoritative lists of names | Collections | Laboratories, including DNA | Lists of names | Identification technologies | Other literature resources |
| Further detail provided in Tables below | | Table 2 | | | Table 5<br>Table 7 | | Table 8 | Table 6<br>Table 7 | |
| Taxonomists (Table 3) | * | ** | * | ** | * | * | * | * | * |
| Expert identifiers (Table 3) | | * | * | | * | * | * | * | * |
| Database managers | | | | * | | | * | | * |
| Citizen scientists (Table 4) | | | * | | | | * | * | * |
| Other interception and survey personnel | | | * | | | | * | * | * |

An effective EDRR will require all actors and resources, appropriately targeted. Reference is made to Tables below where the role or resource is further analyzed

**Table 2** Identification process chains: recommendations

| IPC—aspects hindering rapid identification | Actions to increase rapidity |
|---|---|
| Experts difficult to locate | I. NISC |
| | 1. Establish EDRR Coordination Mechanism ("EDRRCM"), perhaps by expanding role of NISC Secretariat |
| | II. EDRRCM, working with federal and state agencies |
| | 1. Develop and enhance IPCs for EDRR procedure |
| | a. Create and use lists of experts |
| | b. Encourage MOUs between stakeholders including experts to |
| | i. Develop formal networks and IPCs |
| | ii. Ensure timely availability of experts |
| | c. Engage established networks/IPCs to participate in national EDRR |
| | III. Established networks to facilitate IPCs by improving linkages |
| Experts working for unconnected organizations | I. EDRRCM |
| | 1. Develop mechanism to assist partnerships |
| | II. Individual agencies and organizations |
| | 1. Increase collaboration, with formal MOUs where possible |
| | III. Agencies managing IPCs |
| | 1. Consider opening them to other agencies where appropriate and necessary to facilitate identifications in EDRR |
| Experts in distant localities | I. Agencies managing site inspections |
| | 1. To increase efficacy of expertise on site |
| | a. Use professional identifiers at fixed sites |
| | b. Make use of trained citizen scientists |
| | c. Increase use of appropriate identification technologies |
| | d. Work with established networks/IPCs |
| | II. Various stakeholders |
| | 1. To improve rapidity of IPCs |
| | a. Site managers to establish preliminary identifications where possible to facilitate transmission to relevant expert through IPC |
| | b. Users send images (noting that in many cases specimens may be necessary for a precise identification) |
| | c. EDRRCM to recommend targets for rapidity of transmission |
| | d. EDRRCM to work with agencies to develop and emplace standard reporting and specimen transmission system |

USFWS on PoE is a strong example. Department of Defense (DOD) and the USFWS work together on DOD lands, and the Great Lakes Restoration Initiative involves collaboration among USFWS, Environmental Protection Agency (EPA), and USGS.

Federal agencies operating without a national framework to engage with taxonomic capacity may rely more on local expertise. When this is insufficient, individuals may have difficulty locating the appropriate resource or finding an established IPC appropriate to the species in question. Not all IPCs are open to all agencies, and few online expert directories exist. USDA provides suggestions on which labs should receive identification requests (APHIS 2017c). The Aquatic Nuisance Species Task Force maintains an Experts Database by state (USFWS n.d.), including taxonomists. The page also carries links to the Delivering Alien Invasive Species Inventories for

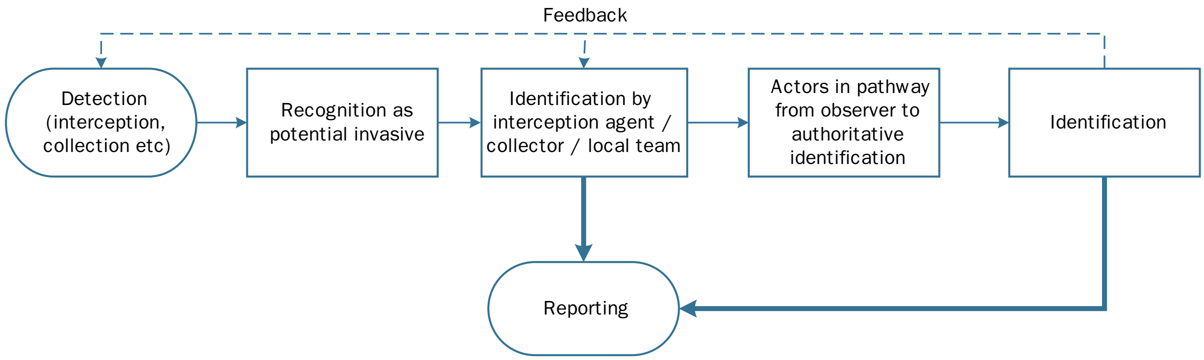


**Fig. 2** Identification Process Chain (IPC) from observation to identification and from identification to management. Feedback may assist future identifications

Europe (DAISIE) expert search (http://www.europe-aliens.org/, accessed 12 March 2019) and to US systems that no longer exist: the National Oceanic and Atmospheric Administration's (NOAA) Taxonomic Cadre and the National Biological Information Infrastructure's (NBII) Taxonomic Resources and Expertise Directory. NBII has been off-line since 2012, at least partially because of budget cuts (USGS 2011), although some elements were later covered by BISON (Biodiversity Information Serving Our Nation). Some professional societies maintain membership lists (e.g., American Society of Plant Taxonomists Membership Directory; https://members.aspt.net/civicrm/profile?gid=25&reset=1, accessed 4 October 2018), but with no guarantee of completeness or expertise. USDA has a web-based search tool for connecting researchers with peers, although it does not search for taxonomists (USDA 2017b). Adoption of Open Researcher and Contributor Identification (ORCID) by taxonomists may also assist in their location (Page 2018).

The rapidity of response in an IPC can be increased by local identification capacity in any of the quadrants in Fig. 1, facilitating finding the appropriate specialist. An example is Preclearance Inspections conducted in some countries exporting to the United States, performed under direct supervision of qualified APHIS personnel (USDA n.d.). USDA preclearance manuals (USDA 2011, 2012a, b, 2013, 2014a, b, 2015) mostly do not include identification aids, although USDA (2011) shows images of bulbs attacked by pests or pathogens, and USDA (2012a) has rather crude line drawings and some photographs (but they do not indicate diagnostic features). Increasingly, image-based systems allow rapid submission and transfer, so the specialist can see the specimens sooner, although images are more effective for some organisms than others (G. Miller, L. Chamorro pers. comm).

Shippers are required to identify plants (and are provided with lists of names), but there is no guidance on technologies or taxonomic standards that should be used. Taxonomic skills and resources in other countries may be absent, so identifications associated with imports to the United States may not be possible, or they may employ different taxonomic concepts and names. While there is no guarantee that the identification given matches US concepts, this is subject to checking at APHIS Plant Inspection Stations (USDA 2007) and may speed the process.

## Expertise and infrastructure

Identification at the point of interception may simply recognize that a potential invasive is present and requires authoritative review, or may provide a preliminary or final identification. Local capacity to deliver this identification is built on informal or formal training and appropriate identification technologies. If identification is not possible locally to the appropriate confidence level, greater taxonomic expertise may be sought in state and federal bodies, such as laboratories maintained by the USDA Agricultural Research Service (ARS), the CDC, and the Smithsonian Institution (SI), and many state universities, although engaging such an entity may lengthen the IPC. Professional taxonomic expertise is required for the most authoritative identifications, to develop and maintain identification technologies, and to manage

**Table 3** Expertise: recommendations

| Expertise—aspects hindering rapid identification | Actions to increase rapidity |
|---|---|
| Expertise for authoritative identifications unavailable | I. All bodies employing taxonomists |
| | 1. Increase support for systematics and taxonomy, both for native and especially invasive species. |
| | 2. Develop identification expertise in life stages of organisms where no identification technologies exist |
| | II. Federal agencies |
| | 1. Plan for necessary taxonomic expertise to be available within an EDRR structure |
| | 2. Develop efficient means to make use of taxonomists outside the US where expertise is lacking. A model might include Australian Biological Resources Study (ABRS)'s grant program supporting projects facilitating areas that will boost Australia's taxonomic capacity |
| | 3. Consider co-funding expert positions |
| Professional identifiers unavailable | I. Federal agencies |
| | 1. Recruit additional inspectors at PoE |
| | 2. Develop expertise to support identifications at regional level |
| | 3. Develop training programs for personnel at field and laboratory level, covering identification of known and potential invasive species, particularly understanding of techniques, resources, and technologies |
| | 4. Build training programs into management systems to ensure that skills are regularly refreshed |
| | II. Government |
| | 1. Ensure funding to federal agencies to contract identification support, including use of eDNA |
| Identifications slow | I. Federal agencies and the EDRRMC |
| | 1. Develop incentives such as grants to develop identification technologies, revise high-priority problematic taxa, and support taxonomic databases |
| | II. Laboratories |
| | 1. Train and recruit technicians to improve speed with which samples are processed and analyzed |

See Table 1 for relevance to a sustainable taxonomic resource for EDRR

the contents of taxonomic databases. Availability of such expertise in a timely manner needs to be planned and managed (Smith et al. 2008). Federal bodies do not supply identification and taxonomic expertise to manage all current requirements for confirming invasive species occurrence; a strategic national EDRR program would provide an opportunity to review and build such capacity efficiently across federal and state agencies, universities, and private companies.

Current trends may indicate projected needs. USDA Systematic Entomology Lab (SEL) identification requests from PoE (each of which might include multiple specimens and species) rose from 9624 in 2004 to 17,755 in 2010, the "urgent" requests from 3572 to 8469 in the same period (A. Solis pers. comm); in 2016 SEL received 30,000 specimens for identification (G. Miller pers. comm). Each day CBP intercepts around 470 plant pests and diseases (Harringer 2016) and seizes around 4548 prohibited plant materials and animal products. Work et al. (2005) suggested that port interceptions were not finding all species, suggesting an insufficient inspection rate and potentially higher identification requirements. An increased detection rate within an EDRR system will increase calls for identifications. Recommendations relating to availability of suitable expertise are given in Table 3.

Expertise availability

Many correspondents stated that obtaining identifications was very time-consuming or impossible. Lack of experts—generally professional taxonomists—appears to be a major problem. Professional taxonomists as discussed here are people who devote a significant part of their work to describing species or carrying out other taxonomic research. The number of such professionals in the United States or globally is unknown. There is general agreement that the number of taxonomists and positions for taxonomists is decreasing (Davis Declaration 2001; Mikkelsen and Cracraft 2001; Agnarsson and Kuntner 2007; Chitwood et al. 2008; Drew 2011; Hauser 2011; Wild 2013; Foottitt and Adler 2017; Wilson 2017). There is an acknowledged shortage of suitable staff in some areas such as field pathology (Miller et al. 2009; Stack 2010), and federal staff in a number of agencies interviewed in preparing this paper reported a lack of taxonomists available for some groups such as grasshoppers and mites. Retired staff are often relied upon; the National Museum of Natural History (NMNH) Entomology Staff directory lists more emeritus personnel, associates, and collaborators than employed researchers. Emeritus personnel alone constitute half as many as currently employed researchers. In the 1970s the SEL had 29 scientists, while it now has 15; SEL does not accept non-urgent identification requests for some taxa (although it sends some non-urgent enquiries to external collaborators when staff are unavailable; G. Miller pers. comm; ARS 2016). In addition to personnel loss, the strong but unofficial peer-to-peer networking is now breaking down as people retire or leave the field.

Perhaps most identifications are undertaken by non-taxonomists employed to identify invasive species, particularly in quadrants A and C in Fig. 1. Key examples are PoE interception staff and employees of agencies supporting other pathway inspections. These government personnel can be regarded as professional identifiers. Most CBP Agriculture Specialists hold a bachelor's or higher degree and have taken a 12-week training course from USDA including pest and disease identification and quarantine regulations, supported by port-specific, post-academy training. There are ca. 2400 CBP Agriculture Specialists at PoE (Lapitan 2016; Harringer 2016), staffing approximately half of the 329 PoE. CBP has reported a shortage of such experts in key high volume PoE, but CBP's Agriculture Program and Trade Liaison (APTL) has developed a dynamic "Agriculture Resource Allocation Model" to address staffing needs based on quantifiable volume and pest risk (M. Atsedu pers. comm). Other federal agencies also have identification skills amongst their staff, although they too report lack of taxonomic expertise at site and regional levels.

Existence of expertise does not guarantee EDRR capacity. The job duties of a taxonomist may not allow time for identifications, or identifications outside of a particular scope (Lyal and Weitzman 2004; Wild 2013). Taxonomists' activities are determined by their institutional and funders' priorities. Experts may also need time to develop their expertise, prepare identification technologies, and revise the taxonomy of problematic groups. That such research is important is exemplified by the story of the Rasberry crazy ant in Houston, where different opinions and a very difficult taxonomic problem delayed effective management and permitted spread of the species (Gotzek et al. 2012; Wang et al. 2016). Consequently, merely evaluating the number of taxonomists in post gives limited information on relevant capacity for EDRR. The declining number of taxonomists inevitably has a negative impact on identification capacity, and any solution must involve both increasing taxonomist numbers and their availability for effective EDRR. Mapping invasive species risk profiles against identification capacity will inevitably reveal gaps both currently and as the potential invasive species pool changes [e.g., SEL does not cover some insect groups, such as grasshoppers, except when urgent (ARS 2016)].

No nation has sufficient taxonomic expertise to support identifications of all of their biota (Secretariat of the Convention on Biological Diversity 2007). Effective coverage of global biodiversity is even more challenging and expertise is widely dispersed globally (Smith et al. 2008). The nature of invasive species means that relevant taxonomic expertise may lie in their countries of origin outside the United States, and information may have to be sought from these specialists; international networks and contacts are required (Davis Declaration 2001; Stack and Fletcher 2007; Stack 2010). This requirement can pose

**Table 4** Citizen science: recommendations

| Citizen science—aspects hindering rapid identification | Actions to increase rapidity |
|---|---|
| Too few citizen scientists engaged | I. All agencies and the EDRRCM |
| | 1. Increase understanding that the role of citizen science in management of invasive species is integral to future success, including to aquatic systems (USFWS 2015) |
| | 2. Enhance citizen science programs, including |
| | a. Public awareness activities |
| | b. Outreach to selected groups |
| | c. Recruitment program |
| Identifications not of appropriate quality | I. EDRRCM, working with federal agencies |
| | 1. Develop and implement identification protocols |
| | 2. Develop and implement training systems, including on the use of identification technologies and the capacity to provide suitable information to the appropriate authorities who can take action |
| | 3. Develop and implement appropriate management techniques for citizen science reports, including data quality |

See Table 1 for relevance to a sustainable taxonomic resource for EDRR

problems that need resolution: locating experts; response time; management of experts; ability of a federal agency to issue a contract to pay for identifications; and impediments in sending specimens between countries from Access and Benefit-Sharing regulations (McCluskey et al. 2017).

Engagement of amateur communities can be more cost-effective than employing researchers and produce more rapid identifications in cases of easily identified invaders (Goldstein et al. 2014; Lodge et al. 2016; Looney et al. 2016). Citizen science is perhaps most required in quadrants B and D of Fig. 1. Some citizen science groups are very local in their activities, benefitting from familiarity with local fauna and flora and sensitivity to unfamiliar species. Groups might be encouraged to develop citizen science skills and engage in invasive species monitoring, even if they would not self-identify as being first responders. For example, existing interest in conservation photography among nature photographers (North America Nature Photography Association 2017) could be harnessed to submit high-quality images with GPS data to appropriate systems. The UK Riverfly Partnership (http://www.riverflies.org, accessed 12 January 2018) comprises conservationists, entomologists, scientists, water course managers, and relevant authorities, working together on aims centered around conservation. In the United States, streamkeepers and others already monitor for invasive species (Johnson 2014), and a wider partnership could be developed with citizen scientists. Citizen scientists may not be able to provide information with as consistent a level of reliability as specialists (Newman et al. 2010; Lewandowski and Specht 2015), and accuracy may decrease with rarer encounters (Swanson et al. 2016). Reliability is improved with appropriate training (Newman et al. 2010; Gardiner et al. 2012; Freitag et al. 2016) and observation and analysis protocols (Tweddle et al. 2012). Most if not all states have Master Gardener and Master Naturalist programs, and Collaborative and Enhanced First Detector Training programs exist at the state or network level, e.g., by the National Plant Diagnostic Network (NPDN n.d.) and Bugwood (Hummel et al. 2012). These programs increase understanding of relevant agency responsibilities, including the appropriate IPC to bring specimens to specialists (Stubbs et al. 2017). Recommendations for mobilizing and managing citizen science engagement with EDRR processes are given in Table 4.

## Collections

Biological collections, including museum, herbarium, and culture collections, are a key resource to support rapid identification of invasive species and provide

**Table 5** Collections and laboratories: recommendations

| Collections and laboratories—aspects hindering rapid identification | Actions to increase rapidity |
|---|---|
| Collections at risk of loss, or inaccessibility through lack of staff | Agencies with scientific collections |
| | Ensure support for long-term sustainability of collections for invasive species activities (Miller 1991; Pape 2001; Entomological Society of America 2016) |
| Specimens for comparison unavailable | Collection-holders |
| | Ensure they have holdings of relevant native and possible invasive species |
| Specimens for comparison incorrectly identified | Collection-holders |
| | Take steps to confirm the identity of invasive species in their collections |
| Diagnostic laboratory capacity insufficient | Relevant stakeholders |
| | Ensure sustainable funding for federal and other public laboratories to provide identification and diagnostics. Funding as research bodies rather than identification services will attract desirable levels of expertise |

See Table 1 for relevance to a sustainable taxonomic resource for EDRR

information on distribution, origin, and biology, etc. (Simpson 2004; Suarez and Tsutsui 2004; Smith et al. 2008; Interagency Working Group on Scientific Collections 2009; Gotzek et al. 2012; Lavoie 2013); they also provide material to develop molecular technologies (Hubert et al. 2008; Galan et al. 2012). To meet these needs, relevant collections must hold examples of both native and non-native species to enable comparison, and specimen identifications in those collections need to be correct; this cannot be assumed (Goodwin et al. 2015; Jacobs et al. 2017; Sikes et al. 2017). Observations, molecular technologies, and DNA sequences should be vouchered by physical specimens in collections (Ratnasingham and Hebert 2007; Packer et al. 2018). Appropriate federal collections exist for vertebrates, invertebrates, and plants. Culture collections have a less clear model. USDA maintains several culture collections, including ARS (2017) and Ft. Dietrich for invasive species. The American Type Culture Collection (https://www.lgcstandards-atcc.org, accessed 4 October 2018) charges for deposit and retrieval, and consequently some researchers send strains overseas (K. McCluskey pers. comm). Despite initiatives such as the US Network of Culture Collections (McCluskey et al. 2017) there is poor US infrastructure for microbial collections, with problematic funding support (Smith 2017).

The last detailed survey of US systematic collections was 1988, with publications on insects (Miller 1991), fish (Poss and Collette 1995), and mammals (Hafner et al. 1997). Gropp and Mares (2009) predicted funding issues in the Natural Science Collections Alliance 2008 survey of North American (federal and non-federal) collections. While most federal collections are growing, there have been problems with declining numbers of trained staff and funding resources (IWGSC 2009). Information on global scientific collections is available online (https://www.gbif.org/en/grscicoll accessed 10 July 2019). Non-federal collection-holders include private bodies and non-governmental bodies such as universities. Unlike federal collections, for which proper care is required by Public Law 111-358 section 104, there is no guaranteed sustainability. For example, the University of Louisiana at Monroe recently disposed of its collection of ca. six million fish and half a million native plants. As with federal collections, declining staff numbers are an issue (Kemp 2015). Recommendations for collections in the context of EDRR are given in Table 5.

## Laboratories

Federal, public, and private laboratories provide diagnostics and identifications of whole organisms, micro-organisms, or fragments (Trebitz et al. 2017). Some are operated by collection-holding institutions, others by federal agencies (e.g., USDA's Center for Plant Health Science and Technology (CPHST) Beltsville laboratory). Both animal and plant diseases are served by networks of laboratories (APHIS 2017b; https://www.nahln.org, accessed 2 October 2018;

https://www.npdn.org, accessed 12 March 2019). Both California and Florida have large State Department of Agriculture laboratories that identify agricultural organisms, while some other states maintain smaller laboratories. No information is available to assess whether the capacity of the extant laboratories suffices for an EDRR program, although NPDN and USDA's National Animal Health Laboratory Network operate in a competitive funding environment, and the use of private facilities suggests insufficient federal capacity. Recommendations for laboratories in the context of EDRR are given in Table 5.

### Identification technologies

The rate at which species are identified can be increased by making identification technologies more readily accessible (all quadrants in Fig. 1). Martinez et al. (2019, this issue) provide a broad, but selective, overview of advanced technologies for achieving EDRR. Below we touch on those technologies identified by the federal agencies as being particularly important for non-native species identification. Identification of some groups relies particularly on one life stage, and absence of this stage limits or prolongs identification, especially if no taxon experts are available (Hauser et al. 2009; Hauser 2011). Thus, although many insects can be identified only from adults, approximately half of submissions to SEL are immature. Specific identification technologies may address this problem [e.g., on intercepted Lepidopteran larvae (Gilligan and Passoa 2014; LeVeen 2014)]. Recommendations related to identification technologies are given in Table 6.

### Molecular technologies

Molecular technologies permit rapid non-specialist identification (Hubert and Hanner 2015). Use of DNA barcodes (Rugman-Jones et al. 2013) or eDNA (Wilcox et al. 2015) makes it possible to detect and identify invasive species effectively and to a rigorous standard (Frewin et al. 2013), and eDNA allows detection even when only few specimens are present in the environment sampled and none have been captured or seen. Use of DNA barcodes at PoE may facilitate rapid identification of immature stages of insects, and it could be incorporated into border security programs as an adjunct to morphological identification (Madden et al. 2019). Increasing use of DNA barcodes may reveal unnamed cryptic species (Weissman et al. 2012; Jaric et al. 2019), which can be referred to by the Barcode Index Number (BIN) system (Ratnasingham and Hebert 2013; Miller 2015). However, names will be required to relate these to extant information, requiring expertise from a taxonomist (Sheffield et al. 2017). DNA use is evolving rapidly (e.g., Ardura et al. 2017; Wilkinson et al. 2017; Roe et al. 2019; Bilodeau et al. 2019). However, more papers test new methods for potential value in invasive species detection than report their adoption as embedded systems.

Use of molecular data relies on a library of DNA sequences (DNA barcodes, other selected genes, or genomes) to identify sequences from unknown organisms. Although large, these libraries are incomplete (Adamowicz et al. 2017; Curry et al. 2018); Wilkinson et al. (2017) estimate that Barcode of Life Data System (BOLD) holds core DNA barcodes for only 15% of land plant species, and intraspecific coverage is even less complete. Some groups have more than 90% coverage for an intensively-sampled area (Zahiri et al. 2017) but may omit non-native species (Hauser 2011). Many correspondents expressed the importance of a global barcode library (D. Lodge, J. Pecor pers. comm), with a priority given to pest species, particularly those with a high likelihood of invasion. For example, the Walter Reed Biosystematics Unit is building a BOLD database of mosquitoes and other disease hosts. Expanding coverage and improving quality may require development of new technologies (Wilkinson et al. 2017) and priorities (Madden et al. 2019). Moreover, ongoing quality assurance and control of identifications in DNA libraries is needed, including re-assessment on addition of new sequences and with taxonomic changes (Curry et al. 2018).

Genetic markers for eDNA also need further development, especially for novel invasive species, and those already developed may not be widely known. Obtaining samples of target species from outside the United States can be difficult and leads to prioritization of easily-obtained species (Great Lakes USFWS team, pers. comm). Increasing sensitivities in many countries around Access and Benefit-Sharing (Secretariat of the Convention on Biological Diversity 2017) and the use of digital sequence information will need to be managed effectively to facilitate obtaining such samples.

**Table 6** Identification technologies: recommendations

| Identification technologies—aspects hindering rapid identification | Actions to increase rapidity |
|---|---|
| Insufficient non-molecular technologies for widespread use | I. Federal agencies, universities and research bodies<br>1. Develop technologies for professional and citizen science use, including apps to cover all priority invasive species that can be identified using these methods, making them site-appropriate where needed<br>2. Prioritize development of non-molecular or molecular technologies to support identification of regularly intercepted problematic life stages |
| Technologies may not be of appropriate quality to produce accurate identifications | I. EDRRCM<br>1. Encourage development of and promote standards for technologies such as apps<br>2. Develop resource list of technologies meeting standards to increase availability, with reviews of their suitability for different taxa and geographical regions<br>II. Stakeholders producing apps and other technologies<br>1. Adopt standards proposed by EDRRCM |
| Sequence libraries incomplete | I. Federal agencies, universities, research bodies, relevant database owners and collection-holders<br>1. Expand authoritative vouchered genetic sequence libraries<br>a. Complete a global DNA barcode library<br>b. Develop eDNA markers for high priority species<br>c. Ensure availability of tissue samples from reliably identified and uncontaminated voucher specimens. Facilitate sourcing specimens from outside the US, including managing ABS regulation requirements<br>d. Prioritize pest species for future DNA library entry and data quality re-evaluation, particularly those with a high likelihood of invasion |
| Sequencing facilities and expertise insufficient or unavailable | I. Federal agencies<br>1. Foster collaborations and partnerships between each other and internally to increase access to sequencing and bioinformatics capabilities<br>2. Increase access to bioinformaticians, bioinformatics analysis programs and database development by their staff<br>3. Invest in hardware to expand sequencing efforts |

See Table 1 for relevance to a sustainable taxonomic resource for EDRR

DNA methods have limitations. Different genes, even "DNA barcodes," perform at different accuracies (Braukmann et al. 2017; Wilkinson et al. 2017). Assays differ in resolution (Amberg et al. 2015), and next-generation sequencing may provide a higher resolution than Sanger sequencing (Batovska et al. 2017). While many studies report over 95% accuracy, claims of 100% accuracy have not been seen. Some taxa have not proven amenable to determination using barcodes (Piredda et al. 2010; Pyšek et al. 2013). While accuracy and rapidity in detection are improving, this does not automatically lead to field use. Variation in results obtained using different methods and continual methodological changes might limit acceptance (D. Lodge, Great Lakes USFWS team pers. comm). Federal agencies with diagnostic standards may require careful evaluation and official approval of methods (e.g., US Food and Drug Administration 2017a). Despite this requirement, many federal agencies are using DNA-based techniques and even extending them, e.g., USGS with eDNA detection kits for Asian carp (Great Lakes USFWS team pers. comm). Using eDNA technologies to detect the presence of sea lamprey in the Great Lakes is under development (Gingera et al. 2016). An issue with expanding sequencing work is the volume of assays possible. USGS has three sequencers with capacity to produce more than 800,000,000 reads in less than 48 h; owing to the large volume of data generated, they have had to invest in infrastructure to store and process them. Increasing use of sequence data will inevitably cause such costs to rise. Correspondents stressed that much of the eDNA work was scalable but would take additional funds to roll out further.

Open technologies for general use

There are many identification technologies, including literature (field guides, dichotomous keys, identification cards, etc.), web sites, and smartphone apps. While the number of apps is increasing, they are insufficient to address all species that might be prioritized. Furthermore, the many web-based resources vary considerably in quality, can be difficult to locate, and may not include all species that might be intercepted (Stack et al. 2006); user assumptions that everything is included may lead to false positives. State-level coverage varies, but because of differing biota it is problematic to use an app developed for one state in another. There is no overall plan to ensure all priority invasive species are covered at the appropriate geographical level, nor is there a means of quality assessment. Identification technologies may be tailored to pathway or targeted inspections (Fig. 2 quadrant C) or general use (Fig. 2 quadrant B), although priorities for the former may be easier to set than priorities for the latter.

Although images do not ensure accurate identifications (Austen et al. 2016), their use can be extremely important (Vásquez-Restrepo and Lapwong 2018; Iwane 2018). Accuracy of image-based identification requires good images, clearly marked diagnostic features, and comparison with similar native species (e.g., Tsiamis et al. 2017). Comparing images of different species facilitates identification, but some systems do not allow this (e.g., http://www.invasive.org, accessed 4 October 2018; iNaturalist 2017). Images not indicating diagnostic features between similar species may lead to errors (Vantieghem et al. 2017). Technologies focusing on relatively easy-to-identify groups such as bumblebees, ladybirds, etc. may function well, but visual-based technologies are inappropriate for more cryptic, less well-marked, or smaller species.

Some quality control systems are in place for images. iNaturalist requires two matching identifications for an image before providing the image and data externally (G. Guala pers. comm). Increasingly, use of image recognition systems will have a role in species identification. However, currently USDA and other federal agencies might not accept technologies such as iNaturalist because there are not sufficient quality assessments, although the National Park Service uses iNaturalist with proper caution and awareness. There is no US equivalent to the Australian PaDIL (http://www.padil.gov.au, accessed 2 October 2018), which provides images and characters for a wide range of exotic organisms in its "Plant Biosecurity Toolbox."

Reliability measures

Responses to reported invasive species are potentially costly and likely to be triggered only when sufficient evidence is available from a risk assessment (Meyers et al. 2019, this issue), including identification reliability. This can be assessed by (1) reliability (authority) of the identifier; (2) reliability of the diagnostic laboratory; and (3) identification method. Although standards provide a measure of assurance, every system carries a risk of false positives or false negatives. An EDRR system needs a means of assessing identification reliability to determine response, balancing the risk of taking action when the identification reliability is not 100% against risks attendant on increasing time through seeking maximum reliability. Setting identification standards will assist this judgement. Recommendations for standards to improve reliability assessment and control are given in Table 7.

Identifier authority and accuracy

There is little clarity on requirements for recognized identifier expertise, and criteria will differ along the IPC. CBP Agriculture Specialists must have their identifications checked by a relevant authority. Since PoE interceptions may have legal consequences, identifiers might have expert witness status (although court appearances are rare for ARS taxonomists [G. Miller pers. comm]). Taxonomists do not have a certification system; instead they are judged on qualifications, publications, and experience. Overall there are likely to be limited options to standardize

**Table 7** Standards: recommendations

| Standards—aspects hindering rapid identification and response | Actions to increase rapidity |
|---|---|
| Uncertainty on correctness of identification; | I. EDRRCM |
| | 1. Commission standard identification requirements for high-risk species for adoption by agencies |
| | 2. Review identifier accreditation options and propose standards |
| | 3. Consider setting and adopting requirements for laboratory accreditation, including required expertise and technologies |
| Challenges in working across agencies | I. EDRRCM in partnership with federal agencies |
| | 1. Develop identification protocols at national or regional levels, to promote standardization and regulatory acceptance across agencies |

See Table 1 for relevance to a sustainable taxonomic resource for EDRR

identifier authority other than training and workplace monitoring if identifiers are employed in this capacity. For citizen scientists courses are available in invasive species identification. The more tailored they are to sites or species, the better the personnel will be equipped, and the more accurate identifications are likely to be. The eBird citizen science project (eBird 2018a) has implemented a system including automatic data vetting and a network of experts to verify reported data (eBird 2018b). However, since citizen scientists often will be operating in quadrant B of Fig. 2 where the potential for error is highest, protocols to manage identification submissions should be used (Chandler et al. 2017; MacKenzie et al. 2017).

Laboratory standardization and quality assessment

Some federal agencies apply laboratory standards (Food Safety and Inspection Service n.d.; Federal Bureau of Investigation DNA Advisory Board 2010; APHIS 2013). A relevant International Organization for Standardization (ISO) standard was adopted by USDA CPHST Beltsville Laboratory (ISO 2017), which is a key component of the PPQ National Plant Pathogen Laboratory Accreditation Program (NPPLAP; APHIS n.d. a). ISO has developed a biobanking standard, ISO 20387: 2018, which will be modified for various collection types (ISO n.d.). Private contractors may use industry standards and accreditations.

Standardization of identification methods

When an agency develops EDRR protocols, the identification method should be specified (e.g., Federal Interagency Committee for the Management of Noxious and Exotic Weeds 2003; Rabaglia et al. 2008; Trebitz et al. 2017). There is no standard definition of a species, either federally or between taxonomists, and agencies apply different standards to identifications depending on their governing laws and policies. This may limit agencies' ability to make use of identifications from others. The US Federal Bureau of Investigation (FBI) uses the best available published science, but other agencies often rely on their own internal laboratories and procedures. US federal law makes use of the Daubert Standard to assess the validity of expert evidence (Berger 2011); some principles may be transferable. The US Food and Drug Administration (FDA) has also provided DNA barcode standards for their 22 major food-borne pest animals (Jones et al. 2013).

Some standards exist for individual species identifications. Some US agencies use International Plant Protection Convention (IPPC) standards (IPPC 2017; Bostock et al. 2014; APHIS 2017d), but most species are not covered by these. USGS and USFWS laboratories have established sampling method and laboratory proficiency standards for molecular detection of chytrid fungus (*Batrachochytrium salamandrivorans*). The FDA uses the "Regulatory Fish Encyclopedia" (USFDA 2017a), including DNA barcodes and electrophoretic methods, and maintains a Reference Standard Sequence Library for Seafood Identification

(RSSL; USFDA 2017b). The USDA Food Safety and Inspection Service (FSIS) makes available an unendorsed list of test kits that have been validated for detection of pathogens (FSIS 2017) and guidance to evaluate the performance of pathogen test kits (FSIS 2010). There are formal guidelines for DNA Barcode inclusion in BOLD, which include vouchering a specimen (Ratnasingham and Hebert 2007; Hanner 2009). Mickevich (1999) sets out some criteria for identification and quality of names included in databases.

## Taxonomic name management

Taxonomic names change as a result of scientific study (Vecchione 2000) at perhaps 1% per year (Smith et al. 2008). A standard list of names is important for information exchange and assessing and managing possible invasive species (Smith et al. 2008; Pyšek et al. 2013; Deriu et al. 2017; Groom et al. 2017), allowing stakeholders to have a single point of reference and remove ambiguity. Data management issues around name providers are addressed by Reaser et al. (2019c, this issue), but there are capacity issues in compiling and maintaining the databases and interpreting and using the contents. Recommendations for taxonomic name management are given in Table 8.

Rapidity of identification needs to be matched by all stakeholders using the same name and species concepts; otherwise there are risks of miscommunication and using incorrect names. No single global source of all scientific names exists, nor does a complete list of US native or invasive species. Without such a list even at the state level, an agency cannot always tell what species are non-native (Great Lakes USFWS team pers. comm).

An authoritative source (name-server) for the currently used names for US federal agencies, the Integrated Taxonomic Information System (ITIS) (Guala 2016), is used by EPA (2000) and USGS and is recommended to its agencies by the Department of the Interior (DOI) (and used by the European Alien Species Information Network [EASIN; Deriu et al. 2017]). It is used by many federal agencies that are signatories to the MoU (https://www.itis.gov/mou.html, accessed 2 October 2018). However, while it is used by some parts of the USDA, it is not used by all (it is not listed in any of the USDA manuals cited in the references to this paper, for example). Gaps in coverage, including of some agriculturally important insects, may preclude its use by at least some parts of USDA.

There are many catalogues and name-serving databases, although these may differ according to the resources used in compilation, the taxonomists producing them, update frequency, and coverage. They may give different names for the same organism or omit species. Expert taxonomists may not refer to databases but use the most recent scientific literature, often not captured by name-servers. Names supplied by experts may therefore not be easily relatable to names being used by other stakeholders. Different identification technologies may also use different names for the same species.

Hidden risks are associated with *species concepts*. Different names applied over time may not be simply and unequivocally linkable to biological entities. If a species is moved between two genera (e.g., the crazy ant *Paratrechina fulva* Mayr is re-named *Nylanderia fulva* Mayr), the two names refer to the same *species concept* with the same biological properties. When two species are discovered to be the same they are subsequently known by the older name, and again share the same species concept. In both examples users must locate information published under both names, so databases should have both (ITIS n.d.; Guala 2016). However, sometimes what was thought to be a single species is discovered to comprise different entities, e.g., the red palm weevil comprising two species: *Rhynchophorus ferrugineus* (Olivier) and *R. vulneratus* (Panzer) (Rugman-Jones et al. 2013), and biological and other observations recorded under the original name cannot with confidence be applied to one or other of the new concepts. Barcode "provisional nomenclature" to enable reference to informal concepts may be helpful (Schindel and Miller 2009). The issue compounds the problems of unconnected databases. Although there are attempts to manage species concepts in databases (e.g., Franz and Peet 2009), no solutions are accepted widely. Notably, most databases lack a mechanism for alerting users to changes in names or concepts.

Federal agencies use a variety of name providers, some referring to different providers in different documents. There may be static lists either included in the document (e.g., USDA 2012b) or online (e.g., APHIS n.d. a, b), or online databases (e.g., ITIS [http://

**Table 8** Taxonomic names: recommendations

| Standards—aspects hindering rapid identification and response | Actions |
|---|---|
| Miscommunication through using different names | I. EDRRCM and name-servers |
| | 1. Raise awareness among stakeholders of potential disparities between databases |
| | II. Federal agencies |
| | 1. Take steps to harmonize resources used for names |
| | 2. Support major publicly-funded databases, and facilitate closer collaboration between them |
| Duplication and errors arising from use of different databases | I. Name-servers (databases) |
| | 1. Work together to develop a single portal to names of all organisms, building on existing investments (e.g., ITIS, PLANTS) |
| | a. Duplication of effort should be avoided |
| | b. Names should be as up to date and stable as possible |
| | c. Names should include all US native taxa |
| | d. Names should include non-native species known to have entered the US and species at risk of entering the US |
| | e. Synonyms should be included |
| | f. Unique identifiers for names should be used (e.g., ITIS Taxonomic Serial Number [TSN]) |
| | 2. Work with national and international bodies (e.g. Biodiversity Information Standards (TDWG), Catalogue of Life, Global Biodiversity Information Facility) to develop standards for interoperability of databases |
| | 3. Employ such standards to improve coverage and avoid duplication and gaps |
| Errors through incomplete or outdated databases | I. Federal agencies and funders |
| | 1. Support taxonomists and name-servers to complete and maintain an authoritative database/federated database of names of native and invasive species |
| | II. Federal agencies |
| | 1. Make use of global databases of invasive species |
| | III. Name-servers |
| | 1. Agree and implement a universal indication of record quality |
| | 2. Develop systems to alert stakeholders when a name is changed or new invasive species is detected in the US (building on the USGS Nonindigenous Aquatic Species database national alert system) |
| Concept changes not understood | I. Name-servers |
| | 1. Develop means of showing concept changes |

See Table 1 for relevance to a sustainable taxonomic resource for EDRR

www.itis.gov, accessed 1 October 2017]). Some USDA preclearance manuals include lists of plant names that shippers should use, including manual-specific lists derived from the literature or unstated sources, Parasitic Plants Database, Convention on International Trade in Endangered Species (CITES) Species Database, Federal Noxious Weed List, Endangered Species Act (ESA) Listed Plants, and US National Plant Germplasm System (GRIN). In some manuals differences between sources are mentioned. PoE inspectors are consequently presented with names of consignment contents but, because there is no standard source of names for the shipper (or quarantine staff) to use, some names given in shipping documents may be questionable and not match current identities.

Some name-serving databases are context-specific, although this can be confusing. The Federal Noxious Weed List (APHIS 2010) is a PDF listing 108 species reached from a website "Federal Noxious Weeds"

(Natural Resources Conservation Service 2017) listing 112 species that is derived dynamically from the PLANTS database (Natural Resources Conservation Service 2018). The USDA *Seeds Not for Planting Manual* (USDA 2014b) link named Parasitic Plants Database leads to an undated PDF list of genera with the latest supporting reference dated 2003 (APHIS n.d. b). The US Bureau of Land Management has lists of weeds of concern that "comply with" the Federal Noxious Weed Lists, State Noxious Weeds Lists, and county lists, compiled by a range of stakeholders. The California Department of Food and Agriculture list of weeds (2018b) differs from the USDA California list from the PLANTS database. Inevitably some names on these lists differ even though they refer to the same species. A brief inspection of the US Regulated Plant Pest Table (APHIS 2017e) revealed a number of outdated names. Species listed present (e.g., state lists of invasive species) depend on identification accuracy. Erroneous identifications and unreliable documentation in area lists can lead to large errors (Vecchione 2000).

A global database tailored for Invasive Species, the Global Invasive Species Database (ISSG), is not referred to in any documents reviewed here, even though an early version of this database identified nearly 200 species from a list of imports into the United States between 2000 and 2004 that might pose a national risk (Browne et al. 2007). BISON (USGS 2017), a web-based federal mapping resource for species occurrence data in the United States and its territories (Guala 2017), will tag records as invasive where possible (although this will not indicate invasive status between states in the lower 48). BISON draws on ITIS names plus resources including iNaturalist and collection records.

The resources used across federal bodies to provide scientific names do not all exchange information and are not equally complete or up-to-date, some delivering outdated names or concepts. Some online PDFs are undated and resources may not be removed from the internet when superseded. ITIS and the PLANTS databases have recently agreed to share resources and align their taxonomies. PLANTS is linked to GRIN (ARS 2015). This process needs support, as does continued population of the databases with appropriate quality control. ITIS stipulates high record quality and provides compilation dates, but Mickevich (1999) and Mickevich and Collette (2000) proposed more extensive criteria to show scrutiny level and verified accuracy for the NOAA/NMFS marine database.

Watch lists (Reaser et al. 2019c, this issue) are developed by federal and state bodies, including by the NPS Exotic Plant Management Teams (EPMT) for National Parks. The Heartland EPMT method was developed by using consensus in the summarized findings of other lists. However, harmonized lists cannot be produced simplistically (Pyšek et al. 2013; Murray et al. 2017).

Names used in legislation or management protocols may not track changes in scientific nomenclature and may refer to outdated concepts, thus not relating to currently recognized problem species. There are procedures for adding names to the Lacey Act list and some of its listed names include alternative scientific names. Some names are listed in legislation at the genus or higher taxonomic level. Thus, when an unexpected diversity was discovered in the snakehead (Conte-Grand et al. 2017), this discovery had no regulatory impact because the Lacey Act lists the entire family (USGS 2004).

## Conclusion

Provision of taxonomic support in the United States is under threat. Taxonomists are retiring and leaving the profession, and positions are not being replaced (Stack et al. 2006). Plant pest diagnostic laboratories are affected by decreasing state support, and dependence on fees reduces submission of samples (Stack et al. 2006). Some state universities are disposing of collections and staff and losing the capacity to manage the collections they hold. Fragmentation and isolation of resources and duplication of databases make expertise and information difficult to locate and use with confidence. Action at a local level may be insufficient when the required information or expertise is available only when when one searches at a global scale.

Significant US federal resources are devoted to the IPC for invasive species. Yet, there are also concerning trends and opportunities for improvement. Underlying almost every area is a need to improve collaboration between federal and state agencies and to develop coherent taxonomic support with sufficient expertise rapidly and easily available. If federal and state agencies continue to operate in the current fragmented and sometimes ad hoc manner, an efficient and effective EDRR process is unlikely, posing a serious risk of invasive species going unmanaged.

Overall, the capacity for rapid and accurate species identification can be improved through the following:

- Establish flexible, yet binding agreements and other coordinating mechanisms among federal agencies, as well as with all others who bear responsibilities for invasive species identification and identification support. The arrangements should detail resource-sharing, delineation of authorities, communications protocols, and sharing and availability of personnel and subject matter experts (Table 2).
- Establish a coordinating body to work with federal agencies and others to facilitate cooperation, information sharing, and standards setting (Table 2).
- Ensure appropriate taxonomic and identification expertise at local, regional, and national levels is available to support EDRR activities, and have those carrying out identifications properly resourced, with staffing and technology, to enable rapid response (Table 3).
- Create a clearinghouse for relevant identification tools, whether online, apps, or paper based, and for sources of identification expertise, and provide recommendations for suitability and quality of identification tools at taxon and regional levels (Table 6).
- Engage with national and international bodies (e.g., Biodiversity Information Standards (TDWG), Catalogue of Life, Global Biodiversity Information Facility) to develop standards for interoperability of databases, employ such standards to improve coverage, avoid duplication and gaps, and enable standardized names to be applied in all cases, including nomenclature, occurrences, legal status, etc. (Table 8).
- Encourage databases serving taxonomic names to collaborate, employ common standards for data exchange and data quality, and develop a portal through which all taxonomic names and their status can be retrieved (Table 8).
- Expand the content of DNA and DNA Barcode libraries to be complete for US native species, and prioritize alien and potential alien species (Table 6).
- Ensure long-term sustainability of biological collections for invasive species activities, including specimens of relevant native and invasive species of confirmed identity (Public Law 111-358 section 104) (Table 5).
- Develop and agree upon standard identification protocols; ensure sufficient diagnostic laboratory capacity and consider developing identifier accreditation systems (Tables 5, 7).
- Engage and empower citizens and citizen science groups to provide identifications of agreed quality using training, technologies, and connections to professional identifiers, and implement quality management systems (Table 4).

The United States does not have a strategy to address the need for rapid identification under EDRR. Such a strategy is needed urgently. Because the United States cannot provide all of the expertise and resources it needs to manage identification of intercepts from other countries, it must have an interest in global capacity. In 2001 the Davis Declaration emphasized the need for international collaboration and strategy to coordinate invasive species taxonomic and information services (Davis Declaration 2001). International networks of taxonomists have been set up, the most extensive being BIONet-International (Jones 1995), although this has been inactive for the past 5 years. Such networks could be revived to support the United States and other countries in identifying invasive species. Networks across the world and within the United States must be resourced to be sustainable and to provide the input required for EDRR. With a critical approach to EDRR and investment in taxonomic capacity, the current risks to effective management can be addressed sustainably.

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REVIEW

# Federal legal authorities for the early detection of and rapid response to invasive species

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**Abstract** The ability of federal agencies to carry out actions or programs is based on their legal authorities. Efforts to improve federal capacities for the early detection of and rapid response to invasive species (EDRR) require careful delineation of legal authorities, regulations, and policies that would enable or limit EDRR. Building on information provided by federal agencies and an inspection of the US Code and the Code of Federal Regulations, we review and identify relevant authorities to determine federal legal capacities, gaps, and inconsistencies to address EDRR. The EDRR process can be examined in the context of four categories, including (1) explicit invasive species authorities, (2) emergency authorities that could be triggered during a crisis or serve as models for enhanced invasive species EDRR authorities, (3) supporting authorities that could be used under agency discretion, and (4) constraining authorities and legal requirements. Although the Plant Protection Act and the Animal Health Protection Act are comprehensive authorities that address the detection of and response to organisms that threaten plant and livestock health, there is no single authority that encompasses EDRR for all invasive species. Rather, there is a patchwork of authorities that unevenly addresses various aspects of EDRR. In addition to gaps in authority, EDRR efforts could be constrained by environmental compliance, as well as subnational governance and private rights. Although some of these gaps could be closed through legislation, others need to be addressed using the discretionary power of federal agencies and their ability to establish cooperation mechanisms with private and subnational entities.

**Keywords** Early detection and rapid response (EDRR) · Guidance · Invasive species · Law · Legal authority · Policy · Regulation · Statute

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## Introduction

According to the United States government, invasive species means "with regard to a particular ecosystem, a non-native organism whose introduction causes, or is likely to cause, economic or environmental harm, or harm to human, animal, or plant health" (Executive Office of the President 2016). Invasive species represent one of the most significant threats to ecosystems (Pimentel et al. 2005); human, animal, and plant health (Pejchar and Mooney 2009; Pyšek and Richardson 2010); infrastructure (Invasive Species Advisory Committee 2016); food production systems (Pejchar and Mooney 2009); military readiness (Meyerson and Reaser 2003; US Department of Defense 2017), the economy (Pimentel 2011); and cultural resources (McNeely 2001; Pejchar and Mooney 2009; US Department of the Interior 2016). Recognizing these impacts, the US government has maintained a policy to prevent the introduction, establishment, and spread of invasive species, as well as to eradicate and control populations of invasive species (Executive Order (E.O.) 13112 as amended by E.O. 13751; Executive Office of the President 1999, 2016). This broad policy statement is underwritten by a range of legal authorities that guide more specific action relevant to particular agencies and invasive species threats. Previous analyses of federal legal authorities related to invasive species provide a general reference point for the analysis presented here (US Government Accountability Office 2001; NISC 2001a; Miller and Fabian 2004; Graham 2011; Corn and Johnson 2013, 2015; Committee on the Movement of Aquatic Invasive Species onto and off of Federal Lands and Waters 2015; Johnson et al. 2017).

In response to a directive in the *2016–2018 National Invasive Species Council (NISC) Management Plan,* we examine authorities and policies that either enable or act as barriers to the early detection of and rapid response to invasive species (EDRR) with a view towards building national capacity for EDRR. Reaser et al. (2019, this issue) define EDRR as a "guiding principle for minimizing the impact of invasive species in an expedited yet effective and cost-efficient manner, where detection is the process of observing and documenting an invasive species and response is the process of reacting to the detection once the organism has been authoritatively identified and response options assessed." Legal and policy frameworks underpin federal engagement and actions across the components embodied in the systemic approach to EDRR (Reaser et al. 2019, this issue). Most notably, they influence where, what, when, how, and by whom detection and response measures are enacted (Morisette et al. 2019, this issue).

Although the focus of our work is on relevant federal laws and policies, we recognize that the federal government, as delineated by the US Constitution, has limited enumerated powers and is intended to function in concert with the authorities granted to states, territories, and tribes, as well as individual rights (e.g., property rights). Herein, we recognize the relevance of laws and policies at both the subnational (e.g., states, territories, tribes, counties, water districts) and international levels (e.g., treaties, agreements, soft law; Shine et al. 2000; Environmental Law Institute 2002, 2004, 2010; Miller 2003; Miller and Fabian 2004; Young 2006; Environmental Law Institute and the Nature Conservancy 2007; Otts and Nanjappa 2016), but they are beyond the scope of this paper.

Invasive species law and policy overlay an institutional landscape, composed of numerous departmental and inter-departmental bodies and programs. A recent analysis by the Congressional Research Service (CRS) identifies at least 32 federal agencies with shared responsibilities for invasive species prevention, eradication, and control efforts or programs (NISC 2001b; Johnson et al. 2017). Some of these agencies are defined by statute, while others are created to run programs or address particular needs. Recognizing that this landscape is subject to change, the present analysis focuses specifically on the legal, and not the institutional, aspects of EDRR.

In order to implement the NISC management plan directive, the NISC Secretariat invited the federal bodies represented by Council leadership to respond to a request for information on federal EDRR legal authorities, gaps, and inconsistencies (see supplementary material (SI 1) associated with Reaser et al. 2019, this issue). Agency responses varied in terms of content and level of detail but provided a starting point for the analysis. To build and expand on the agency-provided information, we reviewed 54 titles of the US Code (USC) using LexisNexis and the Legal Information Institute to identify federal authorities related to invasive species EDRR. Using the statutes' associated notes, we then searched the Code of Federal Regulations (CFR) and relevant judicial decisions for additional information. To determine relevant content, we used terms that relate to EDRR operations, EDRR supporting tools, and invasive species (Table 1). As such, this assessment aims to provide a comprehensive overview of applicable US statutes and regulations, while recognizing that it is not exhaustive given the numerous authorities that touch upon some aspect of invasive species.

This assessment explores a range of authority types including those specific to invasive species, as well as broader statutes and regulations that could be applicable even though invasive species are not explicitly referenced. In the latter case, many of the invasive species-related authorities were not enacted with the specifics of EDRR in mind. However, given the critical need to address new invasions, federal agencies have identified means to use these authorities to incorporate aspects of EDRR into their activities.

Legal interpretations can change over time with input from the judicial system and Congress, as well as agency experience with policy implementation and scientific advances. This paper is intended as a catalog and non-prescriptive analysis of authorities that are directly and indirectly relevant to EDRR. A more thorough evaluation of their efficacy in implementation, funding availability/appropriations, reauthorization, resource allocation, and agency prioritization is beyond the scope of this assessment. The attending guidance on authorities in this volume (Burgos-Rodríguez and Burgiel 2019, this issue) provides more direction on addressing gaps in existing legal capacities.

## The legal context for invasive species[1]

While the US Constitution does not explicitly mention invasive species, it grants Congress authority to legislate, appropriate funds, and authorize federal agencies to take action and issue rules and regulations that may include invasive species. As a result, the executive branch can create policy, guidelines, and programs related to invasive species. Explicit legislation authorizing federal agencies to address harmful and potentially harmful non-native species has been present in the US legal system since the turn of the twentieth century with the enactment of the Lacey Act of 1900 (16 USC §§3371-3378, 18 USC §§42-43) and the Terminal Inspection Act of 1916 (7 USC §7760). However, each federal department or agency relies on different legal authorities. No holistic legislation for invasive species prevention, eradication, control, and coordination across all taxa has ever been enacted. Reports dating back 25 years consistently describe the legal status of federal invasive species programs as fractured and incomplete, resulting in a patchwork of laws, regulations, policies, and programs (Office of Technology Assessment 1993; Miller 2004; Environmental Law Institute 2007; Corn and Johnson 2013; Graham 2011; Johnson et al. 2017). For example, authorities may allow for action on federal but not non-federal lands. Authorities may apply to some categories of invasive species (e.g., those affecting plant health or livestock health), but not others (e.g., those affecting infrastructure or wildlife health). The piecemeal nature of the US system can undermine the effectiveness of efforts to address invasive species, particularly EDRR (US Government Accountability Office 2001) and contrasts with more comprehensive approaches employed outside of the United States such as in New Zealand and the European Union (Public Act 1993, 1996; European Commission 2014).

Despite these limitations, it is still possible to conduct a fairly thorough assessment of existing authorities and examine opportunities to cover gaps and inconsistencies. A number of statutes have been enacted to directly address invasive species. Many of these statutes are focused on a particular species, geographical area, industry, or pathway that has already proven to be a risk and are thus inherently reactive. Authorities to address invasive species are also divided jurisdictionally across federal agencies and subnational governments as well as topically by species and sectors of concern. There are also numerous statutes that when interpreted more expansively could allow federal agencies and departments to address issues related to invasive species and EDRR (Miller 2004; Johnson et al. 2017). Recognizing these differing levels of specificity and focus, we analyzed relevant authorities across four different categories:

*Category 1* Explicit invasive species authorities, including those addressing EDRR programs or actions, as well as those that could be interpreted to allow EDRR programs or actions.

[1] This assessment includes numerous references to the US Code and the Code of Federal Regulations, which can be viewed through services provided by the US House of Representatives (http://uscode.house.gov/browse.xhtml, accessed 5 September 2019) or the Legal Information Institute (https://www.law.cornell.edu, accessed 5 September 2019).

**Table 1** List of search terms related to EDRR operations, EDRR supporting tools, and invasive species

| Cooperative agreements | Environmental compliance | Monitoring | Regulation |
|---|---|---|---|
| *EDRR operations* | | | |
| Coordination | Eradication | Planning | Response |
| Data | Horizon scanning | Preemption | Risk assessment |
| Early detection | Identification | Quarantine | Staffing |
| Emergency | Inspection | Rapid detection | Surveillance |
| Enforcement | Major disaster | Rapid response | Terrorism |
| *EDRR supporting tools* | | | |
| Conservation | Maintenance | Outreach | Restoration |
| Control | Innovation | Research | Training |
| *Invasive species* | | | |
| Alien species | Disease infestation | Invasive insect | Pathogen |
| Aquatic nuisance species | Exotic and endemic animal disease | Invasive species | Pest injurious to agriculture |
| Bioagent | Exotic weed | Nonindigenous aquatic nuisance | Pest |
| Biological agent | Exotic | Nonindigenous species | Plant pest |
| Biological attack | Infectious agent | Non-native invasive species | Predator |
| Biological control organisms | Injurious | Nonnative species | Prohibited wildlife |
| Bioterrorism | Insect infestation | Noxious weeds | Undesirable plant |
| Damaging agents | Insect | Nuisance species | Weed |
| Disease | Invasive brush | Parasitic plant | Zoonotic diseases |

*Category 2* Emergency authorities that are not explicitly designed for, but could include, EDRR actions for invasive species under certain circumstances or could serve as models for enhanced invasive species EDRR authorities.

*Category 3* General authorities that, under the discretion of agencies, could include EDRR actions, as well as those that could explicitly support specific aspects of EDRR.

*Category 4* Constraining authorities and legal requirements that may entail certain assessments or additional review prior to initiating EDRR actions.

The supplementary material associated with this article (SI 2, this issue) contains a list of the authorities referenced below, and in some cases (e.g., Category 3), a more comprehensive listing.

## Category 1: Invasive species authorities

There are a limited number of legal authorities that allow for the detection of and response to invasive species. These authorities can be explicit as in the case of the Plant Protection Act (PPA) (7 USC §§7701 et seq.) and the Animal Health Protection Act (AHPA) (7 USC §§8301 et seq.), or provide discretionary authority for detection or response when authorized to carry out prevention, eradication, and/or control. Some of these authorities are pathway oriented as in the case of mail inspection and ballast water or species-specific as in the case of brown tree snakes (*Boiga irregularis*) and "undesirable bees." The remainder cover multiple EDRR elements for numerous types of organisms such as plant "pests" and diseases, as well as livestock diseases. Although many of these authorities are under the US Department of Agriculture (USDA) in relation to agricultural goods or forests, some include non-agricultural related organisms and non-federal lands.

Category 1 covers invasive species authorities that reference invasive species and/or relevant subcategories (e.g., non-native plant pests and animal diseases) in the context of EDRR programs or actions. In some cases this also includes programs or actions that could readily be interpreted to encompass EDRR. This section includes authorities related to executive orders, plant protection, animal health, inspections, forest health, aquatic invasive species, and additional wildlife or species specific authorities.

*Executive orders*

Under E.O.s 13112 and 13751, federal agencies can use relevant agency programs and authorities to detect and respond rapidly to eradicate or control populations of invasive species in a manner that is cost-effective and minimizes human, animal, plant, and environmental health risks. In addition, they can promote public education and action on invasive species, their pathways, and response measures, with an emphasis on prevention and EDRR. Finally, NISC is charged with advancing national incident response, including EDRR (Executive Office of the President 1999, 2016). In practice, E.O. 13112 has been explicitly used by a number of agencies as an authority to support the development of regulations (33 CFR 148.737, 23 CFR pt. 773 app. A, 43 CFR 46.215).

*Plant health*

The Plant Protection Act of 2000, as amended (PPA) (7 USC §§7701 et seq.), provides for the regulation of the movement of plant pests, plants, and plant products, as well as for quarantine procedures, declaration of emergencies, inspection, eradication, creation of agreements, and enforcement. PPA authorizes inspection of any person, means of conveyance, or premises carrying or believed to be carrying any plant, plant product, biological control organism, plant pest, noxious weed, or article moving into the United States, moving in interstate commerce, or intrastate commerce from or within any state, portion of a state, or premises quarantined as part of an extraordinary emergency declared under PPA (7 USC §7715, 7 CFR 330.105). PPA provides the authority to declare an extraordinary emergency due to the presence of a plant pest or noxious weed that is new to or not known to be widely prevalent in the US and that threatens plants or plant products (7 USC §7715, 7 CFR 330.106). Such a declaration provides USDA broad funding and response authority, including the authority to hold, seize, treat, apply other remedial measures to destroy, or otherwise dispose of such items, as well as authority to quarantine items, premises, and states or portions of thereof to prevent dissemination of or eradicate the plant pest or noxious weed (7 USC §7715, §7772, 7 CFR 301.1 et seq). Other remedial actions are authorized to prevent the dissemination of certain plant pests or noxious weeds new to or not known to be widely prevalent in the United States (7 USC §7714). Also, some USDA functions relating to agriculture import and entry inspection activities are transferred to the Department of Homeland Security (DHS) (see 6 USC §231, §551[d], §552[d], and §557, and the DHS Reorganization Plan of Nov. 25, 2002, which appears as 6 USC §542 note).

*PPA supports the development of programs and activities related to*

- identification and mitigation of threats to the domestic production of crops (7 USC §7721), including the development of plant pest risk assessment standards for certain products (7 CFR 319.40-11);
- control and eradication of noxious weeds, including technical assistance to certain weed management entities (7 USC §7781 et seq.);
- an audit-based certification system and a nursery plant pest risk management system in collaboration with industry, states, and local growers (7 USC §7721);
- an early plant pest detection and surveillance improvement program in consultation with the National Plant Board (7 USC §7721); and
- a Plant and Disease Response Fund to support emergency eradication and research activities in response to economic and health threats posed by pests and diseases affecting agricultural commodities under PPA and the AHPA (7 USC §8321).

While PPA is fairly broad, more specific legal provisions relevant to the management of invasive plants, cooperative efforts, and regulation of seeds are included in the Federal Noxious Weed Act of 1974, the Noxious Weed Control and Eradication Act of 2004, and the Federal Seed Act.

*Animal health*

The Animal Health Protection Act of 2002, as amended (AHPA) (7 USC §§8301 et seq.) consolidates a number of animal quarantine and related authorities resulting in the primary federal authority governing animal health (Johnson et al. 2017). AHPA provides for the regulation of the movement of any animal or related material necessary to prevent the spread of livestock pests or diseases, as well as quarantine procedures, declaration of emergencies, inspection, eradication, creation of agreements, and enforcement. AHPA has a broad definition of movement including mailing, shipping, and release to the environment (7 USC §8302). The USDA may carry out operations and measures to detect any pest or disease of livestock (e.g., drawing of blood, diagnostic testing of animals), including animals at a slaughterhouse, stockyard, or other points of concentration (7 USC §8308). It also authorizes inspection of any person, means of conveyance, or premises carrying or believed to be carrying a regulated animal or article moving into the United States, moving in interstate commerce, or intrastate commerce from or within any state, portion of a state, or premises quarantined as part of an emergency (7 USC §8307). USDA is designated as the lead agency with respect to issues relating to pests and diseases of livestock (7 USC §8310), while the Department of Health and Human Services (HHS) is designated as the surveillance coordinator for zoonotic diseases (7 USC §8319).

As with PPA, a key component of AHPA is the authority to declare an extraordinary emergency triggered by the presence of a pest or disease that threatens US livestock (7 USC §8306, 8316). Under the emergency, USDA can fund, hold, seize, treat, or apply other remedial actions to destroy or dispose of any animal, article, facility, or means of conveyance. In addition, USDA can prohibit or restrict the movement or use within a state, or any portion of a state of any animal or article, means of conveyance, or facility. USDA can take such actions only on finding that subnational governments are unable to control or eradicate a pest or disease after consultation with them. Herein, USDA is authorized to carry out operations and measures to control and eradicate any pest or disease of livestock (7 USCS §8308, 9 CFR ch.1 subch. B). AHPA control and eradication authorities can also be used for the detection, control, and eradication of aquaculture diseases (7 USC §8322).

AHPA supports the development of programs and activities related to

- preclearance agreements of animals or articles at locations outside the US moving into the country (7 USC §8311);
- a record-keeping system to provide for the reliable tracking of animal and plant shipments (7 USC §8320);
- coordinated detection and response to carry out operations and measures to detect, control, or eradicate any pest or disease of livestock, including funding to cooperating industries and states (7 USC §8308) and for veterinary training (7 USC §8319); and
- a network of national animal health laboratories to enhance capability to respond to bioterrorist threats to animal health, provide capacity for standardization, and develop and coordinate veterinary diagnostic laboratory capabilities (7 USC §8308a).

Other legal provisions relevant to the management of predatory wildlife and veterinary biological products for animal disease are included in the Animal Damage Control Act and the Virus-Serum-Toxin Act.

*Additional inspection authorities*

In addition to PPA and AHPA, a number of authorities provide for the inspection of certain agricultural products, wildlife, goods, cargo, people, or means of conveyance which could be pathways of introduction or disease vectors. Most inspection authorities are fragmented among different agencies, statutes, and regulations. One of these authorities, the Terminal Inspection Act (TIA) of 1916 (7 USC §7760) is one of the oldest pieces of EDRR-related legislation. A number of statutes and regulations related to the TIA, as well as the Lacey Act, the Alien Species Prevention and Enforcement Act of 1992, and security related authorities for DHS and the Transportation Security Administration (TSA) authorize EDRR activities; establish and prohibit nonmailable articles; authorize the prohibition and enforcement of wildlife importation; and allow for the inspection of passengers, cargo, and agricultural products imported to the United States and/or in interstate commerce.

*Forest health*

Invasive species can affect forest health in a variety of ways, including through insect infestations, forest diseases, as well as changes in soil composition and wildfire regimes (Wingfield et al. 2015; Boyd et al. 2013). There are multiple authorities addressing the detection and response to these threats. Some of these authorities include the Healthy Forest Restoration Act of 2003 (HFRA), the Cooperative Forestry Assistance Act of 1978 (CFAA), and the Hawaii Tropical Forest Recovery Act of 1992. CFAA authorizes USDA to protect certain trees and forests on USDA land and other federal and non-federal land from natural and man-made causes of harm (16 USC §2104). The HFRA addresses multiple aspects of forest health including fuel reduction, improving the capacity for early detection of insect and disease infestations, and promoting systematic gathering of information to address the impact of insect and disease infestations and other damaging agents on forest and rangeland health (16 USC §6501 et seq.). HFRA also provides for cooperation and assistance in developing treatments and strategies to reduce susceptibility of forests to severe infestation and diseases, and financial assistance to subnational governments for hazardous fuel reduction activities (16 USC §6508, 6553).

*Aquatic invasive species*

Authorities addressing aquatic invasive species include the Nonindigenous Aquatic Nuisance Prevention and Control Act of 1990 (NANPCA), as amended by the National Invasive Species Act of 1996 (NISA), and the River and Harbor Act of 1958, as amended by the Water Resources Reform and Development Act of 2014. NANPCA created the Aquatic Nuisance Species (ANS) Task Force (known as ANSTF), which is charged with developing and implementing a program for waters of the United States “to prevent introduction and dispersal of aquatic nuisance species; to monitor, control, and study such species; and to disseminate related information” (16 USC §4721). NANPCA also calls for a range of research and capacity support components including state management plans, species control plans, formation of regional panels, and programs focused on the zebra mussel (*Dreissena polymorpha*) and brown tree snake.

NANPCA includes reference to early detection in the context of monitoring, but does not reference rapid response (16 USC §4722). The Aquatic Nuisance Species Program (ANS Program) was finalized in July 1994. It provides significantly more detail to the charge within NANPCA to prevent, monitor, and control aquatic nuisance species, including aspects more specifically related to EDRR. With regard to the delegation of authorities across ANSTF membership, NANPCA provides the US Fish and Wildlife Service (USFWS), National Oceanic and Atmospheric Administration (NOAA), and the US Coast Guard with the authority to implement the ANS Program, and other agencies on the Task Force with sufficient authority or jurisdiction from other sources (e.g., PPA) can support implementation (16 USC §4722). ANSTF and associated federal agencies have used the discretion under NANPCA and other authorities to take on EDRR efforts to fulfil their individual missions.

Additionally, NANPCA, NISA, the Clean Water Act of 1972, and the Vessel Incidental Discharge Act of 2018 specifically address the regulation of ballast water as a potential pathway for the introduction of invasive species. These regulations focus more on acceptable standards for treatment of ballast water than on authorizing EDRR actions in the event of a potential introduction.

*Wildlife and specific species*

There are additional invasive species authorities that focus on wildlife collectively and/or particular species. Although these authorities do not necessarily provide for comprehensive EDRR programs, in many cases they could provide for EDRR elements such as detection or eradication. For example, the John D. Dingell, Jr. Conservation, Management, and Recreation Act of 2019 authorizes certain federal departments to plan and carry out activities on their land to protect water and wildlife by managing invasive species. This can includes eradication and population control, as well as research on EDRR methods (P.L. 116-9). Alternatively, provisions in the Lacey Act are focused on preventing the introduction and movement of injurious species by a listing process that prohibits import of injurious wildlife (18 USC §42[a]-[b]). The Act authorizes destruction and enforcement including search and seizure related to the movement of listed species (18 USC §42; 16 USC §3375).

There are also numerous species specific authorities that may include aspects related to EDRR, including: honeybees (7 USC §§281 et seq.; 7 CFR pt. 322), brown tree snakes (7 USC §§8501 et seq.; 16 USC §4728), depredating and otherwise injurious birds (16 USC §§703 et seq., 50 CFR 21.41 et seq.), nuisance mammals and birds, constituting reservoirs of zoonotic diseases (7 USC §8353), cotton insects (7 USC §1444a), crown of thorns starfish (*Acanthaster planci*) (16 USC §§1211 et seq.), jellyfish and other such harmful species (16 USC §§1201 et seq.), mosquitoes (42 USC §247b-21), wild horses (*Equus caballus*) and burros (*Equus africanus asinus*) (16 USC §1333, 36 CFR 222.69), sea lamprey (*Petromyzon marinus*) (16 USC §§931 et seq., §941c, §757b; 33 USC §2309a; 16 USCS §1274 notes), sudden oak death (7 USC §7720), and water hyacinth (*Eichhornia crassipes*), alligator grass (*Alternanthera philoxeroides*), and chestnut plants (*Trapa natans*) (18 USC §46).

The segmentation of authorities described above reflects a patchwork approach to invasive species related to different sectors (e.g., plant and animal health), ecosystems (e.g., forest health), and particular species (e.g., aquatic nuisance species, injurious wildlife). These authorities also allow for different degrees of action related to EDRR activities. For example, authorities under PPA and AHPA extend from monitoring and inspection to emergency response. In other areas, such as with aquatic invasive species those types of authorities are not as discrete, or in many cases the initial intent of the legislation was not for EDRR per se. Finally, these authorities are distributed across a range of departments, including DHS, USDA, Department of the Interior (DOI), US HHS, and the US Environmental Protection Agency (EPA), which may require additional efforts for interagency communication and coordination.

Category 2: Emergency authorities

Category 2 addresses types of emergency authorities that are not explicitly designed for, but could include, EDRR actions for invasive species under certain circumstances or could serve as models for enhanced invasive species EDRR authorities. This section covers authorities related to major disasters (with subsections on agricultural biosecurity, wildfire, and bioterrorism and weapons of mass destruction) and public health services and emergencies.

The US government has multiple emergency programs that involve some form of preparing for, detecting, and responding to a "crisis" event, which can be analogous to EDRR for invasive species. Examples include natural disasters, wildfire, bioterrorism, and pest and disease outbreaks. These national programs generally have robust legal frameworks that allow them to address multiple known and unknown scenarios. Often they are based on a primary piece of legislation that serves as a foundation, which can be modified over time with additional legislative amendments. They can address a broad range of authorities including collaboration with federal agencies and subnational governments, capacity building and training, flexibility in funding, consideration of subnational jurisdictions and private citizen's rights, declaration of emergencies, research, and considerations for environmental compliance. These components are essential elements designed to prepare, detect, assess, and respond to threats.

Authorities under bioterrorism, agricultural biosecurity, and public health emergencies explicitly address biological organisms. Some of these organisms are considered or may be associated with invasive species (e.g., certain disease vectors). Other authorities under this category, while not specific to invasive species, can readily be interpreted to apply. Invasive species have the potential to create a major disaster, cause agricultural and nonagricultural emergencies or epidemics, cause a public health emergency, or be used as a tool for biological warfare (Meyerson and Reaser 2003). Even if the direct applicability of these authorities to EDRR is limited to extreme events, they can serve as models for EDRR efforts. Other models include the Nuclear Incident Response Team; National Urban Search and Rescue Response System; Visible Intermodal Prevention and Response Teams; Hazardous Substance, Pollutant, or Contaminant Response; and Marine Mammal Health and Stranding Response Program. The following two sections examine authorities related to major disasters, emergencies, and public health emergencies.

*Major disasters and emergencies*

The Homeland Security Act of 2002 (HSA) and the Robert T. Stafford Disaster Relief and Emergency

Preparedness Act of 1988 serve as the legislative foundation for disaster authorities, which have been supplemented by a number of additional statutes. HSA and complementary authorities establish a broad framework for DHS leadership in emergency preparedness response to a range of threats. DHS is thereby responsible for coordinating and leading the nation's efforts to prepare for, respond to, recover from, and mitigate against the risk of all hazards (6 USC §314). This includes the planning and development of common capabilities necessary to address a range of threats, including natural disasters, catastrophic incidents, acts of terrorism, and other man-made disasters.

HSA and related acts establish the basic coordination functions for DHS and the Federal Emergency Management Agency (FEMA). This includes planning [i.e., national preparedness plan, coordinated response plan, national disaster recovery strategy (6 USC §741 et seq.; 6 USC §314; 6 USC §771)] and the development of a national preparedness system and national incident management system with federal, state, and local governments, to respond to such attacks and disasters (6 USC §314, 744; see also Burgiel 2019, this issue). It also includes building capacity with partners through the provision of funding, training exercises, technical assistance, planning, and other assistance to build tribal, local, state, regional, and national capabilities necessary to respond to a natural disaster, act of terrorism, or other man-made disaster (6 USC §313 et seq.)

The Stafford Act of 1988 provides broad authority to the president of the United States to declare a major disaster or emergency, triggering access to federal technical, financial, logistical, and other accelerated assistance by affected subnational governments. Invasive species could conceivably fit under the definition of major disaster, emergency, or catastrophic incident particularly in terms of agroterrorism, bioterrorism, or as an underlying driver of wildfire. Wildfire and bioterrorism as distinct threats are covered under these acts, but they are also covered by other, more specific authorities. Although many of these impacts, particularly for agricultural biosecurity, could be covered under the PPA or AHPA (see Category 1), emergency-related authorities could help address any gaps (e.g., non-livestock animals) and expand the availability of rapid response resources.

The Stafford Act authorizes the use of technical and financial pre-disaster hazard mitigation assistance to improve the assessment of vulnerability to natural hazards (42 USC §5133). In addition, it authorizes recovery activities including disaster impact assessments (42 USC §5170a). The National Infrastructure Simulation and Analysis Center is also authorized to support threat assessment for critical infrastructure (42 USC §5195c). The president has extensive authority to provide major disaster (42 USC §5170a) and emergency assistance (42 USC §5192) using any federal agency authority and resources (including personnel, equipment, supplies, facilities, and managerial, technical, and advisory services). Finally, in the specific case of nonindustrial private forest lands, USDA can provide financial assistance to owners who implement emergency measures for restoration purposes in the wake of a natural disaster (16 USC §2206). Herein, USDA used its discretion to include insect and disease infestations in their interpretation of the definition of natural disaster (16 USC §2206; 7 CFR 701.2).

There are also complementary and additional emergency authorities for particular types of threats, including agricultural biosecurity, bioterrorism and weapons of mass destruction, and wildfire. Many of these are also addressed by the National Biodefense Strategy (Executive Office of the President 2018), which provides a framework to coordinate federal efforts addressing biological threats.

*Public health services and emergencies*

In addition to the major disasters described above, there are multiple statutes addressing public health emergencies. These primarily include the Public Health Service Act of 1944 and the Public Health Security and Bioterrorism Preparedness and Response Act of 2002. Taken together these statutes provide a comprehensive legal framework for preventing, preparing for, detecting, assessing, and responding to public health emergencies associated with disease outbreaks or bioterrorist attacks. As with the previous section, these public health authorities can apply to a particular subset of invasive species (e.g., non-native pathogens and their vectors), while also serving as a general example of a more comprehensive approach to EDRR.

Most of the authorities outlined in these statutes relate to HHS, which is mandated to lead federal public health and medical response to public health emergencies and incidents. Responsibilities include preparing the National Health Security Strategy and an implementation plan for public health emergency preparedness and response. Such activities can include integration of public and private medical capabilities with other first responder systems, capacity building, coordination, continuity of operations, strategic initiatives to advance countermeasures, and medical and public health community resilience (42 USC §300hh-1).

HHS is also authorized to develop and implement a plan under which personnel, equipment, medical supplies, and other resources may be effectively used to control epidemics of any disease or condition and to meet other health emergencies or problems (42 USC §243). These activities can be further supported through HHS's issuance and enforcement of regulations necessary to prevent the introduction, transmission, or spread of communicable diseases (42 USC §264), as well as support for research and innovation in the areas of public health emergencies (42 USC §247d-7e; 42 USC §285l-6). HHS may conduct inspection of animals or articles to prevent the introduction, transmission, or spread of communicable diseases from foreign countries (42 USC §264), and is mandated to establish and maintain a list of biological agents that have the potential to pose a severe threat to public health and safety (42 USC §262a).

Finally, HHS is generally authorized to declare, fund, respond to, and "take such action as may be appropriate" to address public health emergencies caused by disease, outbreak of infectious diseases, or bioterrorist attack in line with its National Response Strategy. This includes deployment of emergency response teams (42 USC §247d); prohibition of the entry of certain persons, property, animals, and articles from foreign countries (42 USC §265; 42 CFR 71.63); and establishment and enforcement of interstate and foreign quarantines to prevent the spread of a communicable disease (42 USC §264 et seq.; 42 CFR 70.1 et seq.; 42 CFR 71.1 et seq.). HHS can cooperate with subnational authorities in the enforcement of federal and subnational quarantine regulations as well as other subnational health regulations (42 USC §243), and it can also temporarily reassign state and local public health department or agency personnel funded through programs authorized under the Public Health Service Act (42 USC §247d).

## Category 3: General and supporting authorities

Category 3 includes general authorities that under the discretion of agencies could include EDRR actions, as well as those that could support specific activities in the EDRR system. Currently, federal land management agencies use general authorities to address invasive species. These authorities were not necessarily enacted to specifically address invasive species, but they could be interpreted to allow agencies to take EDRR-related actions in some contexts. This category includes federal agencies' enabling/organic acts (i.e., those pieces of legislation that establish an agency's basic authority over a particular issue or selection of federal lands), as well as authorities related to cultural and natural resource conservation, preservation, restoration, management, and maintenance.

As highlighted in the other assessments in this Special Issue, EDRR activities are not limited to physical detection and response. These efforts are built on and complemented by a range of supporting activities, resources, and tools that underpin effective EDRR. These can include research and innovation, funding, staffing, ability to create cooperative agreements, enforcement, and resource acquisition. There are particular legal authorities that enable the development and implementation of such tools across the full suite of EDRR actions.

This section includes general authorities such as land and water conservation; wildlife and habitat protection conservation, rehabilitation and restoration; and infrastructure. It also includes supporting authorities such as research and innovation; enforcement; mechanisms of cooperation, good neighbor authority, and financial assistance; and volunteers (see SI S2 for a more comprehensive listing of relevant authorities).

### *General authorities: land and water conservation*

Most federal agencies with jurisdiction over public lands and waters have been provided broad authority to manage, create agreements, and regulate the use of such land and waters. Many of them mandate or authorize protection, conservation, restoration, and enhancement of these lands. These terms are very broad or are not defined and rely on agency discretion, which provides flexibility to address the threats posed by invasive species. Some agencies have used their discretion to include invasive species under their definition of management (43 CFR 2812.0-5).

Some of these authorities explicitly include invasive species management (e.g., stewardship contracts for national forest or public land management including control of noxious and exotic weeds under 16 USC §6591c, control of wildfires, insects, pest plants, and diseases in wilderness areas under 50 CFR 35.7, and removal of wild and exotic animals from US Army Corps of Engineers' (USACE) water resources projects under 36 CFR 327.11), while others provide discretion for agencies to take action as they see fit. Federal agencies have used such authorities to carry out invasive species EDRR. A good example is the National Park Service's (NPS) authority to regulate, prohibit, inspect, and decontaminate watercraft entering certain National Park System units (Department of the Interior 2018). Other agencies have been granted general authority for detection (e.g., monitoring and surveillance) and response (e.g., destruction and removal) (54 USC §100101; 100751). NPS can destroy animals and plant life detrimental to the use of any National Park System unit (54 USC §100752) or remove timber to control insects and diseases (54 USC §100753).

*General authorities: wildlife and habitat protection, conservation, rehabilitation, and restoration*

There are numerous authorities related to wildlife and habitat protection, conservation, rehabilitation, and restoration. As in the case of land and water conservation, these terms are broad or are not defined and rely on agency discretion. Wildlife and habitat protection, conservation, rehabilitation, and restoration can require prevention, control, and eradication of invasive species if they directly or indirectly impact wildlife and their habitats. Some authorities explicitly address invasive species, such as the Great Lakes Restoration Initiative (33 USC §1268), but most do not. In addition, there are also emergency restoration and conservation authorities that address natural disasters including invasive species (e.g., 7 CFR 701.2).

One of the major authorities for wildlife protection is the Endangered Species Act (ESA) of 1973 (16 USC §1531 et seq.; 50 CFR pt. 17; 7 CFR pt. 355). ESA is a critical federal environmental statute that could have direct and indirect implications for invasive species. This act provides for the conservation of threatened and endangered species of plants and certain animals. ESA requires federal agencies to ensure that governmental and non-governmental actions authorized, funded, or carried out by federal agencies are not likely to jeopardize the continued existence of listed threatened or endangered species or the destruction or adverse modification of their habitat. ESA could be used to prevent the introduction of invasive species that threaten listed species, as well as for direct actions against invasive species as part of endangered species recovery plans. These actions could include early detection and rapid response.

*General authorities: infrastructure*

Some federal agencies have authority to carry out or provide assistance for maintenance work to protect water, power, transportation, building, and housing infrastructure (Invasive Species Advisory Committee 2016). This work can include highway maintenance (USC Title 23), protection of navigable waters, river and harbor improvement, artificial reef management, dam protection, fishways construction, and maintenance of bridges over navigable waters (USC Title 33). In addition, there is authority for maintenance of reservoirs, irrigation works, and aging infrastructure (43 USC §491-492; 43 USC §510b et. seq.), construction and maintenance of water conservation and utilization projects in the Great Plains (16 USC §§590y et. seq.), and authority for protection and preservation of historic property (54 USC §306101 et. seq.). Federal agencies (e.g., US Department of Transportation) use discretion under such authorities to control certain invasive species, such as roadside vegetation. Similar discretion could be used for invasive species EDRR efforts to protect infrastructure.

*Supporting tools: research and innovation*

Basic and applied science are critical to understand, detect, manage, and eradicate invasive species. Innovative solutions are required to address invasive species that cannot be detected or eradicated by traditional methods (see Martinez et al. 2019, this issue; Reaser et al. 2019, this issue). As referenced above, there are numerous authorities allowing or funding research and innovation. Some federal agencies, like the US Geological Survey (USGS), have limited authority to address the management of invasive species, but play an integral role in conducting the science that management agencies need to inform EDRR efforts and decisions.

*Supporting tools: enforcement*

Enforcement can have dual meaning with regard to invasive species. On the one hand, it can provide for criminal or civil action (e.g., Lacey Act). On the other hand, enforcement authorities can provide for on the ground efforts such as inspection or seizure (e.g., PPA and AHPA). For the purpose of invasive species EDRR, on-the-ground enforcement is critical, and several federal authorities provide for enforcement. In addition, federal agencies can aid other federal agencies and subnational governments in the enforcement of certain authorities. As an example, USDA is authorized to cooperate with states or political subdivisions in the enforcement and supervision of a state's laws and ordinances on national forest system units (16 USC §551a; 36 CFR 241.1), NPS is authorized to cooperate with state law enforcement agencies to enforce state invasive species control laws within park units (54 USC §102701) or assist law enforcement on certain purposes outside park units (54 USC §102711). DOI and Department of Commerce (DOC) can establish agreements for enforcement of federal and state laws related to water and lands under their jurisdiction for the protection of fish and wildlife resources (16 USC §742l). Another example is the Department of Justice's authority to create a law enforcement task force in Hawaii to facilitate the prosecution of violations of federal and state law relating to the wrongful conveyance, sale, or introduction of nonindigenous plant and animal species (34 USC §12641; Resnik 2018). If federal agencies are authorized to enforce a subnational government's invasive species laws and regulations, this could expand their ability to carry out invasive species EDRR.

*Supporting tools: cooperation mechanisms, good neighbor authority, and financial assistance*

EDRR efforts require collaboration among national and subnational governments, as well as the private sector and other non-governmental entities. Most federal agencies have the authority to enter into contracts, grants, cooperative agreements, interagency agreements, awards, and memoranda of understanding (MOU) with other federal agencies, subnational governments, and other entities. This flexibility allows agencies to increase collaboration and can address federal gaps in capacity, resources, personnel, or authority. As an example, NPS currently has agreements to assist state agencies in providing inspection and decontamination of certain watercraft that may be transporting aquatic invasive species. At the local level, a number of federal agencies are involved in the work of cooperative invasive species management areas (CISMAs), cooperative weed management areas (CWMAs), and other cooperative stakeholder programs.

Agencies usually have general authority to enter into cooperation mechanisms, but there is also specific language for natural resources protection. As an example, land management agencies such as the Bureau of Land Management (BLM) and US Forest Service (USFS) have Good Neighbor Authority to enter into agreements with governors to carry out authorized restoration services including activities to treat insect and disease infected trees (16 USC §2113a). NPS has similar language for the protection of natural resources on park units (54 USC §101702). In addition, there are specific mandates to individual NPS park units that require coordination with adjacent land owners for invasive species management as well as discretion to collaborate and create partnerships to control and manage invasive species to protect certain public waters and wildlife (P.L. 116-9). Another example includes the authority for BLM to cooperate with subnational governments for noxious weed assessment and control (43 CFR 4120.5-2).

There is also legislation that allows states to create interstate agreements and compacts (agreements on matters in which there is a common concern) with other states to perform conservation efforts. Some examples include forest and water conservation agreements (16 USC §552), compacts for invasive jellyfish (16 USC §1204), and emergency management assistance compacts (6 USC §761). Statutes that authorize interstate agreements and compacts without the need of Congressional approval strengthen states' abilities to address invasive species with fellow states/territories. Compacts are currently used to address invasive species, such as the invasive species program under the Tahoe Regional Planning Agency (P.L. 96-551).

Finally, it should be noted that federal laws can also preempt subnational governments from taking certain actions, such as enacting or enforcing certain laws and regulations. Some invasive species authorities explicitly preempt state action unless consistent with federal regulations or a demonstrated special need (e.g., PPA 7 USC §7756).

*Supporting tools: volunteers*

Effective and long-term EDRR efforts require human capital beyond current federal staffing capability. Besides cooperation agreements with subnational governments and other entities for staffing support, there are multiple authorities allowing federal agencies to recruit and train volunteers for diverse functions. Some of these functions relate to fire prevention and conservation work. If federal agencies have authority to carry out EDRR efforts, volunteers could be used for support as permitted by law.

Category 4: Constraining authorities

Category 4 includes legislation and legal requirements that both provide essential protection for natural and cultural resources and potentially constrain EDRR efforts. For example, requirements for environmental assessments may delay responses or there may be limitations on particular control measures that can be used during a response effort. In order to ensure due diligence, transparency, and environmental protection, federal actions, including those related to invasive species management, need to comply with these environmental laws and regulations. However, advanced planning and consideration can allow EDRR in light of these laws and regulations.

This section includes authorities related to the National Environmental Policy Act (NEPA), the Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA), ESA National Historic Preservation Act (NHPA), and the Clean Water Act (CWA). It is important to note that these pieces of legislation serve an important function for protecting wildlife, human health, and other environmental and cultural concerns. This review is not intended as a critique of those provisions, but instead a recognition of their intersection with EDRR activities.

International commitments, subnational government's rights, and individual rights could also hinder EDRR actions but they are beyond the scope of the assessment.

*National Environmental Policy Act*

NEPA (42 USC §4321 et. seq.,40 CFR ch.V) requires federal agencies to: analyze the physical, social, and economic effects associated with proposed plans and decisions involving federal agencies or funds; consider reasonable alternatives to the action proposed; and document the results of the analysis. The provisions of NEPA and the Council on Environmental Quality (CEQ) implementing regulations apply to invasive species control and management given the potential for significant impacts to the environment. In this regard response actions on federal lands or using federal funds may require an Environmental Assessment (EA) or Environmental Impact Statement (EIS). Most agencies have their own NEPA implementing procedures (e.g., DOI 43 CFR pt. 46; USDA-APHIS 7 CFR pt. 372; USDA-ARS 7 CFR pt. 520; USDA-FSA 7 CFR pt. 799; USACE 33 CFR pt. 230; FS 36 CFR pt. 220; USPS 39 CFR pt. 775).

EAs and EISs require collection of data and public participation. If EAs and EISs related to EDRR activities are not considered in advance such efforts may be compromised as species can become established or continue to spread while those processes are completed. This is especially true for organisms with greater movement potential (e.g., animals). Compliance with NEPA can also be achieved by not categorizing an action as a "major federal action," streamlining the NEPA process, and/or by creating Categorical Exclusions (CEs) for classes of activity that won't have an adverse environmental impact. CEs can be established through legislation, although NEPA allows federal agencies to create CEs for very specific actions or a broader class of actions. For example, in October 2015, a CE for listing injurious species was developed, allowing the USFWS to streamline the listing process for injurious wildlife under the Lacey Act (Federal Register 2015). Similarly, there are examples where legislation specifically requires agencies to create a CE for certain invasive species related activities (e.g., greater sage-grouse [*Centrocercus urophasianus*] and mule deer [*Odocoileus hemionus*] habitat under 16 USC §6591). Other agencies, like

BLM, USACE and USFS, have developed CEs for invasive species management, and APHIS has incorporated CEs for routine measures into its implementing regulations for NEPA. Currently, more consideration is being given to the need for CEs that enable rapid response actions beyond what may already be allowed in the control context. Finally, NEPA allows waivers of EIS in certain emergencies (40 CFR 1506.11), although to our knowledge they have not been used for invasive species actions.

*Federal Insecticide, Fungicide, and Rodenticide Act*

Under FIFRA, EPA administers the federal registration process for pesticides (7 USC §§135 et seq., 40 CFR ch.I subch.E). FIFRA requires pesticide registration, establishes requirements, and limits the conditions under which they may be used. Under the definition of pest, some of these pesticides may be used to respond to invasive species (7 USC §136, 40 CFR 152.5). Pesticide registration can be an expensive and time consuming process (ELI 2007) which could limit the timeliness of rapid responses. This can include the registration of pesticides by EPA, as well as their subsequent review and approval for use by federal land management agencies. Note that not all invasive species response tools are regulated under FIFRA such as biological control agents, animal drugs, pheromones and pheromone traps, and minimum risk pesticides (40 CFR 152.20–152.30).

EPA has the discretion to exempt federal and state agencies from the provisions of this act through certain emergency exemptions (7 USC §136p, 40 CFR pt. 166.1). These emergency exemptions include a quarantine exemption to control the introduction or spread of any pest that is an invasive species, or is otherwise new to or not known to be widely prevalent or distributed within the US and its territories (40 CFR 166.2). It also provides a public health exemption to control a pest that will cause a significant risk to human health, an exemption to avert significant economic loss or risk to certain biodiversity and the environment, and a crisis exemption when there is insufficient time to authorize a specific quarantine or public health exemption (40 CFR 166.2).

*Endangered Species Act*

The ESA provides for the conservation of threatened and endangered species of plants and certain animals (see Category 3 above). ESA compliance could hinder agency actions associated with invasive species EDRR. This act prohibits certain actions and requires consultation, biological assessments, and issuance of permits for actions that might affect such species or their habitats. These requirements could limit available actions and affect the timeliness of EDRR efforts if they pose a risk to threatened or endangered species. The act and its regulations provide for certain waivers in presidentially declared emergencies and other emergency situations where the life or health of an endangered animal is threatened and no reasonable alternative is available (50 CFR 17.21–17.22; 50 CFR 17.31). Certain invasive species related activities are exempt from the incidental taking of a limited number of threatened wildlife under regulation (50 CFR 17.40, 17.41, 17.42, 17.47).

*National Historic Preservation Act*

The NHPA of 1966 sets forth federal agencies' responsibilities with respect to the preservation of historic property. Compliance with Section 106 of NHPA requires federal agencies to take into account the effects of their undertakings on historic properties through a consultation process, which provides for public involvement and allows the Advisory Council on Historic Preservation an opportunity to comment on the proposed undertaking (54 USC §306107-306108, 36 CFR 800.1 et. seq.). Although the Section 106 process is designed to ensure that federal agency decisions take historic properties into account, compliance with its requirements could hinder EDRR efforts by impacting the timeliness of actions. Federal agencies may be exempted from certain provisions of the NHPA's preservation responsibilities, but this does not apply to their responsibilities under Section 106. Program alternatives to full Section 106 consultation may be available, including exemptions and alternative compliance procedures. However, these may only be implemented by agencies after complying with regulatory prerequisites for such alternatives (54 USC §306108, 306112, 36 CFR 800.12). Absent a program alternative, federal agencies need to determine whether the proposed undertaking has the potential to adversely affect historic properties. If so, they would need to start a Section 106 consultation to determine whether any historic properties may be adversely affected by the proposed undertaking and whether those adverse effects may be resolved through agreement of the consulting parties prior to undertaking EDRR efforts. As mentioned, this could delay or constrain response alternatives and timeliness of actions.

*Clean Water Act*

The Clean Water Act of 1972(33 USC §1251 et. seq., 40 CFR ch.I subch.D) prohibits the discharge of "pollutants" through a "point source" into a water of the US without a National Pollutant Discharge Elimination System (NPDES) permit. The term "pollutant" includes dredged spoil, solid waste, incinerator residue, sewage, garbage, sewage sludge, munitions, chemical wastes, biological materials, radioactive materials, heat, wrecked or discarded equipment, rock, sand, cellar dirt, and industrial, municipal, and agricultural waste discharged into water (33 USC §1362). If EDRR actions involve the addition of a "pollutant" from a point source, then a permit is required. One example would be a pesticide requiring a Pesticides General Permit for invasive species eradication and control (Grad 2018a). If NPDES permitting is not considered prior to EDRR efforts, this could delay efforts or reduce the availability of tools or actions.

While EDRR activities are intended to protect natural, economic, and other resources, their conduct does not exempt them from compliance with other environmental statutes. Failure to address such environmental compliance prior to EDRR efforts might be one of the most limiting factors of success, regardless of the explicit or supporting authorities that a federal agency has. Some agencies have addressed these issues through the consideration and/or development of "hypothetical" EAs, programmatic EIS as well as CEs that take various contingencies into account should response actions be required (Grad 2018b). In this respect, table top EDRR exercises can be useful in determining the necessary legal requirements at the federal, state, and local levels. Finally, many of these statutes allow for exemptions in case of emergencies. This may be another area where engagement with federal agency solicitors could be useful to outline when and how they might apply to emergency response actions to invasive species.

## Key findings and conclusion

Looking across the four broad categories of relevant authorities, the following section summarizes the general findings and concludes with recommendations to advance the legal position of federal agencies in conducting EDRR activities. For more specific guidance on authorities see Burgos-Rodríguez and Burgiel (2019, this issue).

Legal Patchwork: As is the case with US law regarding invasive species in general, there is no single authority that encompasses EDRR for all invasive species. Most of the statutes discussed herein were not explicitly intended to address EDRR for invasive species. The result is a patchwork of relevant authorities and their concomitant regulations, policies, and programs that address or have been applied to various aspects of the EDRR continuum. These authorities approach EDRR, sometimes directly and more often indirectly, from multiple angles, such as

- impacted taxa (e.g., plants, livestock)
- harmful taxa (e.g., noxious weeds) and species (e.g., brown tree snake)
- impacted ecosystems (e.g., forests, rangelands)
- jurisdictions (e.g., National Forests, BLM lands, NPS units)
- pathways (e.g., ballast water, mail inspection)
- agencies (e.g., APHIS, USFWS, USCG)

PPA and AHPA are the most comprehensive pieces of legislation that deal with invasive species, yet they are largely limited to agricultural concerns (e.g., PPA has a wider remit to look at impacts on forests and other ecosystems, but that is often done through the lens of potential commercial impacts, particularly on agriculture). Outside of PPA and AHPA, coverage of invasive species that impact natural areas, wildlife health, infrastructure, and other gaps is fractured as EDRR and emergency elements are restricted to specific sectors, pathways, or species. This is further exacerbated by the fact that rarely do those more specific pieces of legislation directly address the full range of EDRR actions, with rapid response elements being the most common omission.

Theoretically, legislation focused on disasters, public health, and other emergencies may also be applied to invasive species, but that would only be in the most extreme cases of national or subnational emergencies. Their broader benefit may be as positive models for EDRR in other sectors given their focus on establishing preparedness, detection, assessment, and response capabilities. The Stafford Act, Homeland Security Act, and the Public Health Safety Act show how a statute can serve as a core framework for EDRR that is built on and amended over time by additional pieces of legislation. Note that some states have declared invasive species emergencies under state laws but have not triggered relevant federal laws (State of Montana Office of the Governor 2016).The PPA and AHPA are a step in this direction but they are singularly tied to USDA, and would need significant consideration to effectively integrate agencies, species, and impacted areas not under USDA's jurisdiction.

Agency Discretion: Recognizing that there are significant gray areas in the interpretation and application of available authorities, agencies can avail themselves of their legal discretion to take action where consistent with their mission and authorities. Such discretion is greater when dealing with federal lands, waters, and preempted areas of legal authority. Agency solicitors could examine existing flexibilities built into the law or ambiguities where terms are not explicitly defined. For example, this could include: the development of CEs and other means to expedite NEPA and other environmental compliance measures that might hamper response; interpretation of how directives to prevent or control invasive species factor into the elements of EDRR; interpretation of conservation and maintenance authorities; or definition of what constitutes an emergency in the invasive species context. Such an approach will provide some measure of relief towards addressing gaps, but cannot in itself exceed their given authority or make up for the lack of an overarching EDRR authority and would require a degree of internal political will and leadership to prioritize and accomplish.

*Environmental compliance* Of particular importance to this analysis are those laws requiring compliance with various environmental and public health regulations. While not viewed as invasive species regulations, they can have a major impact on the conduct of invasive species control and management, particularly in the context of rapid response. Response efforts can be hindered by mandatory administrative steps. Some of the disaster and emergency statutes do include exceptions for such compliance in emergency situations, however those exemptions are not uniformly carried through legislation that more specifically relates to invasive species. The review of agencies' NEPA implementing regulations, the development of any advanced planning on CEs and programmatic EIS, and the consideration of pesticide registration requirements under FIFRA could facilitate some progress in this area.

*Cooperation* EDRR generally involves a large suite of actors, not just federal agencies working in isolation. Agencies have a broad degree of flexibility in how they can work with subnational governments and other non-governmental entities in support of activities that address potential impacts on federal lands and, in some cases, non-federal lands as well. The other assessments in this volume detail more specifically where this type of cooperation can occur (e.g., detection, identification, information sharing, incident command system). In cases where federal agencies lack authority, they may be able to work with subnational governments under the umbrella of their authorities, which may be complementary or broader.

*Recommendations* Given their breadth of impacts over time, space, and sectors, invasive species already pose a sufficient threat to justify their separate recognition in law. However, it's possible that the breadth of impacts has also served to fragment legal responses in the United States. As noted above, outside the United States, other countries and regional entities, like New Zealand and the EU have in recent years worked to consolidate legal authorities and institutional responsibilities relating to invasive species to ensure more comprehensive coverage and efficient use of resources. Whether such an approach, for invasive species management in general or EDRR more specifically, is viable in the United States is an open question. But the alternative of providing patches whenever a new gap or threat arises may be equally untenable over the long term.

The accompanying guidance note on authorities in this volume (Burgos-Rodríguez and Burgiel 2019, this issue) provides some thoughts for advancing agency capacity to more fully implement EDRR from a legal perspective. Drawing from this review of authorities, some of those central activities would include the following:

1. Considering how to integrate and add to authorities in a more comprehensive manner that allows for improvements with amendments over time.
2. Providing for emergency designation of harmful or potentially harmful nonnative species without additional delays for issuing regulations or processing undue assessments before engaging in EDRR.
3. Using agency discretion to specify and streamline available agency measures to conduct EDRR activities.
4. Using broad authorities to enter into cooperation with subnational and non-governmental entities to cooperate on EDRR activities, particularly in areas where there are gaps at the federal level.
5. Leveraging supporting authorities to enable EDRR, including in areas addressed by other assessments (e.g., information sharing, research, technology development, use of challenge prizes).
6. Acting in accordance with EO 13112, as amended by 13751, to use relevant agency authorities to rapidly detect and respond to invasive species.

Invasive species EDRR must work across multiple jurisdictions and authorities. Although the task might seem daunting, the incremental impacts of invasive species on our nation requires further reinforcement of the complex legal framework that underpins the ability of federal agencies to effectively detect and respond to these threats.

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REVIEW

# Federal legal authorities: guidance for application to the early detection of and rapid response to invasive species

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**Abstract** Federal agency programs and associated actions are contingent on having the legal authority to act. There is no single authority established to direct the early detection of and rapid response to invasive species (EDRR). Rather, a patchwork of authorities unevenly addresses various aspects of the suite of EDRR measures. To support the development of national EDRR capacity, it is essential to delineate the federal legal statutes, regulations, and policies that enable or limit invasive species EDRR. Here we set forth general principles and a checklist of actions that agencies can refer to when they construct a more comprehensive EDRR legal and policy framework for addressing invasive species. This guidance is intended to complement the review and analysis of federal authorities contained elsewhere in this issue (Burgos-Rodríguez and Burgiel in Biol Invasions. https://doi.org/10.1007/s10530-019-02148-w, 2019, this issue).

**Keywords** Early detection and rapid response (EDRR) · Invasive species · Law · Legal authority · Policy · Regulation · Statute

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## Introduction

Federal agencies require legal authority to address invasive species, including in the context of early detection and rapid response (EDRR) (Burgos-Rodríguez and Burgiel 2019, this issue; Reaser et al. 2019a, this issue). Recognizing this, Executive Order (EO) 13112 (Executive Office of the President 1999), as amended by EO 13751 (Executive Office of the President 2016; US Department of the Interior 2016), calls for:

- EDRR to eradicate or control populations of invasive species in a manner that is cost-effective and minimizes human, animal, plant, and environmental health risks.
- An assessment of policy and regulatory frameworks pertaining to the prevention eradication, and control of invasive species, and to address regulatory gaps, inconsistencies, and conflicts.
- Efforts to promote education and action on invasive species, their pathways, and ways to address them, with an emphasis on prevention and EDRR.

With regard to the implementation of this order, the National Invasive Species Council (NISC) is tasked with ensuring that the federal agency and interagency activities concerning invasive species are coordinated, complementary, cost-efficient, and effective. Clarification of agency authorities and expansion of agency capabilities to more effectively undertake EDRR actions individually and with other partners are critical for advancing efforts to address invasive species and their impacts.

Complementing these orders, the *2016–2018 NISC Management Plan* calls for an assessment of federal legal authorities to inform the development of a national EDRR program for invasive species (NISC 2016). The resulting assessment (Burgos-Rodríguez and Burgiel 2019, this issue) reveals that no single federal authority encompasses EDRR for all invasive species. In many cases, existing authorities predate the broader systemic concept of EDRR described by Reaser et al. (2019a, this issue). Instead, a patchwork of statutes, regulations, and policies unevenly addresses various aspects of the suite of actions involved in EDRR with more comprehensive coverage in some areas (e.g., plants, livestock) than others (e.g., non-native wildlife). Although the creation of comprehensive invasive species EDRR legislation might be preferable, federal agencies have some flexibility to carry out and establish EDRR-related actions and programs by interpreting, expanding, and using current statutes, regulations, and policies. This document provides guidance on how to best leverage those authorities with a view toward developing a national EDRR program. This guidance is intended to complement the review and analysis of federal authorities by Burgos-Rodríguez and Burgiel (2019, this issue).

In drafting this guidance, it is important to recognize the following:

- Federal agency actions and programs require legal authorities to conduct invasive species EDRR.
- The source of such delegated powers can be explicit or can stem from other authorities as interpreted by courts or at the discretion of the agencies or the President.
- Federal agencies already use multiple authorities to carry out EDRR efforts and programs, but these are often limited to specific species, taxa, pathways, industries, and/or geographic areas.
- Invasive species do not respect jurisdictional boundaries. Hence, effective EDRR efforts and programs require the flexibility to coordinate across federal, state, and local governments, with non-governmental entities and private land-owners, as well as with other countries.
- International law and obligations need to be considered with regard to their relationship with domestic law and authorities (e.g., international trade, transport, and environmental law).
- EO 13112, as amended by EO 13751, authorizes federal agencies to use relevant authorities for invasive species EDRR. For the purpose of this guidance, final interpretation of an agency's authority rests with that agency.

## General principles

The main categories of authorities applicable to improving legal and policy frameworks include those derived from explicit invasive species authorities, emergency authorities, more general authorities (e.g., related to mission implementation), and constraining authorities and legal requirements that apply to EDRR activities (Burgos-Rodríguez and Burgiel 2019, this issue). Given the case-by-case nature and specificity of authorities across jurisdictions, this guidance note does not detail how EDRR responsibilities should be arrayed across those options. Additionally, since various aspects of EDRR authorities already derive from other legislation, the guidance provided here does not provide model legislation.

Our assessment indicates that a one-size-fits-all solution to federal EDRR authority is impractical and that existing authorities, for the most part, can be employed to determine the necessary content, form, and scope of EDRR capacity. Agencies also need to consider the various logistical, economic, and socio-political implications of legal measures as they look to underpin EDRR-related authorities. Relevant principles include the following:

- *Adaptability* Establish legal frameworks that can work across changing scenarios.
- *Cooperation* Use cooperation mechanisms when possible to create, strengthen, increase scope, and/or address gaps and inconsistencies related to invasive species EDRR actions or programs.
- *Harmonization* Consider approaches and priorities used in neighboring jurisdictions to enhance mutually supportive cooperative efforts.
- *Inclusiveness* Avoid species-specific regulations, actions, and programs in favor of those that can address a broader range of species.

- *Interdisciplinarity* Establish a legal framework utilizing scientific, technical, social, and legal expertise.
- *Proactiveness* Delineate legal authority and establish legal frameworks before a situation arises requiring EDRR efforts.
- *Synergies* Utilize current authorities and programs to enable agency activities across the EDRR spectrum.

## Action checklist

These principles need to be coupled with priority actions. We encourage relevant federal agencies to refer to the following checklist:

### Legal authority

Assess Agencies' Authorities

Federal agencies require legal authority to carry out EDRR actions or programs. Agencies should assess existing authorities that could enable or limit such actions and programs including

- Explicit invasive species authorities.
- Conservation, preservation, restoration, and maintenance authorities that could be applied to invasive species under an agency's discretion.
- Emergency, detection, and response authorities that could be applied to invasive species under specific circumstances or agency's discretion.
- Supporting authorities that enable invasive species EDRR, including research and innovation, funding, staffing, enforcement, resource acquisition, and cooperation.

These authorities should be analyzed in the context of the systematic approach to EDRR. Following the review of federal authorities addressing invasive species EDRR by Burgos-Rodríguez and Burgiel (2019, this issue), this analysis addresses authorities and policies in four major categories: preparedness, detection, risk screening, and response, which generally correspond to the EDRR system outlined by Reaser et al. (2019a, this issue). Agencies can build on their assessments to include agency policies, guidance, administrative adjudications, and other interpretations that supplement existing laws and regulations. Ideally, this effort will identify gaps, inconsistencies, and authorities that require clarification.

Agencies should consider the types of authorities listed in Tables. 1, 2, 3, 4 to support their EDRR activities, recognizing the need to fine-tune elements and that not all may be relevant to their mission and obligations. These categories generally include preparedness (Table 1), detection (Table 2), risk screening (Table 3), and response (Table 4). Agencies may also need to consider authorities to take any additional actions not identified below and those deemed necessary to carry out acts or programs in line with agency's mission and responsibilities.

### *Clarify terms*

Statutes, regulations, and policies can use technical language that is not clearly defined. Agencies should thereby examine existing flexibilities built into the law or ambiguities where terms are not explicitly defined while also striving to standardize terminology as appropriate across relevant agencies and departments. For example, agencies could:

- Develop categorical exclusions and other means to expedite NEPA and other environmental compliance measures that might hamper response.
- Interpret authorities and directives for prevention and control of invasive species and how they relate to EDRR.
- Interpret conservation and maintenance authorities.
- Define what constitutes an emergency in the invasive species context.

### *Clarify discretion*

Recognizing that there are significant gray areas in the application of available authorities, agencies can avail themselves of their legal discretion to act where consistent with their mission and authorities. Agencies currently use their discretion to address certain aspects of invasive species. This discretion could stem from invasive species or non-explicit invasive species authorities (e.g., conservation, preservation, restoration, maintenance, land management). Agency solicitors should evaluate, interpret, and provide opinions on the agency's discretionary power to address invasive species EDRR under these authorities.

**Table 1** Preparedness

| |
|---|
| Having the knowledge, plans, financial resources, tools, trained personnel, delineated responsibilities, programmatic prioritization, and coordination structures in place to streamline activities at each stage in the EDRR process |
| Appropriate funding, authorize expenditures, and/or collect user fees from services, fines, and penalties. This could include the establishment and resourcing of rapid response funding mechanisms |
| Establish and implement federal and intergovernmental response plans, programs, pilot projects, and regional efforts. This can include construction of facilities and other physical means to support EDRR activities |
| Collect and submit data to relevant information and record keeping systems (Reaser et al. 2019b, this issue) |
| Generate watch lists for priority invasive species and geographies (Reaser et al. 2019c, this issue) |
| Develop and enforce regulations, including limitations or prohibitions on importation and movement of organisms and their means of conveyance |
| Review obligations under environmental compliance authorities (e.g., National Environmental Policy Act [NEPA], Federal Insecticide, Fungicide, and Rodenticide Act [FIFRA]) and identify means to facilitate EDRR activities (e.g., categorical exclusions for rapid response activities) |
| Develop best practice guidance and voluntary standards to support relevant aspects of EDRR |
| Provide financial and technical assistance for capacity building, training, research, innovation, and outreach and education |
| Authorize cooperation and delineation of jurisdictions and responsibilities among federal and nonfederal partners. This should include the ability to enter into cooperation mechanisms with subnational and international governments, industry, academia, and others to conduct joint activities, work across jurisdictional boundaries, and share resources |

**Table 2** Detection

| |
|---|
| A process of surveying for, reporting, and verifying the presence of a non-native species before the population becomes established or spreads so widely that eradication is no longer feasible |
| Carry out and provide technical and financial assistance for monitoring and inspection activities, including surveys and assessments (e.g., surveillance, population inventories, sampling), automated targeting systems, record keeping, information gathering and analysis to predict occurrence of organisms, research and development of detection tools and technologies (e.g., eDNA, canine teams), and demonstration programs (Martinez et al. 2019, this issue; Morisette et al. 2019, this issue) |
| Enhance and expand detection capacity at the federal and subnational levels, including through the development and enhancement of monitoring programs and early warning systems for advance notice of new introductions |
| Enter into cooperation mechanisms for monitoring, detection, and surveillance |
| Establish and coordinate with a network of laboratories for identification and assessment of detected organisms (Lyal and Miller 2019, this issue) |
| Establish and use funds for monitoring and detection equipment, resources, and related efforts |
| Establish, cooperate, and maintain inspection stations and other relevant facilities |

Consideration should be given to whether current actions and programs can be used synergistically for invasive species EDRR (e.g., monitoring, detection, surveys) as well as the use of emergency authorities for invasive EDRR.

*Delineate the legal framework*

Building on the assessment and clarifications, agencies should delineate the legal framework for invasive species EDRR. This could be done using guidance, memoranda, and protocols. Drafting of such documents should detail when, how, where, and what type of authority exists, as well as instances where the current legal framework cannot answer those questions.

*Create and implement programs*

Using their delineated legal frameworks for invasive species EDRR, federal agencies should create and implement policies and programs as appropriate.

**Table 3** Risk screening

| |
|---|
| A rapid characterization of the types and degree of risks posed by a population of non-native species in a particular spatio-temporal context |
| Implement and provide technical and financial assistance for systematic information gathering to support assessments, including research on innovative risk screening techniques (Reaser et al. 2019b, this issue) |
| Conduct science-based assessments, including species-specific risk screening, risk analyses, and/or impact assessments (Meyers et al. 2019, this issue) |
| Establish and implement threat identification programs, including comprehensive horizon scanning activities |
| Develop lists based on risk screening and risk analysis efforts to support regulatory and non-regulatory means to reduce risks of introduction |
| Provide authority to take any other actions deemed necessary to carry out acts or programs in line with the agency's mission and responsibilities |

**Table 4** Response

| |
|---|
| A process that is employed to eradicate or control the founding population of a non-native species from a specific location |
| Develop, administer, and implement response plans (e.g., invasive species or geography specific) and related eradication and control programs |
| Declare emergencies and establish quarantines triggering resource and funding assistance, streamlining of certain environmental and administrative compliance, conduct of response actions, and enforcement of special prohibitions and restrictions |
| Establish and manage responses employing the National Incident Management System and Incident Command System frameworks in conjunction with federal and non-federal partners (Burgiel 2019, this issue) |
| Establish and deploy rapid response teams |
| Create and operate response coordination centers |
| Reassign and use employees, resources, funds, and equipment during emergencies |
| Implement and provide technical and financial assistance for rapid response, including but not limited to control, eradication, elimination, destruction, treatment, fumigation, disinfection, disposal, reduction of population, debris removal, and other remedial actions, as well as for research and innovation for eradication and control |
| Support emergency restoration, including the establishment and use of restoration funds |
| Enforce laws and regulations, including holding, seizing, or destroying contaminated or infested materials |
| Enter into cooperation mechanisms for enforcement, eradication, control, rapid response, and fire suppression |
| Authorize non-federal entities to enter and perform eradication and control programs on federal land |
| Clarify the authority to work on private and other non-federal lands |

## Environmental compliance

### *Assess environmental compliance waivers and protocols*

Laws and regulations requiring compliance with various environmental, historical preservation, and public health regulations are of particular importance (e.g., NEPA, Endangered Species Act, FIFRA, National Historic Preservation Act, Clean Water Act). While not typically viewed as invasive species regulations, these can have a major impact on the conduct of invasive species control and management, particularly in the context of rapid response. Response efforts can be hindered by administrative steps that may be overly burdensome in emergency situations. Some of the disaster and emergency statutes do include exceptions for such situations. However, those exemptions are not uniformly implemented through legislation that specifically relates to invasive species. Other agencies already have protocols and waivers for certain non-emergency environmental compliance laws and regulations. Agencies should assess their current invasive species and emergency environmental compliance waivers and protocols.

*Streamline environmental compliance*

Agencies should consider how current protocols and waivers could be used for invasive species EDRR and how they should be amended, expanded, reinterpreted, or created to streamline compliance, as permitted by law. On the one hand, agencies should aim to amend policies or create waivers to expedite EDRR efforts. On the other hand, agencies should also aim to increase their efficiency in compliance with the requirements of environmental laws and regulations.

Mechanisms of cooperation

*Assess cooperative mechanism authority*

EDRR generally involves a large suite of actors, not just federal agencies working in isolation. Agencies have a broad degree of flexibility in how they can work with subnational governments and other non-governmental entities in support of activities that address potential impacts on federal lands and, in some cases, non-federal lands as well. Cooperation mechanisms can be used to create or carry out EDRR programs and actions. Such mechanisms could be used to resolve jurisdictional issues, delineate responsibilities, establish protocols and standards, and address resource and funding allocation. In addition, such agreements could be used to address gaps in federal authority that are covered under the authority of non-federal partners (e.g., state agencies). Agencies should assess what cooperation mechanisms could best be used for invasive species EDRR in view of their specific mission and roles. Cooperation mechanisms may include

- Compacts
- Enforcement agreements
- Good neighbor authority
- Interagency agreements
- International agreements
- Memoranda of understanding and agreement
- Technical and financial assistance

*Establish mechanisms of cooperation*

Building on the assessment, agencies should establish cooperation mechanisms with federal and non-federal partners beforehand. Cooperation mechanism templates and protocols should be readily available to address unforeseeable circumstances not covered by existing cooperation mechanisms. Cooperation mechanisms could be used, as permitted by law, to delineate responsibilities, roles, and jurisdiction between federal and nonfederal partners; carry out EDRR actions and programs with federal and nonfederal partners both on federal and nonfederal land; allow states to create compacts for invasive species EDRR and management (e.g., Tahoe Regional Planning Agency); share enforcement responsibilities, enforce subnational laws and regulations, or allow subnational entities to enforce federal laws and regulations; create invasive species partnerships (e.g., Cooperative Invasive Species Management Areas and Cooperative Weed Management Areas); share resources with federal and nonfederal partners; and establish volunteer programs and standards.

Legal clearinghouse

*Create a legal authorities clearinghouse*

Building on the legal framework, environmental compliance, and cooperation mechanisms assessments, agencies should contribute to a centralized clearinghouse that contains policy- and law-related guidance, memoranda, and protocols; environmental compliance waivers, exemptions, and assessments (e.g., categorical exclusions, permits, environmental assessments, environmental impact statements, programmatic environmental impact statements); and mechanisms of cooperation. Such a clearinghouse would provide a centralized repository, reduce redundancy, and foster rapid response by facilitating access to legal documentation on invasive species EDRR.

## Conclusion

The invasive species issue is one of urgency and importance at international, national, and subnational scales. Collaboration and coordination among the federal government, subnational governments, academia, the private sector, and stakeholders are needed to minimize the impact of invasive species on the environment and economy, as well as human, animal, and plant health. Since federal agencies need legal authority to carry out programs and actions, it is imperative that they are able to consistently interpret and delineate enabling and constraining authorities relevant to invasive species EDRR. The guidance offered here is not intended to be comprehensive but does provide a framework for exploring the options, jurisdictional arrangements, and limits of applicability (e.g., gaps and inconsistencies) that need to be resolved for an effective national EDRR system.

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REVIEW

# The incident command system: a framework for rapid response to biological invasion

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**Abstract** The incident command system (ICS) is a framework for organizing and directing on-site, tactical responses to a particular event or series of events. ICS provides a command structure for coordination, information flow, analysis, decision-making, communications, and implementation in an authoritative and standardized manner. The ICS framework has been used for emergency response in a variety of situations where the environment, human health, or other resources are at risk, including wildfires, natural disasters, terrorist attacks, oil and chemical spills, infectious disease outbreaks, and invasive species. This paper outlines the key components of ICS, as well as major elements for building ICS capacity. It concludes with a list of considerations for applying ICS in the invasive species context.

**Keywords** Early detection and rapid response (EDRR) · Emergency response · Incident command system (ICS) · Invasive species · Rapid response

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## Introduction

The ability of federal agencies to rapidly respond to a newly detected invasive species is substantially enhanced by pre-planning and coordinated action (Reaser et al. 2019a, this issue). Recognizing this, Presidential Executive Order 13751 expressly calls upon the National Invasive Species Council (NISC) to "advance national incident response, data collection, and rapid reporting capacities that build on existing frameworks and programs and strengthen early detection of and rapid response to invasive species (EDRR), including those that are vectors, reservoirs, or causative agents of disease" (Executive Office of the President 2016). Similarly, the *2016-2018 NISC Management Plan* calls for building the capacity of federal agencies and partners to implement EDRR programs (NISC 2016).

The Incident Command System (ICS) is a framework for directing on-site, tactical responses to a particular event or series of events (US Department of Homeland Security 2017). The federally mandated model for incident response is embodied in the National Incident Management System (NIMS) developed by the Federal Emergency Management Agency (FEMA) and used throughout government (US Department of Homeland Security 2003, 2017). From the federal perspective, ICS provides a command structure for coordination, information flow, analysis, decision-making, and implementation in an authoritative and standardized manner. This framework has been used for emergency response in a variety of situations where human health, the environment, or other resources are at risk, including from natural disasters (Lutz and Lindell 2008), wildfires, terrorist attacks, oil and chemical spills (Moynihan 2007), infectious disease outbreaks (California Emergency Medical Services Authority 2014; Animal and Plant Health Inspection Service 2015), and invasive species. It should be noted that emergency response activities can also present a risk for the introduction and/or spread of invasive species (e.g., movement of hitchhiker species on vehicles, disposal of infested debris). The ICS process can facilitate the analysis of mitigating measures, such as the use of protocols to address those risks (e.g., firefighting equipment, watercraft). ICS standardizes the on-scene incident response process to provide an integrated organizational structure that can address the complexity and demands of an emergency where multiple agencies share management responsibilities or contribute to actions.

This paper provides guidance for applying ICS for effective, cost-efficient response to biological invasions, in keeping with the principle of EDRR (Reaser et al. 2019a, this issue) and relevant US government frameworks (Executive Office of the President 2016; NISC 2016; US Department of the Interior 2016). In view of the comprehensive principle of EDRR discussed by Reaser et al. (2019a, this issue), ICS comes into play as the response measure that is planned and executed on the ground after risk and feasibility screening identify this need. Once a potential invasive species has been detected, identified, and management (eradication or containment) measures are deemed warranted and feasible, ICS can be used to strategically guide on-scene actions, providing the structure by which government agencies and their partners cooperatively make decisions and mobilize resources. Ideally, ICS's on-site focus is complemented by the broader approach to incident management outlined in the NIMS and more specific sectoral guidance (e.g., FEMA's Emergency Support Functions).

## The ICS Approach

The National Response Framework (Framework) provides guidance for national responses to all types of disasters and emergencies. The Framework recognizes NIMS as the defining standard for the conduct of command and management structures responding to emergencies (US Department of Homeland Security 2016). Recognizing that there are a wide variety of emergency incidents, as well as a variety of potentially relevant agencies and partners, NIMS is designed to provide a common framework to achieve a common response goal (US Department of Homeland Security 2017). Within NIMS, ICS serves as the model for effective cross-jurisdictional coordination when an incident requires response from multiple emergency management and response agencies.

As described in NIMS,

> ICS is a standardized approach to the command, control, and coordination of on-scene incident management that provides a common hierarchy within which personnel from multiple organizations can be effective. ICS specifies an organizational structure for incident management that integrates and coordinates a combination of procedures, personnel, equipment, facilities, and communications. (US Department of Homeland Security 2017, 24)

Employing ICS as a standard protocol helps establish, develop, and maintain skills, processes, and roles necessary for coordination across different types of institutions. When incident management responders from different organizations come together to address an issue, they know what to expect and how to act according to their particular role in the ICS system.

The five major functional areas of ICS activities include Command, Operations, Planning, Logistics, and Finance/Administration (see Fig. 1). Each of these areas defines key personnel and their role within the response framework.

- *Command* includes the incident commander in charge of the overall incident, as well as command staff that consist of a public information officer, safety officer, and liaison officer. If the response encompasses multiple jurisdictions or authorities over a situation, a "unified command" structure is established to jointly manage and direct incident activities under a common set of objectives, strategies, and incident action plans.

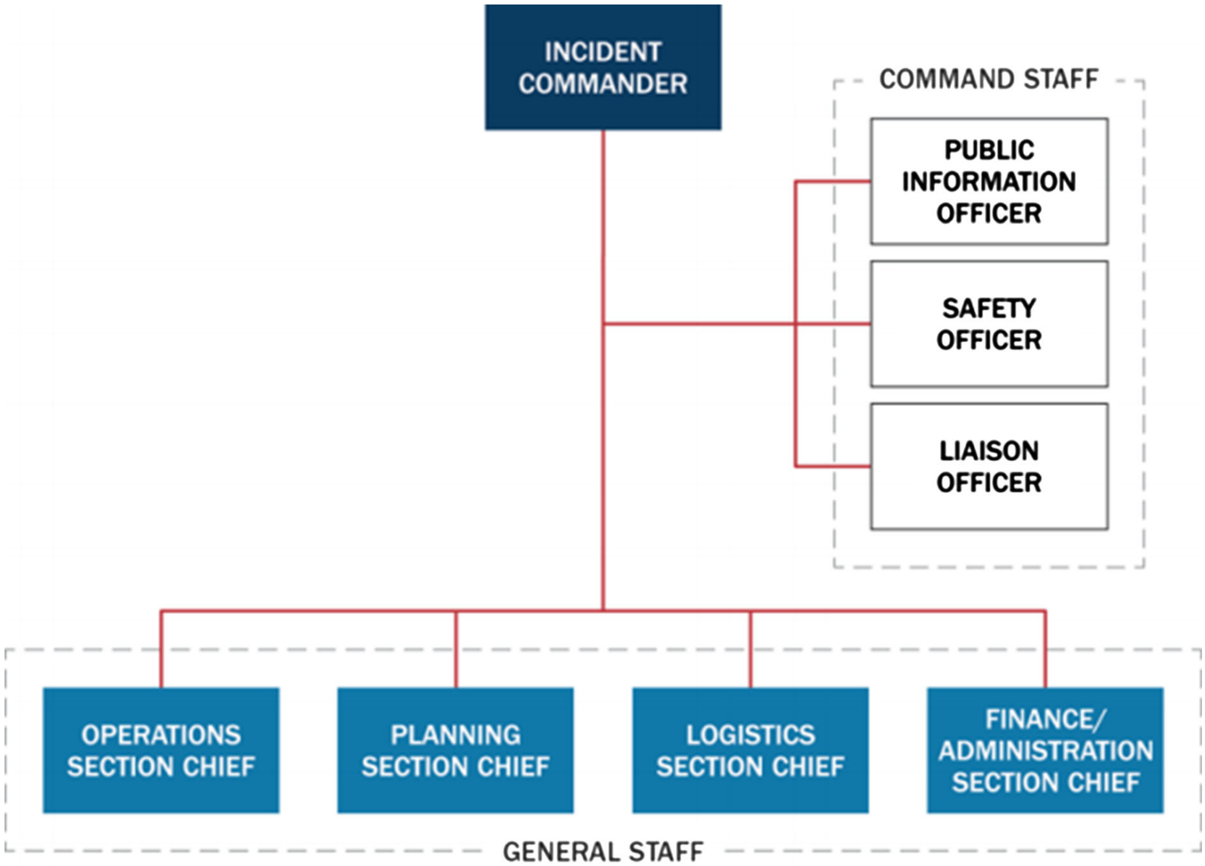



**Fig. 1** Example of ICS organization with a single Incident Commander. This model represents the leadership components for an ICS operation. The incident commander serves as the overall lead (where multiple agencies are involved this would be a unified command unit). Additional command staff officer roles are designated for public information, safety, and liaisons. General staff chiefs oversee the discrete areas of operations, planning, logistics, and finance and administration. Depending on the size of an ICS action, these roles can be held by separate individuals (in the case of a large response) or they can be combined under a single individual (for a small response) (US Department of Homeland Security 2017)

- *Operations* is responsible for managing tactical operations at an incident within the context of the incident action plans.
- *Planning* collects and evaluates information on the situation and resources, and then processes it for use in developing action plans. This can be in the form of incident action plans, briefings, and map and status board displays.
- *Logistics* is responsible for providing facilities, transportation, communications, supplies, equipment maintenance and fuel, food services, medical services, and other off-incident resources.
- *Finance/Administration* manages all of the financial aspects of an incident. Not all incidents will require this support, so this section may only be activated if there is a particular need.

Other elements of NIMS, including the use of Multi-Agency Coordination Centers, Emergency Operations Centers, and Joint Information Centers, also support the implementation of ICS (US Department of Homeland Security 2017). Effective use of ICS and more broadly NIMS is critically dependent on reliable, up-to-date information (Reaser et al. 2019b, this issue).

Standardization of the ICS organizational chart and associated terms does not limit the flexibility of the system. A key principle of ICS is its flexibility, given that there will always be unique aspects to any incident (e.g., situation itself, resource and staffing availability, applicable laws). The standardization of the ICS framework and roles does not limit this flexibility. For example, the ICS structure can vary in scale from a small routine operation up to a larger operation for addressing major catastrophic events (FEMA 2008). ICS has also been routinely applied outside of the emergency context as a means to coordinate planned activities.

The description above is a cursory overview of ICS, and more detail and documentation on its operation are available at https://training.fema.gov/emiweb/is/icsresource/index.htm (accessed 25 September 2019).

## Application of ICS to invasive species

When is it appropriate to apply ICS as a means to improve invasive species response capacity? ICS is particularly appropriate when multiple agencies are addressing a complex situation under temporal and other constraints. However, the benefit that ICS offers in terms of clear roles and terminology can also support operational- and cost-efficiency as a standard operating procedure in more routine applications, especially for organisms that can spread (or be spread) quickly. Criteria or triggers for engaging ICS in an emergency context need to be clear and detail what does (or does not) constitute an invasive species emergency. These criteria and triggers can also be linked to the development and operation of detection programs.

Core concepts of ICS include

- common terminology,
- integrated communications,
- modular organization,
- recognized command structure,
- manageable supervisory structure,
- consolidated action plans,
- comprehensive resource management,
- pre-designated incident facilities.

An ICS action needs to have concrete objectives that can be broken down into discrete operational periods designed to meet those objectives. Those periods generally have their own incident action plan to describe the operational period outline, structure, and goals for appropriate action. Those incident action plans typically include the incident objectives, health and safety information, staff assignments, communications plan, meeting schedules, contact information, as well as maps and other important field data.

ICS can be used across a range of scales from resource-intensive exercises involving hundreds of personnel and multiple jurisdictions to much smaller incidents confined within a single agency and/or management unit. To assist in the appropriate scaling of ICS, the process of incident complexity analysis can provide guidance on incident management requirements. FEMA has a generic complexity assessment template and more specific assessments have been developed to evaluate wildfires, which could serve as a possible analog for detailing an invasive-species focused complexity analysis (FEMA n.d.; National Interagency Fire Center 2018). It is also important to note that ICS has been used in more routine, non-emergency actions to address invasive species.

Based on information provided by federal agencies in their responses to a survey of federal EDRR capacities (Reaser et al. 2019a, this issue), ICS has been used by federal agencies and partners in a number of cases involving invasive species. For example, federal and state agencies on the Asian Carp Regional Coordinating Committee (ACRCC) used ICS in actions to address the risk of Asian carp in the Chicago waterway system (Tetra Tech 2010a, b). The US Department of Agriculture's (USDA) Animal and Plant Health Inspection Service's (APHIS) Plant Protection and Quarantine (PPQ) branch uses ICS and NIMS as core elements of their response programs (e.g., Asian longhorned beetle [*Anaplophora glabipennis*], fruit fly [*Rhagoletis cerasi* (Linnaeus)]) and incorporates those elements into a series of New Pest Response Guidelines targeting high risk plant pests (APHIS 2008, 2017a, b). APHIS also uses ICS when responding to invasive animals, most recently in collaboration with the US Fish and Wildlife Service to eradicate the New World screwworm (*Cochliomyia hominivorax*) from Florida (APHIS 2017c). Protocols to address potential introductions of aquatic invasive species on marine debris resulting from the 2011 Japanese tsunami detailed the need for deployment of the ICS framework in joint agency responses to help address jurisdictional boundaries and other policy concerns (National Oceanographic and Atmospheric Administration et al. 2012). Additionally, many of the National Park Service Exotic Plant Management Teams and US Fish and Wildlife invasive species strike teams employ ICS in conjunction with their partners as a standard operating procedure (T Hogan, J Klavitter pers. comm).

## Coordination

The broader set of structures outlined in NIMS along with ICS help to facilitate coordination across different agencies and organizations pursuing a mutually agreed upon, time-sensitive objective. While this system details the command functions, a number of additional aspects of coordination are critical to ICS's effective operation. ICS and associated incident action plans are crucial for guiding activity during an emergency and can be greatly facilitated by having a contingency or response plan in place beforehand.

Depending on the operation, a single incident commander may be appropriate for a single agency exercise, whereas a more developed unified command may be needed when multiple agencies are involved. Where there are multiple actors, agreements and memoranda of understanding developed prior to an incident are critical for establishing commitments and procedures related to resources and authorities. Mutual aid agreements, such as the Great Lakes–St. Lawrence River Basin Water Resources Compact, provide an assurance that funding and other resources will be available in an emergency and outlines how such resources are requested and funded as well as the roles of each party. Such agreements can also address triggers for activation, permitting, communication protocols, as well as the roles and responsibilities of involved parties.

State agency partners are an integral player in using ICS. Given their particular authorities, expertise, and resources, they often serve as the lead in an incident/unified command structure. For example, the Illinois Department of Natural Resources served as the lead agency for the major ICS actions focused on Asian carp in the Chicago area waterway system in 2009 and 2010, as well as subsequent smaller responses. Such invasive species activities can also be connected to broader all-hazard emergency response systems or state emergency operation plan.

The physical layout of the response is also important for coordination. In complex incidents, an incident command post is used to facilitate rapid communication with responders and field teams, and includes meeting spaces, computers, wireless and satellite connectivity, and other onsite facilities and logistical details, which are important enabling factors for coordination. Systems for checking in and out personnel, vehicles and equipment, and chemicals/treatments are critical for ensuring safety and smooth operations and for meeting resource tracking and fiscal responsibilities.

While focus is predominantly given to carrying out the response to the detected invasive threat, attention also needs to address demobilization and concluding an ICS operation. This includes orderly cessation of operations, finalizing accounting and data summaries, conducting post-exercise evaluations and debriefing sessions to secure feedback for optimizing future responses, and ensuring that all ICS personnel have formally signed out.

## Preparedness and planning

Preparedness and planning are fundamental to the effective implementation of ICS actions. It is important that responders have introductory training in ICS, while those in leadership positions receive more advanced, position- and team-specific training (e.g., ICS 300 and 400 level; see https://training.fema.gov/emiweb/is/icsresource/trainingmaterials.htm and https://training.fema.gov/emi.aspx, accessed 15 March 2019). FEMA and others also provide training opportunities to teams designated to support response actions, including through tabletop exercises or simulations and shadowing opportunities for live support actions when practicable. Lack of training can result in communication breakdowns across the chain of command given the specific nature of ICS roles, terminology, and execution.

Regular mock exercises, both tabletop and in the field, that cover a variety of scenarios are essential for establishing and retaining skills, building coordination and relationships across agencies and involved entities, and identifying key aspects of response that require improvement. Discussion-based exercises can highlight potential gaps in regulatory policies for managing spread, gaps in knowledge about the invasive species itself, effective survey, detection and control methods, and some of the logistical and technological needs that could lead to a safe and successful response. When expertise is needed for training or actual events, agencies can seek guidance from standing incident management teams from other governmental agencies or private entities to aid in developing functional programs and responses.

Broader emergency management or rapid response plans can guide ICS structure application for various scenarios, including priority geographies and target species. Such planning can incorporate the flow of information from a temporal (when to release information) and stakeholder (who is to receive information) perspective. As an example, federal and state agencies in the Great Lakes region develop an annual Asian Carp Action Plan, which is supplemented by an updated Asian Carp Monitoring and Response Plan (ACRCC 2018a, b). Figure 2 outlines the "Planning P" that the Monitoring and Response Working Group (MRWG) of the Asian Carp Regional Coordinating Committee uses to develop their incident response plan. In the Pacific Northwest, federal agencies, states and others have developed the Columbia River Basin Interagency Invasive Species Response Plan to address invasive mussels/Dreissenids (Columbia River Basin Team 2014). The state of Montana is also drafting its own Dreissenid Rapid Response Plan, which would align with the broader regional effort.

Use of data-based decision support trees, figures, and flowcharts can facilitate decision-making and overall understanding of operations further contributing to informed response management. Planning should include an understanding of logistical needs relevant to the scale and nature of the response action including site access, transportation, operations center, facilities for dining/housing/medical treatment, information system connectivity and communications, security, financial management, equipment storage, etc.

Planning also relies on and needs to secure relevant, reliable, and up-to-date information on a number of topics, including

- local geography, including maps of available access points (e.g., roads, boat launches) and logistical considerations (e.g., staging areas, transportation, housing),
- biological and ecological knowledge of high priority invasive species that might be targeted,
- available response tools for those high priority invasive species, including pertinent compliance information (e.g., for pesticide applications),
- available assets and resources from participating agencies to support the response effort,

**Fig. 2** The Asian Carp Regional Coordinating Committee's ▶ planning "P" for ICS actions. The Planning P represents the process that the Asian Carp Regional Coordinating Committee (ACRCC) uses to develop an incident action plan in response to an identification of Asian carp in the upper Illinois waterway. An identification triggers a number of initial activities by the Monitoring and Response Work Group including targeted assessment, initial response actions, and coordination with the broader ACRCC. This feeds into strategic planning activities to determine elements of a unified response plan. During the coordination, preparation and approval of the plan the Communications Work Group engages along with other ACRCC and stakeholder agencies. The final step is the execution of the plan and assessment of progress (Tetra Tech 2017)

- agency authorities over relevant geographies, facilities/resources, and compliance matters.

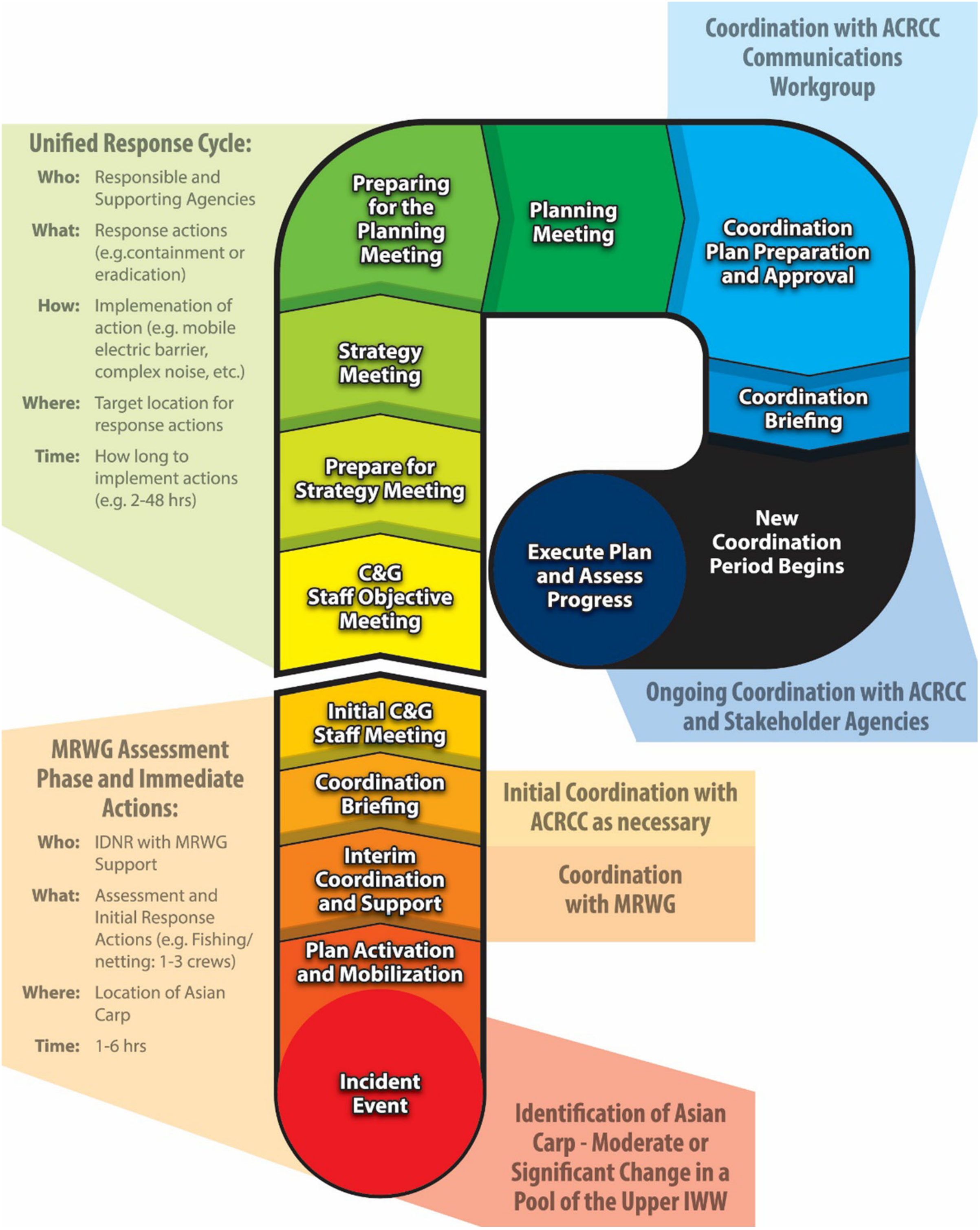
Finally, development of communication protocols, rapid response standard operating procedures, financial planning procedures, and other relevant guidance is particularly important for the effective and efficient performance of responders.

## Communications

Clear communication is integral to all aspects of ICS from the perspective of internal operations, as well as external engagement with the public and media. Internal communications need to be concise, easy to understand, and use plain language especially when multiple agencies or disciplines are engaged. Ideally, agency communication staff are participants in the response exercise.

Generally, the initial alert or notification will come from the affected jurisdiction prior to the establishment of the ICS response. The ICS communications process incorporates the ability to activate and mobilize personnel, facilities, and resources for an ICS response. An initial mobilization briefing may be useful for clearly communicating mission objectives and relevant plans and protocols in use. Information on proper demobilization is also critical to ensure safety and a proper close to operations.

Information needs to flow both vertically and horizontally within the prescribed communication channels of the ICS organizational structure to ensure continuity of operations and safety, as well as to respect local, regional, state, and federal authorities and responsibilities. Relevant content includes


Coordination with ACRCC Communications Workgroup
Unified Response Cycle:
Who: Responsible and Supporting Agencies
What: Response actions (e.g.containment or eradication)
How: Implemenation of action (e.g. mobile electric barrier, complex noise, etc.)
Where: Target location for response actions
Time: How long to implement actions (e.g. 2-48 hrs)
Preparing for the Planning Meeting
Planning Meeting
Coordination Plan Preparation and Approval
Strategy Meeting
Coordination Briefing
Prepare for Strategy Meeting
New Coordination Period Begins
Execute Plan and Assess Progress
C&G Staff Objective Meeting
Ongoing Coordination with ACRCC and Stakeholder Agencies
MRWG Assessment Phase and Immediate Actions:
Who: IDNR with MRWG Support
What: Assessment and Initial Response Actions (e.g. Fishing/ netting: 1-3 crews)
Where: Location of Asian Carp
Time: 1-6 hrs
Initial C&G Staff Meeting
Coordination Briefing
Interim Coordination and Support
Plan Activation and Mobilization
Initial Coordination with ACRCC as necessary
Coordination with MRWG
Incident Event
Identification of Asian Carp - Moderate or Significant Change in a Pool of the Upper IWW

updates on key operational activities (e.g., safety considerations, weather, when pesticides are applied, when divers are in/out of the water). Regular operational briefings are important for communicating vital information about the response, as well as to ensure that information is being shared from the top down as well as from the bottom up.

An established communications protocol or framework can detail many of these aspects, including information on agency representatives and personnel contacts in key positions, a call tree/alert roster detailing communications flow, technical information on media in use (e.g., radios, WiFi), etc. The connectivity and technological support necessary to backstop communication requirements need to be considered (e.g., data access/transmission, GIS information, mapping/tracking tools).

An "incident" involving invasive species can increase public awareness, concern, and even alarm. From an external perspective, communications with and messaging to the public and media need to be incorporated early in the planning stages with a focus on gaining trust in and support for operations. NIMS details the use of Joint Information Centers, which play a major communications role in supporting incident response. A public information officer(s) can be designated in the command structure to handle external engagement. They would meet with other incident/unified command staff to inform the preparation of remarks and development of consistent messages. This also helps to ensure that agencies have situational awareness of ongoing communications activities.

Resources

Securing the necessary resources for ICS operations is a critical role and requires close coordination across those responsible for finance/administration, operations, planning, and logistics. Resources can take a number of forms including funding, personnel, vehicles and equipment, as well as technical knowledge and skills. Additional supporting elements for ICS operations specific to invasive species will vary upon location and event but may include

- specialist(s) to provide technical/scientific advice to the Command and General staff during the planning and operational phases of a rapid response (e.g. an environmental specialist/unit to consider potential environmental ramifications and regulatory requirements of treatment options),
- a Joint Information Center to support external communications to the public,
- an onsite mobile command unit as well as communication and computer facilities for support staff.

**Building ICS capacity**

While the previous sections are useful for detailing key topics related to ICS and incident response, they do not answer the critical question of how one starts to build ICS into response protocols. Fortunately, ICS is practiced in a range of other sectors at various jurisdictional scales (e.g., municipal, state, federal). Building on that experience can be an effective way to move forward. Integration of ICS into invasive species response includes the following elements:

Planning: Response plans are critical for identifying key actors, geographies, potential threats, management measures, and resources. They can incorporate ICS as the command structure for responses designed to meet objectives outlined in response plans.

Context: Usually a local, state, or federal agency may be involved in hazard response associated with other threats (e.g., wildfire, disease outbreaks). The plans and informational resources can be a useful template for building ICS capacity focused on invasive species. Given the standardization of the ICS format, joint training and sharing of personnel can also provide opportunities to rapidly build capacity.

Training: Basic training of personnel in ICS is essential to avoid communication and operational failures. Advanced training for invasive species focused staff is also helpful for facilitating implementation of ICS and communicating to decision-makers. Joint training with other hazard response teams can also sensitize additional personnel that could be engaged in an invasive species response.

Exercises: Mock exercises are critical for identifying gaps and obstacles. Initially, tabletop exercises can help with identification of key personnel and other informational needs. Field exercises can be valuable for identifying logistical and resources challenges. Exercises thereby provide key lessons learned to improve response capacity and to keep personnel versed in ICS.

Criteria: Clear criteria for what triggers an ICS response are essential to ensure efficiency in its initiation as well as confidence in the decision-making process. This might include specific geographical areas or species prioritized by jurisdictions and their broader stakeholder community.

Resources: A range of resources are required to properly implement ICS including personnel, administration, communications, logistics, equipment and supplies, etc. At a basic level this implies sufficient funding, potentially from a dedicated source, as well as the political support to use it to address an invasive species incident. Such resources can be leveraged through the exploration of resource sharing agreements with surrounding jurisdictions and other relevant state and federal agencies.

## Key findings and conclusion

Within the broader scope of a national EDRR program, ICS can play a more instrumental role in standardizing the conduct and management of on-site response activities to invasive species. ICS application would facilitate cooperation among government agencies and their partners, improving the effectiveness and cost-efficiency of interventions. The following elements provide a checklist for improving ICS application to invasive species EDRR:

- *Rapid Response Plans* Develop response or contingency plans that incorporate ICS to enable rapid response to high priority invasive species.
- *Personnel and Training* Require emergency response training for appropriate field-level and management staff and take advantage of co-training opportunities with other all-hazard response teams.
- *Exercises* Regularly conduct tabletop and in field exercises to identify gaps, obstacles, and other needs, including clarification of issues around authorities, resources, communications, and logistics.
- *Cooperative Mechanisms* Explore options for developing and supporting cooperative arrangements with other federal agencies, as well as with states and local partners. Such interagency arrangements could include details on resource-sharing, delineation of authorities, communications protocols, and sharing of personnel and subject matter experts.
- *Incident Management Teams* Consider formation of an on-call incident management team that can implement ICS-structured response operations in their mission areas (e.g., Dreissenid mussels in the West, Asian carps in the Great Lakes).
- *Clearinghouse* Collate information on agency ICS and response resources to improve coordination, information sharing, and identification of lessons learned. Materials could include key agency contacts, staff resources and expertise, rapid response plans, interagency agreements, hotwash (after-action review) summaries from previous exercises, species- and geographic-specific information related to agency priorities, and other resources related to the application of ICS and NIMS to invasive species. This could inform the development of additional guidance materials for use by federal, state, and local agencies and their partners.

Rapid response efforts designed to eradicate or contain a newly detected invasive species are often highly complex efforts, involving a multitude of agencies, authorities, and resources. Rapid response measures often need to be employed under challenging conditions that include logistically difficult geographies, incomplete information, limited budgets, substantial time constraints, and the scrutiny of the public and media. To make things even more challenging, invasive species are self-perpetuating and self-mobilizing; the problem can grow while responders get organized. The ICS structure, when coupled with appropriate training, planning, and cooperative arrangements, provides an organizational model for facilitating coordination under tough circumstances while heightening safety and efficiency. ICS has proven its effectiveness both generally across a wide array of emergencies and specifically in the context of invasive species responses. While the EDRR process encompasses a broader suite of activities, it is clear that ICS can help advance response capacity.

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REVIEW

# Putting a federal capacities assessment to work: blueprint for a national program for the early detection of and rapid response to invasive species (EDRR)

**Jamie K. Reaser**

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**Abstract** This paper responds to national policy directives intended to improve the US government's capacity to protect national security from the adverse impacts of invasive species. It is the final, synthesizing contribution to a Special Issue of *Biological Invasions* comprising 12 papers that collectively inform the development and implementation of a national program for the early detection of and rapid response to invasive species (EDRR). The blueprint sets forth policies, goals, and actions to be taken by relevant Executive Branch agencies and components of the Executive Office of the President to develop a national EDRR program, appropriations permitting. It is designed to function as guidance for advancing federal policy through Presidential, Secretarial, and/or Congressional directives. Those committed to protecting national security, the economy, and the well-being of American people are forewarned that our ability to establish a national EDRR program is undermined by the diminishment of the federal workforce; institutional structures, policies, and programs; and directly applicable leadership mechanisms, including the National Invasive Species Council, Invasive Species Advisory Committee, and their managerial Secretariat.

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**Keywords** Detection · Response · EDRR · Invasive species · Federal capacities

## Introduction

A comprehensive approach to biosecurity encompasses a full range of risk management practices intended to defend against harmful and potentially harmful biological organisms, the vast majority of which are invasive species (Meyerson et al. 2009). The US government defines an invasive species to mean, "with regard to a particular ecosystem, a non-native organism whose introduction causes, or is likely to cause, economic or environmental harm, or harm to human, animal, or plant health" (Executive Office of the President 2016). Three presidential executive orders (EO) have explicitly recognized and focused on the threats posed to national security by harmful non-native species, tasking federal agencies to take a high-level, coordinated, and cost-efficient approach to invasive species prevention, eradication, and control (Executive Office of the President 1977, 1999, 2016). Many other presidential directives have complemented these executive orders, reinforcing national security concerns and establishing action plans for specific sectors. For example, the White House Council on Climate Preparedness and Resilience's priority agenda (Climate and Natural Resources

Working Group 2014) recognized the need to mitigate invasive species as an ecosystem stressor and called for a national approach to improving invasive species detection and response capacities (published as US Department of the Interior 2016). Although the linkages are not explicitly acknowledged, the National Biodefense Strategy (Executive Office of the President 2018) focuses on invasive pathogens and was informed by the US Invasive Species Advisory Committee (ISAC)'s briefing paper on invasive species impacts on wildlife health (ISAC 2018).

The 12 papers in this Special Issue of *Biological Invasions* deliver on a *2016–2018 National Invasive Species Council (NISC) Management Plan* (National Invasive Species Council 2016) priority action calling for "…scientific, technical, and institutional assessments in order to determine the capacities and resources necessary to establish a national early detection and rapid response program…" (hereafter, "federal capacity assessments"). They also advance two of the seven duties set forth for NISC implementation in EO 13751 (Executive Office of the President 2016):

- advance national incident response, data collection, and rapid reporting capacities that build on existing frameworks and programs and strengthen early detection of and rapid response to invasive species, including those that are vectors, reservoirs, or causative agents of disease, and
- support and encourage new technologies and practices, and promote the use of existing technologies and practices, to prevent, eradicate, and control invasive species…

In the first overview paper of the series, Reaser et al. (2019a, this issue) define the early detection of and rapid response to invasive species (EDRR) as a guiding principle for minimizing the impact of invasive species in an expedited yet effective and cost-efficient manner, where "detection" is the process of observing and documenting an invasive species, and "response" is the process of reacting to the detection once the organism has been authoritatively identified and response options have been assessed (i.e., risk and feasibility screening completed). Recognizing that EDRR is a non-linear, iterative process, the authors present a conceptual framework that portrays EDRR as the tenet for an integrated system (Fig. 1) rather than a step-wise set of components addressed in a linear manner, as has been typical of other EDRR frameworks (see discussion in Reaser et al. 2019a, this issue). The paper concludes with a short list of cross-cutting, catalytic actions to establish the foundation of a national EDRR program. The ten following papers in the series address specific components of the framework.

Here, I synthesize the primary needs identified by the federal capacity assessments into a blueprint for developing a national EDRR program. Figure 1 is to be referenced as the organizational framework for the paper. The papers in the Special Issue that explicitly identify the need for and/or guide federal actions are referenced within the blueprint. In content and format, the blueprint is explicitly designed to function as guidance for advancing federal policy through Presidential, Secretarial, and/or Congressional directives.

The survey of federal agency EDRR programs and capacities on which the assessments are based was substantially lacking in response from some agencies and on certain topics (see discussion in Reaser et al. 2019a, this issue). Although the NISC Secretariat staff and contractors augmented this information as feasible, resource limitations necessarily resulted in assessment gaps. In particular, the assessment team was not able to evaluate fully the effectiveness of existing EDRR programs, capacities of federal institutional frameworks (see Burgos-Rodríguez and Burgiel 2019a, this issue), types of response measures used and their effectiveness across taxa and context, or the applicability of the wide range of federal and federally-funded biodiversity inventory and monitoring programs to EDRR. The assessment authors also recognized the need to develop a feasibility screening process and associated decision support tool(s) (Reaser et al. 2019a, this issue).

When implementing the blueprint, agencies must consider at least four, potentially inter-related, needs for technical and institutional flexibility: spatio-temporal scale, taxa, available resources (particularly personnel and budget), and socio-political receptivity. Although the papers in our series make this point from various perspectives, none of the papers explicitly focus on these parameters. In large part, this reflects the lack of complete and in-depth response from relevant agencies. It is also an artifact of the tendency of technical journals to focus on scientific research rather than management approaches and their

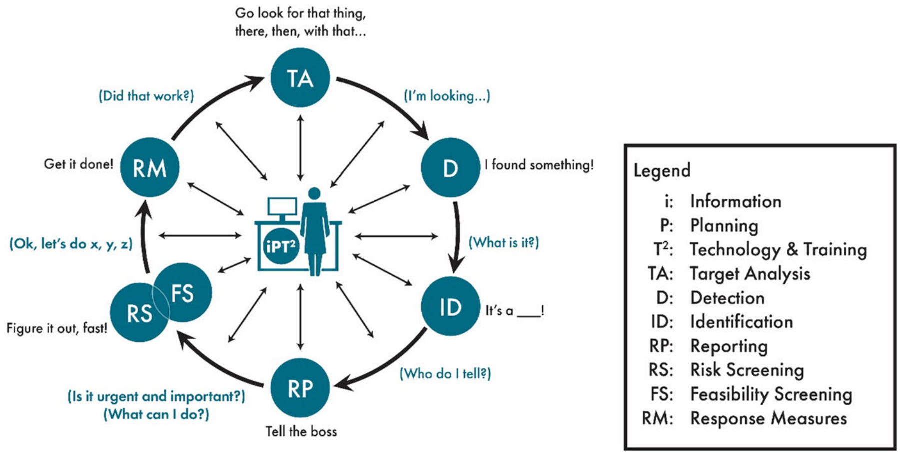


**Fig. 1** EDRR: a comprehensive system. In this model, the blue circles represent the primary actions (components) that need to be enacted in a step-wise manner for the effective detection of and response to a biological invasion. A legend clarifies the meaning of the letters in the circles. The associated commentary reflects the primary questions, observations, and directives that guide the process from one component to the next. At the core of the process, represented by the person and work station, are the informational and technical inputs necessary for the system to function. Arrows point in both directions in an effective system because the information and other outputs generated by one component are strategically used by other components. As is true of all models, this is a simplified depiction of reality; implementation of EDRR is a complex, iterative process that requires context-specific adaptation

outcomes. Action items to help fill aspects of these information gaps are included in the blueprint.

## The blueprint

### Purpose

The United States must sustain and expand efforts to protect national security, the economy, and the American people from the adverse impacts of invasive species across all sectors of society. Ideally, invasive species are detected and responded to along invasion pathways into the country or at our national borders, prior to entering the country. The federal government bears primary leadership responsibility for these actions. When these pathway management and border control efforts fail to intercept harmful or potentially harmful non-native species, the costs of action increase dramatically and the burden of defense falls upon land management and transportation agencies across all levels of government, the private sector, and the public. A high-level, whole-of-government approach is thus needed to facilitate the collaboration, communication, cost-efficiencies, and innovation necessary for effective EDRR.

### Policy

The federal government must coordinate and use applicable federal frameworks, investments, assets, and expertise to detect and respond to invasive species incursions in an effective and cost-efficient manner. Fundamentally, this requires agencies to support and facilitate access to the information, planning, technologies, and training that enable EDRR. In order to secure national assets and the well-being of Americans, federal agency actions must take into consideration and complement preparedness, planning, and implementation efforts of other countries; state, territorial, tribal, and local governments; non-governmental organizations; the private sector; and the general public.

### Goals

Consistent with Executive Orders 13112 and 13751 and other relevant national directives, the heads of federal agencies and relevant components of the Executive Office of the President (collectively, Agencies) shall, to the maximum extent permitted by law and other logistical feasibilities, carry out aforementioned policy by enabling and enacting actions to achieve the following EDRR capacity goals:

(a) *Coordination, integration, and communication* Agencies shall improve the coordination, integration, and communication of EDRR-related activities to enhance the collective benefits of federal programs and investments, as well as to strategically complement and integrate activities across Agencies and with state, territorial, tribal, and local officials. A key aspect of EDRR communication is the timely and accurate reporting of invasive species observations and interceptions, as well as anticipating and communicating the scale of potential spread and impact.

(b) *Legal and institutional capacity building* Agencies shall complement, harmonize, and expand the legal and institutional frameworks necessary to enable the rapid detection of and response to invasive species incursions prior to, upon, and after entry into the United States. This includes, but is not limited to, establishing cooperative agreements for invasive species EDRR among jurisdictional institutions from local to international scales of authority.

(c) *Planning and decision support* Agencies shall support EDRR-related planning approaches (including Incident Command Systems, and decision support tools, such as target analysis, risk screening, feasibility screening, watch lists) to increase the speed and effectiveness of invasive species detection and response measures.

(d) *Data collection, mobilization, and analysis* Agencies shall collect and share EDRR-relevant information (including data on non-native species occurrence, identification, biology, risks and impacts, response options and effectiveness), mobilizing it into an inter-operable, open-access, national invasive species information infrastructure (including databases, clearinghouses, and analytical and depiction tools) to strengthen the decision-making capacities required for timely detection of and effective responses to invasive species incursions.

(e) *Scientific, technical, technological capacity building* Agencies shall enhance EDRR efforts by carrying out and supporting relevant research, technology innovation and transfer, and technical training, including by addressing impediments to taxonomic capacity and fostering contributions from citizen scientists as an urgent matter.

(f) *Response measures* Agencies shall facilitate and expand capacities to respond rapidly and effectively to invasive species incursions by addressing any barriers associated with legal and institutional frameworks, planning and coordination, decision support, and technological or technical capacity, as further described in goals a–e.

Actions

To further the aforementioned policies and goals, as made feasible by the availability of appropriations, Agencies should act cooperatively as follows:

(a) Coordination, integration, and communication

   (i) Create a glossary of EDRR-relevant terms; examine term ambiguities, inconsistencies, and flexibilities; and harmonize or standardize terms as feasible, communicating and institutionalizing these terms to facilitate their understanding and application (Burgos-Rodríguez and Burgiel 2019b, this issue; Reaser et al. 2019a, this issue).

   (ii) Develop and routinely update a publicly-accessible EDRR operational plan that demonstrates the relevance of EDRR to Agency missions, as well as their authorities, roles, and responsibilities relevant to EDRR components (Fig. 1). Include contact information for authoritative focal points (Reaser et al. 2019a, this issue).

   (iii) Undertake and publicly report the findings of an inventory of Agency assets for supporting a national EDRR program, including programs currently focused on addressing invasive species and those programs that could be cost-effectively modified to expand federal capacities for addressing invasive species (e.g., inventory and monitoring programs currently focused on native species) (Meyers et al. 2019, this issue; Reaser et al. 2019a, this issue).

(iv) Taking (a-iii) into consideration, resume and enhance the EDRR cross-cut budget, making it applicable to the effective leveraging of existing agency resources and development of multi-agency funding proposals to address common needs for additional resources.

(v) Establish flexible yet binding agreements and other coordinating mechanisms among federal agencies, as well as with all others who bear responsibilities for the management of invasion pathways and recipient ecosystems. The arrangements should detail resource-sharing, delineation of authorities, communications protocols, and sharing of personnel and subject matter experts (Burgiel 2019, this issue; Lyal and Miller 2019, this issue).

(b) Legal and institutional capacity building

(i) Delineate and communicate a national legal and institutional framework for enabling the early detection of and response to invasive species across taxa and geographies. The framework should support Agencies to act in accordance with Executive Orders 13112 and 13751, as well as other complementary executive guidance (Burgos-Rodríguez and Burgiel 2019a, b, this issue; Lyal and Miller 2019, this issue; Reaser et al. 2019a, this issue).

(ii) Analyze and publicly report on Agency authorities and mechanisms for authority (such as compacts, enforcement agreements, good neighbor authority, interagency agreements, international agreements, memoranda of understanding and agreement, technical and financial assistance) for their ability to facilitate and/or serve as barriers to implementing a national EDRR program. This should include explicit invasive species authorities and mechanisms, as well as a wide range of permitting and enacting authorities and associated mechanisms (including compliance waivers and protocols) that could be applied at an Agency's discretion (Burgos-Rodríguez and Burgiel 2019a, b, this issue).

(iii) Harmonize and streamline authorities and associated mechanisms, giving priority attention to environmental compliance agreements, to expedite EDRR and increase operational cost-efficiencies (Burgos-Rodríguez and Burgiel 2019a, b, this issue).

(iv) Establish authorities and associated mechanisms to fill gaps in the national and legal institutional framework, including to provide emergency designation of harmful or potentially harmful non-native species without additional delays for issuing regulations or processing undue assessments before enacting EDRR (Burgos-Rodríguez and Burgiel 2019a, b, this issue).

(v) Direct Agency solicitors to evaluate, interpret, and provide opinions on discretionary powers to address EDDR under Agency authorities, giving particular consideration to whether current actions and programs can be used synergistically for EDRR and how emergency authorities and associated resources can be applied to EDRR (Burgos-Rodríguez and Burgiel 2019b, this issue).

(c) Planning and decision support

(i) Develop invasive species response or contingency plans that incorporate Incident Command System principles and protocols to be applied by incident management teams operating along invasion pathways, at ports of entry, and across regional scales (Burgiel 2019, this issue; Morisette et al. 2019, this issue).

(ii) Regularly conduct table-top and in-field exercises to identify gaps, obstacles, and other planning needs, including clarification of issues around authorities, resources, communications, and logistics (Burgiel 2019, this issue).

(iii) Develop and communicate performance metrics for EDRR decision support tools (including target analysis, risk screening, feasibility screening, and watch lists), recognizing that different ecosystems, pathways, and taxonomic groups may require separate but complementary approaches (Meyers et al. 2019, this issue; Morisette et al. 2019, this issue; Reaser et al. 2019c, this issue).

(iv) Conduct, report on, and enact the findings of a needs assessment for standardizing, strengthening, and expanding use of science-based decision support tools within and across Agency EDRR programs, including providing sufficient staffing for conducting decision support analyses, applying advanced technologies, and making tools and their outputs publicly accessible through decision support toolkits consistent with regulatory approaches (Martinez et al. 2019, this issue; Meyers et al. 2019, this issue; Morisette et al. 2019, this issue; Reaser et al. 2019c, this issue).

(v) Along invasion pathways into the United State and at national borders, prioritize planning and decision support for species new to trade or increasing in trade popularity to reduce propagule pressure and the burden of response (Meyers et al. 2019, this issue; Morisette et al. 2019, this issue; Reaser et al. 2019c, this issue).

(d) Data collection, mobilization, and analysis

(i) Facilitate greater access to the information required for EDRR decision-making by establishing and supporting user-friendly, open access, centralized, searchable clearinghouses that include relevant authorities and authorizing mechanisms, planning protocols and supporting information, decision support tools and analyses, reports on the effectiveness of response measures, and training course curricula. The clearinghouses should be integrated with relevant local, regional, national, and international databases, as well as their associated analytical and data depiction tools (Burgiel 2019, this issue; Burgos-Rodríguez and Burgiel 2019b, this issue; Lyal and Miller 2019, this issue; Meyers et al. 2019, this issue; Morisette et al. 2019, this issue; Reaser et al. 2019a, b, c, this issue; Wallace et al. 2019, this issue).

(ii) Establish a coordinated framework of interoperable information systems, recognizing that information systems not initially designated for EDRR may be applicable (Lyal and Miller 2019, this issue; Meyers et al. 2019, this issue; Reaser et al. 2019b, this issue; Wallace et al. 2019, this issue).

(A) In order to operationalize the coordinated information framework, Agencies should:

a. Establish a government-wide invasive species data management policy for designated data custodial roles and management responsibilities from agency to programmatic levels, address relevant legal and policy issues (including privacy and security), and institutionalize invasive species information management guidelines. The policy should be authoritative and specific enough for agencies to discern their obligations, address sensitive data-sharing concerns, and direct the mobilization of federal data into publicly available information systems, yet sufficiently flexible to account for unanticipated needs and emerging opportunities

(Reaser et al. 2019b, this issue; Wallace et al. 2019, this issue).

b. Identify, improve, and sustain federal information systems that are vital to the operation of a national EDDR program, assess their relationships (e.g., for duplicative or integrative functions), and develop and implement a plan for improving, sustaining, and making these systems more cost-effective over the long-term. This should including building the capacity to join datasets to improve biological, geo-spatial, and socio-economic analyses (Reaser et al. 2019b, this issue).

c. Identify, develop, and support relevant data standards, including those that delineate critical aspects of invasive species biology and population parameters needed to distinguish which non-native species are invasive and priorities for response measures, North American Invasive Species Management Association mapping standards, and metrics for capturing the environmental and socio-economic impacts of invasive species (Wallace et al. 2019, this issue).

d. Establish an agreement for data sharing among the primary information systems for non-native species occurrence data in the United States (Wallace et al. 2019, this issue).

e. Mobilize non-native species occurrence data into publicly accessible central data integrators/aggregators that are coupled with appropriate analytical and decision support tools, using the Biodiversity Information Serving Our Nation (BISON) information system (https://bison.usgs.gov, accessed 19 September 2019) and interoperable data sources. Facilitate this effort by developing and implementing an ongoing national campaign for non-native species data collection and mobilization (Morisette et al. 2019, this issue; Reaser et al. 2019b, this issue; Wallace et al. 2019, this issue).

f. Encourage databases serving taxonomic names, such as the Integrated Taxonomic Information Service (ITIS) (https://www.itis.gov/, accessed 25 September 2019) to address gaps in taxonomic groups that have a high propensity for invasiveness as a matter of priority (Wallace et al. 2019, this issue).

g. Foster the development and sharing of EDRR-relevant analytical and data depiction tools, including tools for specialized data searches, mapping and other spatial analyses, species identification, decision support, and response evaluation (Martinez et al. 2019, this issue; Reaser et al. 2019b, this issue).

h. Continue US engagement in international information standard-setting bodies, frameworks, and platforms, including the Global Biodiversity Information Facility (GBIF; https://www.gbif.org, accessed 19 September 2019).

(B) In order to enhance the information content accessible through the coordinate information framework, Agencies should as a priority:

a. Make federal pathway and ports-of-entry non-native species intercept data publicly accessible to the extent legally feasible (Reaser et al. 2019b, this issue).

b. Incorporate and enable analysis of species-in-trade data (including species, quantities of imports, and countries of origin and transit) that are contributed by industries or by harvesting non-native species trade data from social media via web crawling tools (Meyers et al. 2019, this issue).

c. Include information on invasive species impacts and management options, including their effectiveness (Wallace et al. 2019, this issue).

d. Facilitate ready access to biological data that enable detection and response technology development by, for example, building and linking to genetic libraries (DNA fingerprinting) to enable identification tool development and cell lines of current and potential invaders to allow in vitro screening of potential control agents (Lyal and Miller 2019, this issue; Martinez et al. 2019, this issue).

(e) Scientific, technical, and technological capacity building

(i) Further our knowledge of species biology, ecology, and impacts, including the implications of interactions among species, spatio-temporal variation in risks, and interactions between invasive species and other drivers of environmental change (Reaser et al. 2019b, this issue; Meyers et al. 2019, this issue; Morisette et al. 2019, this issue).

(ii) Advance invasive species detection and response technologies, collecting and sharing data on their efficacy. Give priority to surveillance, identification, and response tools that are socially acceptable, cost-efficient, and effective for multiples species and contexts. Facilitate this work by supporting a culture of innovation and communities of practice (Martinez et al. 2019, this issue; Morisette et al. 2019, this issue).

(iii) Increase and modernize research facilities to advance new technological response measures in a manner consistent with changing regulations, new approaches, study replication needs, and regional efficiencies (Lyal and Miller 2019, this issue; Martinez et al. 2019, this issue).

(iv) Maximize and expand technical staff capacities by detailing staff between agencies, creating interagency collaboratives, and expanding partnerships with non-federal institutions, particularly with the private sector or academia (Lyal and Miller 2019, this issue; Martinez et al. 2019, this issue).

(v) Support citizen science initiatives and open-access, low-cost detection, identification, and reporting tools for public application to EDRR (Lyal and Miller 2019, this issue; Martinez et al. 2019, this issue).

(vi) Promote, as a matter of urgency, adequate taxonomic and identification expertise and associated financial and technical resources, including standardized identification protocols, at all scales (Lyal and Miller 2019, this issue).

(vii) Ensure long-term sustainability of biological reference collections, including representatives of specimens from native and introduced ranges linked to evidence of impact where feasible (Lyal and Miller 2019, this issue).

(viii) Support and further the use of prizes and challenges to encourage technology development and dual-use application for invasive species of high priority concern (Martinez et al. 2019, this issue).

(ix) Require routine and consistent training for appropriate field-level and management staff, giving particular attention to identification capacity, Incident Command System operation, and emerging technology application (Burgiel 2019, this issue; Lyal and Miller 2019, this issue; Martinez et al. 2019, this issue).

(f) Response measures

(i) In removing barriers to response capacity by implementing the relevant actions identified in (a)–(e), Agencies should also:

(A) Recognize, assess, and report on the dynamic socio-economic and cultural factors that influence response capacity (Reaser et al. 2019a, this issue).

(B) Incorporate the aforementioned factors into feasibility screening decision support tools (Reaser et al. 2019a, this issue).

(C) Develop science-based social marketing campaigns that address socio-economic and cultural barriers to response measure implementation (Reaser et al. 2019a, this issue).

## Conclusion and cautionary notes

Despite numerous calls for a comprehensive approach to US biosecurity (Meyerson and Reaser 2002a, b, 2003), protecting the nation from the adverse impacts of invasive species remains an urgent and largely unaddressed policy need (Meyerson et al. 2019). If effectively harnessed, the growing interest in EDRR by government agencies and the public, particularly citizen scientists, could lead to developing a national EDRR program that vastly improves biosecurity. The Executive and Legislative branches have available the necessary reasoning, authorities, and mechanisms to transition the blueprint herein from concept to operational reality. However, there is a long history of federal government failure to clarify and prioritize EDRR-relevant programmatic needs, or to support the requisite frameworks and initiatives once these are identified (Reaser et al. 2019a, b, this issue; Simberloff et al. 2005). Furthermore, our ability to establish a national EDRR program is currently being undermined by the diminishment of the federal workforce; institutional structures, policies, and programs; and directly applicable leadership mechanisms, including the National Invasive Species Council (NISC), Invasive Species Advisory Committee (ISAC), and their managerial Secretariat (Meyerson et al. 2019; pers. obs.). We must either adequately invest in our nation's future or prepare for the extraordinary costs of the consequences, including major economic damage and lives lost.

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