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Review

Early detection monitoring for aquatic non-indigenous species: Optimizing surveillance, incorporating advanced technologies, and identifying research needs

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ABSTRACT

Following decades of ecologic and economic impacts from a growing list of nonindigenous and invasive species, government and management entities are committing to systematic early- detection monitoring (EDM). This has reinvigorated investment in the science underpinning such monitoring, as well as the need to convey that science in practical terms to those tasked with EDM implementation. Using the context of nonindigenous species in the North American Great Lakes, this article summarizes the current scientific tools and knowledge — including limitations, research needs, and likely future developments — relevant to various aspects of planning and conducting comprehensive EDM. We begin with the scope of the effort, contrasting target-species with broad-spectrum monitoring, reviewing information to support prioritization based on species and locations, and exploring the challenge of moving beyond individual surveys towards a coordinated monitoring network. Next, we discuss survey design, including effort to expend and its allocation over space and time. A section on sample collection and analysis overviews the merits of collecting actual organisms versus shed DNA, reviews the capabilities and limitations of identification by morphology, DNA target markers, or DNA barcoding, and examines best practices for sample handling and data verification. We end with a section addressing the analysis of monitoring data, including methods to evaluate survey performance and characterize and communicate uncertainty. Although the body of science supporting EDM implementation is already substantial, research and information needs (many already actively being addressed) include: better data to support risk assessments that guide choice of taxa and locations to monitor; improved understanding of spatiotemporal scales for sample collection; further development of DNA target markers, reference barcodes, genomic

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workflows, and synergies between DNA-based and morphology-based taxonomy; and tools and information management systems for better evaluating and communicating survey outcomes and uncertainty.

Contents

1. Introduction

Nonindigenous species (NIS) threaten biodiversity and the functioning of ecosystems and economies worldwide (Pejchar and Mooney, 2009). In the USA, invasive species cause damage exceeding $120 billion annually (Pimentel et al., 2005), and in the North American Great Lakes, the most heavily invaded freshwater system in the world (Pagnucco et al., 2015), the loss in ecosystem services caused by NIS introduced by the ship-borne invasion pathway alone is an estimated $138 million annually (Rothlisberger et al., 2012). Even localized invasions can result in dramatic and costly losses in ecosystem services (Walsh et al., 2016). With ever-increasing global commerce, and in the absence of effective surveillance and management, the danger posed by NIS introduced to ecosystems worldwide will also increase (Keller et al., 2011; Lodge et al., 2006; Pagnucco et al., 2015). Early detection monitoring (EDM) is a critical component of efforts to mitigate threats posed by NIS, allowing for new invaders to be responded to (e.g., by eradication or containment – Lodge et al., 2006; Mehta et al., 2007; Vander Zanden et al., 2010) and the effectiveness of prevention measures to be evaluated. Accordingly, EDM is now being called for in national and international policies and initiatives. For example, the 2012 Great Lakes Water Quality Agreement between Canada and the USA includes a commitment to establishing an aquatic NIS early detection and rapid response network.

Early detection monitoring falls under the umbrella of biological assessment, and shares the general aims and concerns regarding survey designs, collection approaches, and taxonomic challenges. However, EDM differs from other biological assessment in ways that have significance for sampling design and resources. Because detection is only "early" if organisms are found while still few and localized (i.e., rare) and rare organisms are inherently difficult to find, EDM programs are particularly challenged by the need to reconcile limited resources with comprehensive sampling. EDM programs may need to search a broad suite of habitats with a broad range of methods to avoid missing elusive NIS, which runs counter to the repeatability and standardization that other biological surveys typically seek. Early detection monitoring is particularly demanding regarding taxonomic processing because of the need for thorough sample searches and highly-resolved organism identification, whereas assessments of biologic condition via indicator taxa can be robust with coarser searches and taxonomy (Carter and Resh, 2001). Finally, EDM programs particularly need to quantify survey effectiveness and uncertainty, as a firm basis for communicating outcomes, choosing management responses, and adaptively refining survey designs.

In this article, we review current capabilities and scientific understanding for the design and implementation of EDM and discuss areas where further development and testing is needed. Our presentation is structured around major decision points confronting those charged with implementing EDM (Fig. 1) namely: 1) What and where should be monitored? 2) How should the survey be designed with respect to effort and its allocation? 3) What will the collection and identification effort consist of? And 4) How will the survey outcome be evaluated and communicated? We frame our review in the context of aquatic NIS in the North American Great Lakes, but the challenges, decision points, and science tools discussed are applicable to EDM broadly.

2. What and where should be monitored?

Two contrasting approaches to the question of "what to monitor for" have been the subject of EDM development. One approach searches for preidentified species of concern (*target-species monitoring*, hereafter), while the second conducts *broad-spectrum monitoring* aimed at finding any new NIS within broad taxonomic groups. While target-species monitoring most directly and efficiently incorporates knowledge of imminent NIS, broad-spectrum monitoring enables the discovery of unexpected NIS while also yielding biodiversity information relevant to evaluating NIS impacts and other ecological questions (Simmons et al., 2015). Both target-species monitoring and broad-spectrum monitoring (also sometimes referred to as active vs. passive surveillance – Simmons