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PERSPECTIVE

The state of Canada's biosecurity efforts to protect biodiversity from species invasions

Connor H. Reid[a*], Emma J. Hudgins[a], Jessika D. Guay[a], Sean Patterson[a], Alec M. Medd[a], Steven J. Cooke[ab], and Joseph R. Bennett[ab]

[a]Department of Biology, Carleton University, 1125 Colonel By Dr., Ottawa, ON K1S 5B6, Canada; [b]Institute of Environmental and Interdisciplinary Science, Carleton University, 1125 Colonel By Dr., Ottawa, ON K1S 5B6, Canada

*connorreid@cmail.carleton.ca

Abstract

Invasive alien species (IAS) pose threats to native biodiversity globally and are linked to numerous negative biodiversity impacts throughout Canada. Considering the Canadian federal government's commitments to environmental stewardship (e.g., the Convention on Biological Diversity), the successful management of IAS requires an understanding of how federal infrastructure, strategies, and decisions have contributed to previous outcomes. Here, we present an analysis of current efforts by the federal government to prevent IAS establishment in Canadian ecosystems and the unique challenges associated with Canadian IAS management. We then examine historical and current case studies of IAS in Canada with variable outcomes. By drawing comparisons with IAS management in the United States, Australia, and New Zealand, we discuss how the Canadian government may refine its policies and practices to enable more effective responses to IAS threats. We conclude by considering how future interacting stressors (e.g., climate change) will shape how we address IAS threats, and list six lessons for successful management. Most importantly, Canada must regard biodiversity impacts from IAS with as much urgency as direct economic impacts that have historically garnered more attention. Although we focus on Canada, our findings may also be useful in other jurisdictions facing similar challenges with IAS management.

Key words: biosecurity policy, non-indigenous species, invasive species management, biodiversity targets, Canada

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Introduction

The Earth is currently facing a biodiversity crisis, as current extinction rates are generally estimated to be about 1000 times background rates (albeit with considerable taxonomic and geographic disparities, see Pimm et al. 2014). Invasive alien species (IAS; see **Box 1** for definitions) are a major contributor to many modern-day extinctions (Young et al. 2016), being implicated in ~54% of International Union for the Conservation of Nature (IUCN) documented extinctions (Clavero and García-Berthou 2005; **Box 1**). Colautti et al. (2006) predicted that the management efforts and economic losses from IAS presently or imminently established in Canada could cost up to $34.5 billion (CAD) per year. To mitigate the ecological and economic impacts of IAS, risk assessment frameworks can be developed, which have historically highlighted the importance of adequate investment in prevention and

Box 1. Operational definitions for relevant terminology used in this paper.

Biosecurity (= environmental biosecurity): The active prevention, mitigation, and eradication of IAS outbreaks to maintain the integrity of natural ecosystems, human—nature relationships, relevant industries, and public health.

Invasive alien species (IAS): "Animals, plants or other organisms that are introduced into places outside their natural range, negatively impacting native biodiversity, ecosystem services, or human well-being" (IUCN 2017).

Proactive (preventative) management: The practice of creating and implementing policies to prevent IAS establishment in novel areas, encompassing prevention, early detection, and rapid response (eradication of small populations).

Pathway: Routes by which IAS are transferred from one ecosystem to another, which may be deliberate and (or) accidental.

Reactive management: The practice of creating and implementing policies to mitigate the impacts of IAS once they have become established in novel areas.

Vector: Specific routes of transfer within a given pathway by which IAS are transferred.

early-invasion control (Leung et al. 2002; Diagne et al. 2020). Losses associated with intentionally introduced IAS, such as goldfish (*Carassius auratus*) in the Laurentian Great Lakes (Nathan et al. 2015), can be mitigated over the long term through comprehensive risk assessment protocols that identify species likely to become invasive and allocate management efforts in line with these risks (e.g., Keller et al. 2007). Many nations have responded to the biodiversity crisis by setting targets in accordance with the Convention on Biological Diversity (CBD) to conserve and promote biodiversity, some of which address the threats of IAS through proactive management (vs. reactive management; **Box 1**) and future risk identification. One of Canada's biodiversity targets stated that, "By 2020, pathways of invasive alien species introductions are identified, and risk-based intervention or management plans are in place for priority pathways and species" (Target 11; Convention on Biological Diversity 2020).

IAS establish in novel areas via numerous pathways and vectors (see **Box 1** for definitions) that can be managed and controlled to help reduce the risks of IAS impacts. In brief, pathways are routes by which IAS are transferred, while vectors are specific means or methods of transfer within a given pathway. Saul et al. (2017) provided a comprehensive list of pathways based on several previous categorisations, divided into five general categories: release (e.g., biological control), escape (e.g., aquaculture), transportation as a contaminant (e.g., pathogens infecting transported animals), transportation as a stowaway (e.g., organic packing materials), and corridor (e.g., canals). IAS may be associated with multiple pathways, such as zebra mussels (*Dreissena polymorpha*) which may colonize new systems via transport (shipping) contamination, dispersal through waterways, bait bucket transfer, or other pathways (CABI 2019).

Biosecurity is a term that has a number of uses and definitions, with many focusing on preventing/combating biological warfare and other public (human) health concerns (e.g., Koblentz 2010). Here, we define biosecurity in an environmental sense, similar to definitions used by the federal governments of Australia (DAWE 2020a) or New Zealand (New Zealand Biosecurity Institute 2020).

We limit our discussion of biosecurity to the multi-stage management of IAS outbreaks for the sake of human and environmental well-being (see **Box 1** for a formal definition). From this perspective, IAS represent a major biosecurity concern at any jurisdictional level (i.e., local/municipal, provincial, federal, etc.) and, more importantly, are not bound by political borders.

In this paper, we focus on biosecurity within Canada. Similar to other countries, effective biosecurity is crucial to Canada as its residents depend on the stability and function of a wide range of ecosystems. The environment is a critical component of cultural values for many of Canada's Indigenous Peoples and non-Indigenous Canadians (Haluza-DeLay et al. 2009), and in a recent poll (June 2021), ~29% of respondents listed environmental issues including climate change as one of their top priorities (Angus Reid Institute 2021). Furthermore, as a member of the United Nations (UN), G8, and G20 countries, as well as a signatory to the CBD, Canada is a global conservation leader whose national policies have the potential of global impact.

The purpose of this perspective is to elucidate how Canada is addressing biosecurity threats to biodiversity conservation at the federal level. We focus on proactive or preventative management (see **Box 1**, **Fig. 1**) aimed at stopping IAS from establishing (but not spreading) within Canada. Here, we consider IAS entering Canada from the United States (US) over shared borders to be cases of novel establishment rather than spread. While we acknowledge the important involvement of Canada's various provinces and territories in biosecurity, particularly beyond the prevention stage (reactive management, **Box 1**), we do not aim to describe these efforts, nor the efforts of Canada's myriad nongovernmental organizations (NGOs) aiming to manage species invasions (e.g., the Invasive Species Centre, Canadian Wildlife Federation) within this manuscript. Instead, we begin by highlighting the factors that differentiate Canada from other nations with regards to biosecurity. We go on to compare the state of Canada's federal biosecurity with those of other nations possessing

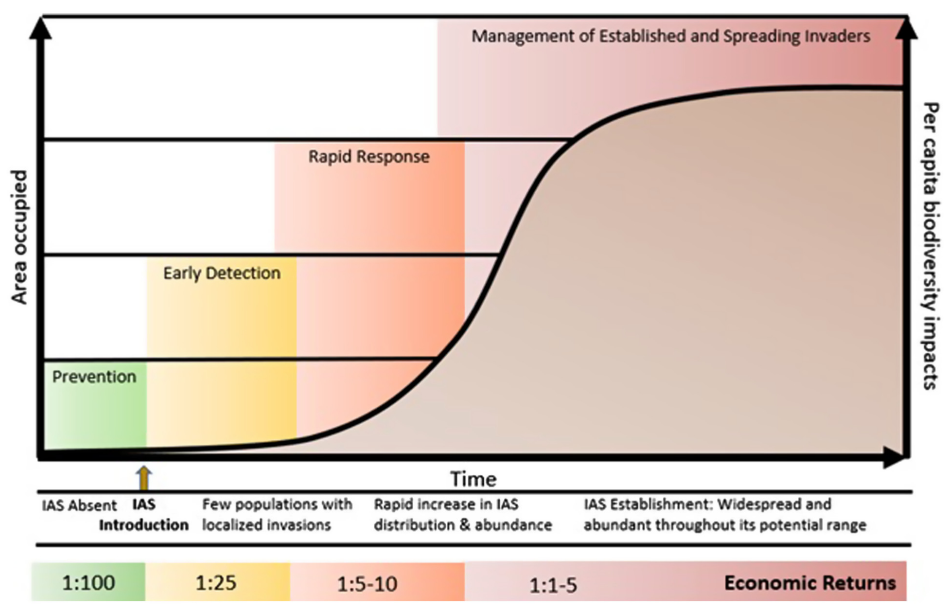

Fig. 1. Species invasion curve (adapted from figure 2 in Department of Primary Industries (2010)) displaying both the area occupied by a novel IAS and the per capita biodiversity impacts associated with invasion over time (according to the stages of invasion). The economic returns of taking effective action at each stage are approximated below the main figure. Australian economic return values listed at each invasion stage are also applicable in Canada (Invasive Species Centre 2019).

similar organisational and (or) biosecurity challenges. With the aid of four case studies, we then identify strategies that have contributed to effective or ineffective efforts to prevent IAS invasions across pathways. Next, we discuss the potential ramifications of future interacting stressors such as the effects of climate change and increased trade on pathway/vector dynamics. We conclude by providing recommendations for policy changes, citizen involvement, and better knowledge dissemination and communication.

What makes Canada unique

Achieving successful biosecurity outcomes requires implementation of regionally appropriate policies. Preventing the establishment of invasive species in the world's second largest country is a daunting task due to unique geographic, ecological, and demographic risk factors. Canada has three vast coastlines (Atlantic, Pacific, and Arctic), which are susceptible to the introduction of marine IAS. Canada shares ~8 891 km of border with the US (US Census Bureau 2011), and thus there exist many potential entry points for the secondary spread of terrestrial IAS from the US (Perrault et al. 2003). The Laurentian Great Lakes and other shared waterbodies also make Canada highly vulnerable to secondary spread of aquatic IAS that establish in US freshwater systems (Vander Zanden et al. 2008). In addition, Canada has a vast land and water cover, a very low population density, and largely intact natural ecosystems, especially in the northern regions (Statistics Canada 2011). While reduced road density may result in fewer incidents of invasion and less human-mediated IAS dispersal (particularly for northward spread), IAS may be able to rapidly disperse across the landscape if they establish in a largely unfragmented region with suitable habitat (Hastings et al. 2005). Eradication of IAS is known to be substantially more costly than prevention (Leung et al. 2002; **Fig. 1**), and this may be especially true in Canada, given the vastness and general intactness of the landscape. Moreover, eradication efforts often pose greater logistical challenges than prevention efforts, as the former generally require coordination among federal, Indigenous, and provincial/territorial governments. Large-scale eradication may also have unintended negative ecological consequences (Kopf et al. 2017).

Preventing populations from establishing requires early detection, which is difficult in uninhabited areas or those with low population densities. Fortunately, the Canadian identity is closely associated with wilderness (Erickson 2013), which can help explain why Canadian citizens are collectively highly motivated to protect nature (Wright et al. 2019). Canadians' connection with nature could allow for quicker detection or prevention of IAS spread, if capitalised on by promoting public awareness campaigns such as the "Don't Move Firewood" initiative, and through partnerships with knowledge mobilization organizations such as the Invasive Species Centre (invasivespeciescentre.ca). In the absence of interventions, however, common Canadian recreational activities such as camping, boating, and fishing can contribute to the dispersal of IAS (Johnson et al. 2001; Koch et al. 2012; Drake and Mandrak 2014; Jentsch et al. 2020). These perverse outcomes can be especially problematic when individuals attempt to alter ecosystems, even with good intentions, without consulting with evidence-based groups or authorities in conservation (e.g., game fish introductions or release of pets into the wild).

Additionally, Canada is located on the traditional territories of many Indigenous Nations whose ways of life are closely linked with nature. Many Indigenous Peoples in North America are concerned about the ecological and cultural repercussions of invasive species and may be interested in partnerships with other stakeholders and governments to combat them, to achieve mutual benefits (Reo et al. 2017). These partnerships can potentially aid both biosecurity outcomes and inter-community relations (Gratani et al. 2011). In addition, natural resource-based industries such as forestry, fisheries, and agriculture have the potential to be severely impacted by IAS (Meyerson and Reaser 2003; Lovell et al. 2006). Given that these are three important sectors of Canada's economy (total value added = Current CAD$ 32 Billion (1.9% of gross domestic product); World Bank 2020), limiting IAS outbreaks in Canada would protect Canada's cultural and economic well-being.

Canada's biosecurity efforts across invasion stages

Due to the wide range of ways in which IAS may impact Canada, many groups and organizations have invested in biosecurity, including all levels of government (federal, provincial, municipal), academic institutions, NGOs, businesses, and Indigenous communities. For the purposes of this paper, we will focus on federal government efforts and will therefore summarize the federal policies and regulations that have been implemented to combat IAS (relevant federal Acts and Regulations are presented in **Table 1**).

In 2002, Canada's Invasive Alien Species Strategy—a national plan for responding to IAS—was approved by Ministers of Wildlife, Forests, and Fisheries and Aquaculture from federal, provincial, and territorial governments. This strategy is composed of four stages: (*i*) prevention of new invasions, (*ii*) early detection of new invaders, (*iii*) rapid response to new invaders, and (*iv*) management of established and spreading invaders (**Fig. 1**) (Government of Canada 2004).

The prevention stage is the most effective and cost-efficient stage of the strategy and occurs before the IAS has entered Canada (Government of Canada 2004). The Canadian government has adopted and joined numerous surveillance strategies where risk mitigation is conducted either preborder or at the border, such as the Canadian Ballast Water Program or international wood packaging standards. These measures seek to monitor intentional introductions and identify and prohibit unintentional or illegal introductions. Should an unintentional or illegal IAS introduction occur, the early detection stage aims to detect the species through both site-specific and general surveillance of protected areas, urban ecosystems, and agricultural ecosystems using taxonomic expertise (Government of Canada 2004). The rapid response stage occurs once an IAS has arrived in the country and is at risk of establishment. Prepared action plans and emergency funds for such events are used for the prompt eradication, containment, or control of the IAS (Government of Canada 2004). Should all prior stages fail, and the IAS become established, long-term management of the species is required to mitigate subsequent negative impacts, including those on local and regional biodiversity, industries, and ecosystem services. Management of IAS may involve physical, chemical, biological, or integrated methods. Risk analyses and benefit–cost analyses are used to prioritize management strategies for the most threatening species in the latter two stages (Government of Canada 2004).

Presently, there is no central department or agency overseeing all preventative biosecurity efforts in Canada across invasion pathways. The Centre for Biosecurity within the federal government focuses solely on public health threats and does not consider biodiversity threats or biosecurity concerns as defined herein (Government of Canada 2017). Federal departments or agencies involved in biosecurity and IAS management that consider biodiversity threats include Fisheries and Oceans Canada (DFO), Canadian Food Inspection Agency (CFIA), Natural Resources Canada (NRCan), and Agriculture and Agri-Food Canada (AAFC). Transport Canada and the Canada Border Services Agency (CBSA) work with these departments and agencies to enforce regulations at Canadian borders and monitor international travel and trade activity across entry pathways. Concerning IAS introduced to Canada for aquaculture, horticulture, agriculture, livestock, forestry, or other ornamental purposes, responsibility primarily rests with the CFIA and the CBSA. The CFIA provides importation regulations and requirements for plants, animals, and other organisms, as well as freely available tools (e.g., the Automated Import Reference System; CFIA 2021) for species importations covering a multitude of purposes. The CBSA works with federal and provincial authorities to prevent IAS introductions into Canada and enforces species transport regulations (including importation) at Canada's borders (CBSA 2020).

Table 1. Federal Acts/Regulations in Canada that either contain specific reference to invasive alien species (IAS) or focus on topics relevant enough to potentially warrant specific references to IAS.

Act or Regulation	Governing Act	Identifier	Target IAS	IAS-relevant action(s)	Link	Other notes
Acts/Regulations with specific reference to IAS						
Fisheries Act	N/A	R.S.C., 1985, c. F-14	Aquatic invasive species	Permits federal regulations on aquatic invasive species definitions, listings, prevention, and management	laws-lois.justice.gc.ca/eng/acts/F-14/FullText.html	
Aquatic Invasive Species Regulations	*Fisheries Act*	SOR/ 2015-121	Aquatic invasive species	Authorises federal, provincial, and territorial Ministers to control and manage aquatic invasive species through spread mitigation, fishing, management efforts, public education, and trade controls	laws-lois.justice.gc.ca/eng/regulations/SOR-2015-121/FullText.html	Fishing regulations (e.g., bait restrictions, targetable species) not detailed as these are province- or territory-specific
Regulations Establishing Conditions for Making Regulations Under Subsection 36(5.2) of the *Fisheries Act*	*Fisheries Act*	SOR/ 2014-91	Aquatic invasive species	Permits conditional use of “deleterious substances” in managing aquatic invasive species	laws-lois.justice.gc.ca/eng/regulations/SOR-2014-91/FullText.html	
Order Designating the Minister of the Environment as the Minister Responsible for the Administration and Enforcement of Subsections 36(3) to (6) of the *Fisheries Act*	*Fisheries Act*	SOR/ 2014-21	Aquatic invasive species	Clarifies which Minister(s) are responsible for aquatic invasive species management in their respective jurisdictions	laws-lois.justice.gc.ca/eng/regulations/SI-2014-21/FullText.html	
Fishery (General) Regulations	*Fisheries Act*	SOR/ 93-53	Aquatic invasive species	Clarifies that Ministry-issued licenses are required to fish for aquatic invasive species, but that no cost be associated with such licences	laws-lois.justice.gc.ca/eng/regulations/SOR-93-53/FullText.html	
Potentially relevant Acts/Regulations with indirect/no reference to IAS						
Species at Risk Act	N/A	S.C. 2002, c. 29	None	N/A	laws.justice.gc.ca/eng/acts/S-15.3/FullText.html	Contains no mention of IAS
Canadian Environmental Protection Act, 1999	N/A	S.C. 1999, c. 33	None	N/A	laws-lois.justice.gc.ca/eng/acts/C-15.31/FullText.html	Does not directly allude to IAS
New Substances Notification Regulations (Organisms)	*Canadian Environmental Protection Act*, 1999	SOR/ 2005-248	All nonmicrobial	States that the importation or manufacturing of nonmicroscopic organisms must be accompanied by assessments of invasiveness potential	laws-lois.justice.gc.ca/eng/regulations/SOR-2005-248/FullText.html	Providing assessment of invasion potential alone does not necessarily constitute an independent guideline for working with IAS

(*continued*)

Table 1. (*concluded*)

Act or Regulation	Governing Act	Identifier	Target IAS	IAS-relevant action(s)	Link	Other notes
Plant Protection Act	N/A	S.C. 1990, c. 22	None	N/A	laws-lois.justice.gc.ca/eng/acts/P-14.8/FullText.html	Refers to "pests" but no specific reference to IAS (either pest species or other plants)
Oceans Act	N/A	S.C. 1996, c. 31	None	N/A	laws-lois.justice.gc.ca/eng/acts/O-2.4/FullText.html	Highlights importance of biodiversity for Marine Protected Areas, no mention of IAS
[Various Marine Protected Area regulations, (e.g., Laurentian Channel Marine Protected Areas Regulations - SOR/2019-105)]	*Oceans Act*	Various	None	N/A	Various	No mention of IAS
Canada National Marine Conservation Areas Act	N/A	S.C. 2002, c. 18	None	N/A	laws-lois.justice.gc.ca/eng/acts/C-7.3/FullText.html	No mention of IAS
Seeds Act	N/A	R.S.C., 1985, c. S-8	None	N/A	laws-lois.justice.gc.ca/eng/acts/S-8/FullText.html	Condemns sale and movement (import, export, etc.) of seeds that may cause environmental harm, but no direct mention of IAS
Seeds Regulations	*Seeds Act*	C.R.C., c. 1400	None	N/A	laws-lois.justice.gc.ca/eng/regulations/C.R.C.,_c._1400/FullText.html	Refers to need for data on potential environmental harm for approval of seeds intended for restricted or unrestricted release, but no direct mention of IAS
Wild Animal and Plant Protection and Regulation of International and Interprovincial *Trade Act*	N/A	S.C. 1992, c. 52	None	N/A	laws-lois.justice.gc.ca/eng/acts/W-8.5/FullText.html	Enables Ministerial action against imported plants or animals that may threaten the environment, but no direct mention of IAS
Wild Animal and Plant Trade Regulations	Wild Animal and Plant Protection and Regulation of International and Interprovincial *Trade Act*	SOR/96-263	None	N/A	laws-lois.justice.gc.ca/eng/regulations/Sor-96-263/FullText.html	No mention of IAS or potential threats to the environment

Note: For Regulations, their governing Acts are listed; for both Acts and Regulations, their identifiers, target IAS and relevant actions (if applicable), and links are provided. All Acts/Regulations are current to 2020-11-17.

Aquatic IAS such as Asian carp (see section "On the horizon "success"—Asian Carp" for list of species), sea lamprey (*Petromyzon marinus*), and zebra mussels (*D. polymorpha*) are primarily managed by DFO, and terrestrial IAS, including insects, plants, and other animal classes, are primarily managed by the CFIA. DFO has regulations under the *Fisheries Act* to prevent IAS, such as importation, possession, transportation, and release prohibitions which are enforced by federal fishery officers and guardians (R.S.C., 1985, c. F-14; **Table 1**). Transport Canada supports the prevention of aquatic IAS introductions by regulating ship-mediated vectors, such as ballast water, hull fouling, commercial fishing, recreational boating, and ship cargo. Ballast water is one of Canada's most thoroughly regulated vectors, with the implementation of the Canadian Ballast Water Program in 2017 (Transport Canada 2015). These regulations complement the existing standards for ballast water exchange and ballast water treatment that have been in place since 2006. In 2010, Canada ratified the International Convention for the Control and Management of Ship's Ballast Water and Sediments 2004 (BWMC; Scriven et al. 2015), which took effect in 2017 (Transport Canada 2019). The BWMC has established standards for the management of ballast water and sediments for internationally bound ships to reduce the transport of aquatic IAS. Although the imposition of these standards has become standard practice for the shipping industry, there appear to be no enforced regulations in place to prevent IAS introductions into Canada from other maritime activities such as commercial fishing and recreational boating (Transport Canada 2011; Government of Ontario 2019).

Shipping is a common pathway for terrestrial IAS (such as invasive insects and plant pests) through the vector of wooden packaging material, which is regulated predominantly by the CFIA, as well as by the Canadian Forest Service (part of NRCan) under the *Plant Protection Act* (S.C. 1990, c. 22; **Table 1**). The transportation of wood materials via air, rail, marine, and roadway is strictly regulated and enforced by both Canadian Plant Protection and Border Services officials. Domestic transportation is subject to prohibitions between regulated and unregulated areas as well as phytosanitary certificate requirements. International transportation, other than the continental US, must comply with the requirements listed in the CFIA D-98-08 and D-02-12 policies (CFIA 2016; CFIA 2020a). Furthermore, the CFIA, NRCan, and NRCan-CFS (Canadian Forest Service) have established strict wood packaging import standards conforming to the International Standards for Phytosanitary Measures (ISPM 15) under the International Plant Protection Convention of the UN's Food and Agriculture Organization (IPPC 2019). For instance, the Canadian Heat Treated Wood Products Certification Program, a phytosanitary certification program in accordance with the ISPM 15 and listed in the CFIA D-13-01 policy, requires wood product imports to be heat treated to prevent the transfer of plant pests such as wood-boring insects (CFIA 2019b). The ISPM 15 standards are monitored by CFIA inspectors and ensure that wood packaging materials are free of insects and diseases, reducing the risk of IAS spread through international trade.

The CFIA also manages other terrestrial IAS such as invasive plant species that may impact native ecosystems or insects and animals that may impact the agricultural livestock sector. International imports, sales, and movements of plants are regulated under the Seeds Act (R.S.C., 1985, c. S-8; **Table 1**). Plant imports must meet the phytosanitary requirements outlined in the CFIA D-12-01 policy listed under the *Plant Protection Act*, and regulated invasive plants require import permits (CFIA 2019a). Moreover, the CFIA Plant Health Surveillance Unit National Plant Protection Survey Program conducts regular surveys for early detection of potential invaders (CFIA 2020b). Agricultural biosecurity is managed with the AAFC National Farm-Level Biosecurity Planning Guide, which encompasses several agricultural industries (avian farms, beef cattle farms, the bee industry, etc.; CFIA 2013). This strategy fosters a collaborative relationship between the government and the agricultural sector and enforces protocols to safeguard public health, economic returns, and environmental impacts, but is seldom focused on impacts to biodiversity.

While in-depth discussion of nongovernmental efforts is beyond the scope of this paper, many NGOs help in the fight against invasive species by collaborating with stakeholders, partner organizations, and the public to share knowledge and technology for effective IAS management. For instance, the Canadian Council on Invasive Species works primarily to prevent IAS introduction through major pathways, and the Invasive Species Centre has created the Early Detection and Rapid Response Network in Ontario to involve the public in community science (CCIS 2020; ISC 2020). Furthermore, certain NGOs, such as the Invasive Species Council of British Columbia and the Conservation of Arctic Flora and Fauna, collaborate with Indigenous communities to understand how IAS may impact their communities and discuss new initiatives (ISCBC 2020; CAFF 2020).

The Canadian government submitted a report to the CBD in 2018 to present progress toward the 2020 aforementioned biosecurity target (Government of Canada 2018). The report stated that Canada was on track to achieve this target, that they had identified priority pathways, strengthened the regulatory framework for preventing and controlling IAS, and had outlined knowledge gaps. Priority pathways identified included shipping, horticulture, the aquarium and pet trade, commercial transport containers, road construction, and recreational pathways (i.e., recreational boating). Many identified pathways had become regulated or partially regulated, such as aquaculture, agriculture, packaging materials, forestry products, and plant products. The IAS regulatory framework was improving and both legislative and regulatory tools for preventing and controlling IAS had been strengthened since 2014. For instance, risk assessments and management plans had been finalised for high-risk pathways such as ballast water, recreational boating, and wood packaging material. Additionally, national plans had been created for priority IAS such as Asian carp, emerald ash borer (*Agrilus planipennis*), *Lymantria dispar* var. *asiatica*, zebra and quagga mussels (*D. polymorpha* and *D. bugensis,* respectively), and research was being conducted continually to address IAS. Finally, key knowledge gaps outlined in the report were emerging animal diseases, the pet trade, e-trade, and cross-border dispersal from the US (Government of Canada 2018).

Comparisons with other countries

Here we provide an overview of federal IAS management in the US, Australia, and New Zealand, which are developed and primarily English-speaking countries with large research budgets and the capacity to identify, address, and respond to IAS challenges similar to those seen in Canada. These countries also each have a long history of Indigenous land stewardship followed by European colonisation, during which extensive and unmanaged introductions of non-native species occurred. The US and Canada have shared IAS risks brought about by the large borders and ecosystems shared by the two countries. Effective biosecurity in Canada therefore often relies on efficient communication and cooperative efforts with the US, which in turn requires an understanding of how the US government is organised to address biosecurity threats. Australia and New Zealand are both widely recognised for their IAS management efforts in recent years, and like Canada, are Commonwealth countries with highly similar federal government structures who have ratified the CBD. Thus, Canadian biosecurity policy changes may more easily mirror successful strategies in these countries because of comparable governmental organization compared with other nations. In addition, there may be lessons and ideas for biosecurity in Canada from Indigenous leadership and Indigenous–settler government cooperation on biosecurity matters in Australia and New Zealand. We acknowledge that Canada, the US, Australia, and New Zealand do not have directly comparable governments in many respects and that adopting strategies from one jurisdiction to another is not a simple process. However, we present promising lessons and ideas that we feel can be implemented in spite of the differences among our federal governments (see **Table 2** for a summary).

Table 2. Comparative summary of biosecurity efforts in Canada, the US, Australia, and New Zealand.

	Canada	United States	Australia	New Zealand
Responsibilities				
Federal government primarily responsible for proactive management	✓	✓	✓	✓
Centralised biosecurity authority			✓	✓
Interagency body that leads and coordinates biosecurity initiatives		✓		
Government representative(s) for biosecurity			✓	✓
Individual federal agencies responsible for biosecurity initiatives relevant to their agency responsibilities	✓	✓	✓	✓
Rigorously and consistently enforced biosecurity controls for international shipping and travel			✓	✓
Regular federal reviews/updates on proactive biosecurity efforts		✓	✓	✓
Indigenous Peoples/communities appear to be involved to a large extent in all aspects of biosecurity				✓
Citizen scientists have clear, incentivised roles in IAS identification and proactive management			✓	✓
Challenges				
Shared international border(s)	✓	✓		
Past extinctions and present threats to endemic species from IAS			✓	✓
Climate change exacerbating biosecurity challenges	✓	✓	✓	✓
Bright spots				
Extensive public education on biosecurity			✓	✓
Extensive promotion and recognition of public engagement in biosecurity			✓	✓
Protection of biodiversity as a main goal of biosecurity initiatives			✓	✓

Note: IAS, invasive alien species.

United States

Policy and governmental management

In the US, federal law takes precedence over state law (because of the Supremacy Clause of their Constitution), which has led to a consistent countrywide IAS prevention effort. While Canada's federal laws can also be applied nationally, provincial provisions are currently ignored for important biodiversity legislation (e.g., the *Species at Risk Act*). In the US, Executive Order (EO) 13112 (Executive Office of the President 1999; amended by EO 13751, Executive Office of the President 2016) set the mandate for Federal IAS management and established the National Invasive Species Council (NISC), an interdepartmental body to oversee implementation of the EO. Included in NISC's duties are the planning, leading, and coordinating of Federal efforts to prevent, eradicate, and manage IAS, as well as advising on international policy (NISC 2019). NISC is co-chaired by representatives from the US Department of Agriculture (USDA), the Department of Commerce, and the Department of the Interior and works with member representatives from relevant federal agencies, inter-agency bodies, other stakeholders, and nonmember representatives (NISC 2019).

To guide IAS management, NISC develops management plans every three years and annual work plans (NISC 2016; NISC 2020a). Individual agencies lead initiatives to prevent the introduction, establishment, or spread of invasive species as outlined in EO 13751. In addition, state, territorial, regional, and local governmental bodies and agencies lead biosecurity initiatives in their jurisdictions (DOI 2016). Invasive species surveillance and risk modelling is supported by the relatively plentiful species distributional data for IAS and their host species in the US compared with Canada (such as the USDA Forest Service's Forest Inventory and Analysis program). Many states and regions have also established their own invasive species councils to plan and coordinate action, and Indigenous communities have authority over IAS management on traditional territories (DOI 2016).

Nongovernmental management

There do not appear to be any NGOs exclusive to the US that work in IAS prevention. The National Institute of Invasive Species Science comprises both government and NGO partners, but ultimately falls within the purview of the United States Geological Survey (NIISS 2018). We note that many important transborder biosecurity NGOs such as the National Alien Invasive Species Management Association (naisma.org) and the Early Detection and Distribution Mapping System (eddmaps.org) were founded in the US. International or multinational organisations operate or have representation within the US, such as the IUCN and The Nature Conservancy. Notably, several agencies work with both Canada and the US for joint conservation and IAS management initiatives, such as the Great Lakes Fishery Commission, which is currently involved in the monitoring and management of Asian carp (GLFC 2019).

Major initiatives, engagement, and future directions

In line with EO 13751, NISC Management Plans and Work Plans focus on advancing efforts to: (*i*) provide federal leadership, (*ii*) coordinate efforts, (*iii*) educate and promote involvement, (*iv*) remove barriers to action, (*v*) assess and strengthen capacities, and (*vi*) foster innovation. The latest Management Plan (2016) and Work Plan (2020) dedicate considerable attention to improving the coordination of prevention efforts such as "Early Detection and Rapid Response" initiatives (NISC 2016; NISC 2020b). In fact, improving coordination of IAS management was one of the main reasons for EO 13751 to amend EO 13112, in recognition that the success of many past efforts relied on collaboration among all levels of government, stakeholders, and the private sector. Partnerships among multiple organizations/agencies and community volunteers was commonly related to the success of the projects (Holland et al. 2018).

Australia

Policy and governmental management

In Australia, the Department of Agriculture, Water, and the Environment (DAWE) is the primary agency responsible for IAS management and environmental biosecurity (DAWE 2020a, 2020b). DAWE administers the *Environment Protection and Biodiversity Conservation Act 1999* (EPBC Act; DAWE 2020a) and the environmental biosecurity regulations (Biosecurity Regulation 2016) under the *Biosecurity Act 2015* (DAWE 2020b). The Chief Environmental Biosecurity Officer is the main representative for environmental biosecurity and advises the Australian federal government on environmental biosecurity issues (DAWE 2020c). The Australian federal government also has an Inspector-General of Biosecurity, who conducts independent reviews of biosecurity in Australia and publishes annual reports independent of the DAWE (IGB 2020). State and territory governments also have key roles in biosecurity and IAS management within their jurisdictions (DAWE 2020d). The Intergovernmental Agreement on Biosecurity sets the roles, responsibilities, and governance arrangements for biosecurity responses among all levels of government (DAWE 2020e). In addition, the Australian federal government partners with Indigenous communities to strengthen the biosecurity response, including the Indigenous Rangers program, which employs and benefits from the Traditional Knowledge of Indigenous Peoples for IAS management (NIAA 2020).

Nongovernmental management

Nongovernmental partners, including NGOs, industry, community groups, and community members contribute to biosecurity in Australia (DAWE 2020d). The Invasive Species Council is the sole NGO in Australia responsible for IAS management at the national level. With the guidance of a scientific advisory committee, they undertake a diverse range of activities concerning IAS prevention, mitigation, and eradication, including assisting DAWE and other organisations with promoting and implementing biosecurity efforts, policies, and laws; promoting public involvement and outreach, volunteer opportunities, and citizen science; and publishing annual reports on Australian biosecurity efforts (Invasive Species Council 2020).

Major initiatives, engagement, and future directions

Australia is a biodiversity hotspot with many endemic species; however, many have gone extinct or are currently at risk because of IAS impacts (DAWE 2020f). To raise awareness and prepare for impending IAS threats to Australia, the DAWE has created *The National Priority List of Exotic Environmental Pests, Weeds and Diseases* (the Priority list) (DAWE 2020f). Also, each year the DAWE presents the Australian Biosecurity Awards, which include several categories open to individuals, groups, organisations, and government, to recognise significant contributions to Australian biosecurity (DAWE 2020g).

New Zealand

Policy and governmental management

In New Zealand, the Ministry for Primary Industries (MPI) leads the biosecurity system, administers the Biosecurity Act of 1993, advises the Minister for Biosecurity (a position that does not exist in Canada), provides border inspectors, and maintains a rapid response system to IAS (MPI 2020a). Government agencies, such as the Ministry of Health, the Department of Conservation, and the Environmental Protection Authority, lead operations when a pest or disease affects their agency responsibilities (MPI 2016; MPI 2020a). Regional councils lead biosecurity initiatives in their regions (MPI 2020a). Indigenous Māori iwi, partnered with the government through the Treaty of Waitangi, are increasingly being recognised for their contributions to New Zealand's biosecurity and their roles, knowledge, and perspectives are being reflected to a greater extent in biosecurity policy and management (MPI 2016; MPI 2020a). While biosecurity responsibilities are generally well defined, the MPI has developed the Biosecurity (Process for Assignment of Responsibility for Decision on Harmful Organism or Pathway) Regulations 2016, made under section 165(5) of the *Biosecurity Act 1993* to facilitate the assignment of responsibilities should management responses not have clearly defined leadership roles (MPI 2020b).

Nongovernmental management

NGOs, industry partners, local communities, Māori groups, and other stakeholders contribute to pest management and biosecurity in New Zealand (MPI 2016). The independent Māori Biosecurity Network brings together interested individual Māori and collectives to lead initiatives and to ensure representation of the Māori voice within New Zealand's biosecurity system (Lambert et al. 2018). Industry organisations, particularly Government Industry Agreement partners, also lead management of IAS affecting their members or operations (MPI 2020c; MPI 2020a). In addition, businesses, landowners, and individuals are expected to manage their own biosecurity risks (MPI 2016). Under the Biosecurity Act 1993 (section 162A), those that have incurred a loss as a result of IAS management can claim compensation, which provides individuals and businesses with financial security and helps to encourage early IAS reporting (MPI 2020d).

Major initiatives, engagement, and future directions

New Zealand is home to many endemic species, but like Australia has a history of devastating IAS impacts on biodiversity (DOC 2020). To improve biosecurity and combat IAS, the MPI has developed the following strategic directions: (*i*) "A biosecurity team of 4.7 million", (*ii*) "A toolbox for tomorrow", (*iii*) "Smart, free-flowing information", (*iv*) "Effective leadership and governance", and (*v*) "Tomorrow's skills and assets" (MPI 2016). To help achieve a biosecurity team of 4.7 million, a separate biosecurity brand called This is Us was created to promote engagement (This Is Us 2020). One way in which This is Us promotes engagement is through the New Zealand Biosecurity Awards, which recognise and celebrate people and organisations for their contributions to biosecurity (This Is Us 2020).

Case studies of biosecurity successes and failures

Table 3 highlights the diversity of invasion pathways that facilitated the invasion of many current and future IAS in Canada. From this, we selected four case studies that present a diverse representation of

Table 3. Invasion pathway categories, pathways, and example IAS that have posed or are likely to pose significant threats of invasion.

CBD Category	CBD Pathway	Example species
Release	Biological control	Grass Carp (*Ctenopharyngodon idella*) Western Mosquitofish (*Gambusia affinis*) Ferret (*Mustela furo*)* Guppy (*Poecilia reticulata*)
	Erosion control	European Alder (*Alnus glutinosa*)
	Fishery in wild	**Northern Snakehead (*Channa argus*)** **Common Carp (*Cyprinus carpio*)** Brown Trout (*Salmo trutta*)
	Hunting in wild	European Hare (*Lepus europaeus*) Eurasian Collared-Dove (*Streptopelia decaocto*)
	Improvement	Earthworms (*Lumbricus rubellus, L. terrestris*)*
	Release for use	Mute Swan (*Cygnus olor*)* **Common Carp (*Cyprinus carpio*)**
	Other	Goldfish (*Carassius aurata*) **Northern Snakehead (*Channa argus*)** Horse (*Equus caballus*)* Earthworms (*Lumbricus rubellus, L. terrestris*)* Guppy (*Poecilia reticulata*) Red-Eared Slider (*Trachemys scripta elegans*)
Escape	Agriculture	Earthworms (*Lumbricus rubellus, L. terrestris*)*
	Aquaculture	Grass Carp (*Ctenopharyngodon idella*) **Northern Snakehead (*Channa argus*)** *Codium fragile tomentosoides* Pacific Oyster (*Crassostrea gigas*) Common Carp (*Cyprinus carpio*) Chinese Mitten Crab (*Eriocheir sinensis*) Spiked Watermilfoil (*Myriophyllum spicatum*) Mediterranean Mussel (*Mytilus galloprovincalis*)

(*continued*)

Table 3. (*continued*)

CBD Category	CBD Pathway	Example species
	Zoo/Aquaria/Botanical gardens	Mute Swan (*Cygnus olor*) Horse (*Equus caballus*)* Earthworms (*Lumbricus rubellus, L. terrestris*) Purple Loosestrife (*Lythrum salicaria*)* Spiked Watermilfoil (*Myriophyllum spicatum*)
	Pet	Goldfish (*Carassius aurata*) **Northern Snakehead (*Channa argus*)** *Daphnia lumholtzi** **Common Carp (*Cyprinus carpio*)** Ferret (*Mustela furo*) Guppy (*Poecilia reticulata*) Eurasian Collared-Dove (*Streptopelia decaocto*) Red-Eared Slider (*Trachemys scripta elegans*)
	Farmed	Horse (*Equus caballus*)* Ferret (*Mustela putorius furo*)*
	Forestry	European Alder (*Alnus glutinosa*)
	Horticulture	Garlic Mustard (*Alliaria petiolata*) Wavy Bittercress (*Cardamine flexuosa*) Reed Sweet-grass (*Glyceria maxima*)* Ivy (*Hedera helix*) Earthworms (*Lumbricus rubellus, L. terrestris*)* Purple Loosestrife (*Lythrum salicaria*)* Spiked Watermilfoil (*Myriophyllum spicatum*) Armenian Blackberry (*Rubus armeniacus*)
	Ornamental	European Alder (*Alnus glutinosa*) Goldfish (*Carassius aurata*) Common Carp (*Carpinus cyprio*) Western Mosquitofish (*Gambusia affinis*) Reed Sweet-Grass (*Glyceria maxima*)* Ivy (*Hedera helix*) Purple Loosestrife (*Lythrum salicaria*)* Common Reed (*Phragmites australis*) Guppy (*Poecilia reticulata*)
	Research	Common Reed (*Phragmites australis*)
	Live food	**Northern Snakehead (*Channa argus*)** Western Mosquitofish (*Gambusia affinis*)
	Other	Earthworms (*Lumbricus rubellus, L. terrestris*)* Common Reed (*Phragmites australis*)
Transport (Contaminant)	Nursery material	Creeping Thistle (*Cirsium arvense*)
	Bait	Quagga Mussel (*Dreissena rostriformis*) Zebra Mussel (*Dreissena polymorpha*)
	Food	Purple Loosestrife (*Lythrum salicaria*)*
	Animal	*Daphnia lumholtzi** *Didemnum* spp. Common Storksbill (*Erodium cicutarium*) Slender Rush (*Juncus tenuis*) Purple Loosestrife (*Lythrum salicaria*)* Wire Weed (*Sargassum muticum*) South African Ragword (*Senecio inaequidens*)

(*continued*)

Table 3. (*continued*)

CBD Category	CBD Pathway	Example species
	Parasites (animals)	Red Worm (*Mytilicola orientalis*)
	Plants	Emerald Ash Borer (*Agrilus planipennis*)* *Lymatria dispar*
	Parasites (plants)	Beech Bark Disease (Neonectria faginata)*
	Seed	Common Storksbill (*Erodium cicutarium*)
	Timber	Emerald Ash Borer (*Agrilus planipennis*)*
	Habitat material	Perennial Pepperweed (*Lepidium latifolium*) Earthworms (*Lumbricus rubellus, L. terrestris*)*
Transport (Stowaway)	Angling	Round Goby (*Neogobius melanostomus*)
	Container	German Wasp (*Vespula germanica*)*
	Hitchhikers (Plane)	Common Storksbill (*Erodium cicutarium*)
	Hitchhikers (Boat)	*Codium fragile tomemtosoides* *Daphnia lumholtzi* *Didemnum* spp. Mediterranean Mussel (*Mytilus galloprovincalis*) Brown Rat (*Rattus norvegicus*) Wire Weed (*Sargassum muticum*)
	Machinery	Quagga Mussel (*Dreissena rostriformis*) Zebra Mussel (*Dreissena polymorpha*) Purple Loosestrife (*Lythrum salicaria*)* Reed Sweet-grass (*Glyceria maxima*)*
	People & luggage	Creeping Thistle (*Cirsium arvense*) Red Turpentine Beetle (*Dendroctonus valens*) Slender Rush (*Juncus tenuis*) *Lymatria dispar* Purple Loosestrife (*Lythrum salicaria*)* Reed Sweet-grass (Glyceria maxima)*
	Organic packing	Emerald Ash Borer (*Agrilus planipennis*)* *Lymatria dispar* ***Lymantria dispar var. asiatica*** Asian Long-horned Beetle (*Anoplophora glabripennis*)^ German Wasp (*Vespula germanica*)*
	Ballast	Spiny Waterflea (*Bythotrephes longimanus*) Pacific Oyster (*Crassostrea gigas*) *Didemnum* spp. Quagga Mussel (*Dreissena rostriformis*) Zebra Mussel (*Dreissena polymorpha*) Chinese Mitten Crab (*Eriocheir sinensis*) Purple Loosestrife (*Lythrum salicaria*) Mediterranean Mussel (*Mytilus galloprovincalis*)
	Hull fouling	Pacific Oyster (*Crassostrea gigas*) *Didemnum* spp. Quagga Mussel (*Dreissena rostriformis*) Zebra Mussel (*Dreissena polymorpha*) Spiked Watermilfoil (*Myriophyllum spicatum*) Mediterranean Mussel (*Mytilus galloprovincalis*) Wire Weed (*Sargassum muticum*)

(*continued*)

Table 3. (*concluded*)

CBD Category	CBD Pathway	Example species
	Vehicles	**Spotted Lanternfly (*Lycorma delicatula*)** *Lymatria dispar* Purple Loosestrife (*Lythrum salicaria*) Reed Sweet-grass (Glyceria maxima)*
Corridor	Waterways	Common Carp (*Cyprinus carpio*) **Asian Carp (spp.)** Quagga Mussel (*Dreissena rostriformis*) Zebra Mussel (*Dreissena polymorpha*) Chinese Mitten Crab (*Eriocheir sinensis*) Reed Sweet-Grass (*Glyceria maxima*)* Perennial Pepperweed (*Lepidium latifolium*) Spiked Watermilfoil (*Myriophyllum spicatum*) Common Reed (*Phragmites australis*)

Note: Pathways and categories are listed as described by Saul et al. (2017) based on Convention of Biological Diversity (CBD) categorisations, with unrepresented pathways omitted (e.g., "Transport (Stowaway) - Other"). A species in **bold** denotes an invasive alien species (IAS) on the horizon of invasion;
"^"indicates an IAS that has been present in Canada but is currently considered to have been eradicated. Most species are drawn from the Global Invasive Species Database (GISD) list of biodiversity-impacting IAS;
*denotes that a species is also present on the IUCN's list of the 100 worst invaders (iucngisd.org/gisd/100_worst.php). Underlined species listed are not drawn from the GISD list but are considered established by CABI's Invasive Species Compendium (cabi.org/isc/).

current and future challenges to Canadian biosecurity. Two case studies illustrate IAS threats within the last few decades and two describe IAS threats that are currently on the horizon. In both cases, one example is considered a "success" and the other a "failure", with each reflecting how well and efficiently Canada was able to or is likely to direct efforts to prevent the establishment of each IAS (though we note that these designations should not be interpreted as an attempt to predict indefinite prevention/eradication success). We acknowledge that our selection carries inherent biases towards available information on (and perceptions of) various IAS (e.g., Pyšek et al. 2008).

Historical "failure"—zebra and quagga mussels

Zebra and quagga mussels are proficient filter feeders native to the Black Sea region (Son 2007). Both species are able to spread throughout lakes and river systems, encrusting hard surfaces and substrate (e.g., rocks, endemic mollusc shells, human infrastructure; Karatayev et al. 2011) with high resulting annual management costs (Meyerson and Reaser 2003). Zebra and quagga mussels were introduced to the Laurentian Great Lakes through ballast water released by ships originating from areas with native or introduced populations. Zebra mussels were first recorded in the American portion of Lake Erie in 1986 (Carlton 2008) and have since established in the Canadian portion of the lake through a combination of natural spread and unintentional human aid (e.g., hull fouling; Brown and Stepien 2010). In abundance, zebra mussels can induce changes in substrate via accumulations of copious shell fragments, rapidly increasing water clarity by filtering plankton and small debris, and subsequent cascading impacts on food webs, nutrient cycling, and community assemblages (Karatayev et al. 2002). Negative impacts on fish communities are likely as small reductions in fitness or reproductive success compound over time. For instance, zebra and quagga mussels may worsen the diet quality of species such as lake whitefish (*Coregonus clupeaformis*; McNickle et al. 2006) or the number of viable deposited eggs in at-risk fishes such as lake trout (*Salvelinus namaycush*; Marsden and Chotkowski 2001).

At the time of their introduction to Canada, there were no safeguards in place to anticipate and prevent the establishment of zebra and quagga mussels. In 1989, the federal government began implementing large-scale (i.e., nonlocal) ballast water management programs to manage various aquatic IAS; however, compulsory regulations were not introduced and enforced until 2006 (see Scriven et al. 2015 for a detailed timeline of Canadian ballast water regulation). Since these preventative measures were made compulsory, no IAS appear to have established in the Great Lakes via ballast water, although introductions have occurred in Canada's less well-regulated marine systems (Scriven et al. 2015).

Historical "success"—Asian long-horned beetle

Asian long-horned beetles (ALB; *Anoplophora glabripennis*) are native to China and Korea but have been unintentionally transported outside their native range by international trade, primarily via their contamination of wood packing material (Hu et al. 2009). ALB larvae damage trees primarily through larval tunnelling, which compromises tree vascular tissues and structural integrity, eventually leading to tree mortality (Hu et al. 2009). ALB were first found in North America in 1996, when a population had become established in the US (Haack et al. 2010). They have since become established on two separate occasions in Canada (NRCan 2020). The ALB introduced to Canada near Toronto in 2003, and incomplete eradication efforts resulted in a small population that remained undetected in the area until 2013 (Turgeon et al. 2015), whereafter it was eradicated (NRCan 2020). A third introduction to Canada was reported in Edmonton in 2019, but a population is not thought to have established (CFIA 2019c). ALB prefer maples (*Acer* spp.) as host trees but will colonise other common hardwood trees (NRCan 2020). ALB invasions in Canada could lead to devastating biodiversity losses, which may affect the livelihoods of all peoples living in Canada, including Indigenous communities, and cause billions of dollars in damages to Canadian industries including forestry, maple syrup, and tourism (NRCan 2020). Under the *Plant Protection Act* introduced in 1990 (**Table 1**), the federal government has maintained the power to carry out inspections on shipping containers and other cargo in search of pest species (including potential IAS). However, the brief establishment of ALB in Canada (as well as the 2013 re-emergence) appears to have been noticed first by community members rather than caught through government efforts (CTV News 2019; Taylor 2021), although CFIA inspections did reportedly prevent another introduction in 2020 (Taylor 2021). Thus, while historical "success" in ALB prevention may be attributed more to sheer chance and astute citizens, the federal infrastructure that can coordinate successful prevention efforts has long been in place (even if enforcement could be more rigorous).

On the horizon "failure"—spotted lanternfly

Spotted lanternflies (SLF; *Lycorma delicatula*)—a species of planthopper (Fulgoromorpha)—are native to parts of the east and southeast Asian mainland. SLF had established invasive populations in Korea and Japan, as well as the US, by no later than 2014 (Leach and Leach 2020). SLF's preferred host is the invasive tree-of-heaven (*Ailanthus altissima*; Barringer et al. 2015). SLF are not known to have become established in Canada yet; however, tree-of-heaven can be found in eastern Canada (Dara et al. 2015). SLF larvae feed on numerous cultivated plants, including grape vines and fruit trees, and many common trees native to Canada (e.g., red maple (*Acer rubrum*), American beech (*Fagus grandifolia*); Avanesyan and Lamp 2020; Dara et al. 2015). The build-up of honeydew (liquid secretions) from SLF feeding on host trees promotes sooty mould (Ascomycota spp.) growth and other detrimental consequences beyond direct damage from feeding (Dara et al. 2015).

Since tree-of-heaven has an extensive distribution in the US, SLF could establish in Canada via spread from areas bordering Canada containing tree-of-heaven populations (Rowe et al. 2020), particularly in the empirically derived high-suitability areas in southern Alberta and Saskatchewan, Ontario, Quebec, and the Maritime provinces (Wakie et al. 2020). Southern Ontario contains the most suitable habitat for SLF and is also closest to existing invasive populations in the US (Wakie et al. 2020). While SLF is likely to have negative consequences on biodiversity, agriculture (e.g., vineyards), and forestry, knowledge on the likely impacts in Canada remains largely theoretical (Urban 2020). Canada does not appear to be well-prepared for preventing SLF cross-border establishment or other outbreaks and may become particularly vulnerable, as climate change promotes the northward expansion of more suitable environmental conditions from the US. The invasion pathways of SLF have not been rigorously identified; however, both adults and deposited egg masses may be transported on wood or non-plant surfaces such as vehicles (Dara et al. 2015), making transport contamination pathways likely. The federal government is aware of this species as a likely looming threat (CFIA 2019c); however, no clear active monitoring plans are currently in place.

On the horizon "success"—Asian carp

Asian carp is a blanket term referring to four cyprinid fishes: grass carp (*Ctenopharyngodon idella*), silver carp (*Hypophthalmichthys molitrix*), black carp (*Mylopharyngodon piceus*), and bighead carp (*Hypophthalmichthys nobilis*) (George et al. 2017). Asian carp were first introduced to North America in 1963, with numerous subsequent introductions of each species for aquaculture and biological control/habitat manipulation (Kelly et al. 2011). Escape or intentional release of these large fish can quickly lead to established populations in natural ecosystems. The Canadian government has long been aware of the threat of Asian carp, as certain species have propagated up the Mississippi River Basin towards the Laurentian Great Lakes (e.g., Mandrak and Cudmore-Vokey 2004). Asian carp can access Lake Michigan from the Chicago Area Waterway System, an artificial corridor between the Mississippi River and Laurentian Great Lakes watersheds (Wittmann et al. 2014). Grass carp currently pose the largest threat to Canada as spawning has been observed in the Sandusky River, a tributary of Lake Erie (Embke et al. 2016). Ivan et al. (2020) predicted that established Asian carp populations could lead to major changes in ecosystem structure and function in the Great Lakes. Empirical evidence indicates that Asian carp invasions can negatively impact the biomass of planktivorous fishes such as gizzard shad (*Dorosoma cepedianum*) (Phelps et al. 2017), aquatic vegetation, and species that rely on pre-existing cover (Cudmore et al. 2017). In addition, silver carp are known to jump as high as 3 m out of the water when disturbed by boat activity and other sounds (Vetter et al. 2017), leading to high-velocity fish–human collisions. Subsequent introductions or dispersal through connected waterbodies can lead to further exploitation of inland Canadian waters, many of which south of 60 °N (i.e., southern borders of the Territories) are conducive to the survival and establishment of Asian carp (Cudmore et al. 2017). Restrictions on fish movement, aquaculture, and sale are in place in both Canada (Ontario and Quebec) and the US (Cudmore et al. 2017). To date, none of the species are confirmed to be established (reproducing), but 28 grass carp have been captured in Canadian zones of the Great Lakes (primarily Lakes Erie and Huron; DFO 2019), and three bighead carp were captured in western Lake Erie in the early 2000s (DFO 2020). Community monitoring is also being employed, where sightings can be reported over email or telephone (dfo-mpo.gc.ca/contact/invasive-species-especes-envahissantes-eng.html). Further monitoring technologies (e.g., eDNA detection; Guan et al. 2019) are being developed for more stringent future monitoring. The effectiveness of future efforts relies on continued cooperation and partnerships with the US, who have been investing in domestic spread mitigation technologies (e.g., dispersal barriers) that can contribute to establishment prevention in Canada (Cudmore et al. 2017).

Lessons and recommendations for the future of biosecurity in Canada

Value biodiversity in addition to existing economic and industrial interests

IAS in Canada have been leading causes in biodiversity loss. For example, the sea lamprey contributed greatly to population crashes in Great Lakes lake trout populations (Coble et al. 1990) and the extinctions of longjaw and deepwater ciscoes (*C. alpenae* and *C. johannae*, respectively; Miller et al. 1989). IAS must be addressed to meet aims of preserving biodiversity in line with both international (e.g., CBD) and domestic (e.g., the *Species at Risk Act*, which contains no mention of IAS) agreements and initiatives. The Canadian federal government appears to be most willing to respond to IAS that pose substantial economic risks towards major industries, rather than those that pose risks to biodiversity and other, less direct economic impacts. While agriculture, forestry, and fisheries represent a substantial portion of the economy, Canada also possesses unique and biodiverse landscapes that hold significant cultural value, ecosystem services, and benefits to other economic sectors (e.g., tourism). Much of the country's natural ecosystems remain intact or nonindustrialised, so a tendency to give disproportionately more attention to lands and waters associated with direct industrial benefits is unsustainable and incompatible with Canada's biodiversity targets under the CBD.

Canada's Natural Sciences and Engineering Research Council (NSERC) recently committed to creating a centralised repository of biodiversity monitoring data (Canadian Biodiversity Observation Network). The centralisation and sharing of countrywide biodiversity data will help overcome the data limitations surrounding Canadian IAS surveillance and risk modelling compared with the US. We commend this initiative and believe that the collection of IAS-relevant data will be central to the success of this framework.

Consolidate regulatory frameworks

Effective biosecurity requires leadership and coordination. Having centralised government agencies (or a unit within an agency) that direct biosecurity-relevant guidelines and initiatives appears to be highly effective in Australia and New Zealand. Implementing a central authority to lead and oversee biosecurity efforts could benefit Canada greatly. This authority would ideally be tasked with identifying Canada's biosecurity priorities, as well as coordinating the roles of agencies at multiple levels of government in IAS research and management. A consolidated federal authority could boost the efficacy of provincial or territorial efforts by laying the groundwork for consistent, standardised courses of action for different IAS management scenarios. Furthermore, this strategy could facilitate communications with other government agencies concerned with relevant interests and activities (e.g., climate change, economics, parks and land use, etc.). We are not necessarily advocating for an entirely new government department, but perhaps a unit not unlike the Canadian Wildlife Service that operates within Environment and Climate Change Canada. We note the easier implementation of centralised federal measures in the US due to the Supremacy clause of the US Constitution, but we believe the Canadian federal government could ensure provincial biosecurity policies are written into federal law and enforced (unlike the provincial provisions in the *Species At Risk Act*).

Strengthen partnerships with the public and Indigenous Peoples

The benefit of mass engagement in biosecurity has been recognised in New Zealand, where they have put substantial effort towards their 2025 strategic direction "A biosecurity team of 4.7 million" (MPI 2020e). To improve engagement in Canada, we recommend increasing investment in IAS and biosecurity education. Initiatives such as efforts against the use of live bait (which may be brought into Canada from other countries, especially the US) can help foster best practices within the general public. Community science can be an invaluable asset in IAS education and monitoring (see section Historical "success"—Asian long-horned beetle), with tools such as reliable wildlife identification apps becoming increasingly viable for practical use. Industry and businesses could also be provided with the knowledge, tools, resources, and regulations to mitigate their own IAS risks, and (or) create an industry partner program to lead initiatives as seen in New Zealand (MPI 2020c). We also recommend that Canadian policy makers consult better with stakeholders and rights holders on biosecurity and ensure that Indigenous perspectives and knowledge are represented. If executed effectively, partnership between Indigenous groups and governments can benefit biosecurity initiatives and relations (Gratani et al. 2011). The Canadian federal government may also wish to consider recognising biosecurity efforts, perhaps through the presentation awards such as those in Australia and New Zealand (DAWE 2020g; This Is Us 2020).

Strengthen partnerships with other countries

We encourage Canada to prioritise discussing biosecurity with trading partners, particularly at international conferences where multinational trade agreements may be developed. Further, we recommend that Canada continues to develop trade agreements/standards to reduce biosecurity threats. The International Convention for the Control and Management of Ships' Ballast Water and Sediments offers a good example of what is achievable at the international level to mitigate IAS risk (IMO 2019). We also recommend that Canada encourages other countries to make biosecurity a priority and that Canada openly share its strategies, developments, and both "successes" and "failures", such as those presented in the case studies section of this paper, to improve biosecurity worldwide. In addition, we recommend that Canada uses other countries' biosecurity successes, including those presented in this paper for the US, Australia, and New Zealand, as models for future policy development. Finally, we advise that Canada and the US increase collaborative efforts due to the shared risk across the large land border, the Laurentian Great Lakes, and coastal marine waters. A good example is binational collaboration around Asian carp management efforts (see Cudmore et al. 2017).

Adapt to future conditions

Canada's biosecurity policies should be flexible and anticipate future changes (**Table 4**). Human population increase and climate change will likely create new biosecurity threats and exacerbate existing ones. It is imperative that Canada maintains flexible policies that are regularly reviewed and adapted to incorporate new information. Future research on IAS must compensate for taxonomic and geographic biases in the availability of current knowledge and social perceptions of IAS (Pyšek et al. 2008; Kapitza et al. 2019). More efficient data-sharing platforms and alert systems can be used to accelerate communication of novel biosecurity-related findings. New technologies and IAS treatment techniques should be proactively developed and embraced. Some recently developed technologies include instruments to detect wood-boring insects, recycled plastic pallets as an alternative to wooden pallets, hull fouling resistant paints, and eDNA use for early detection of aquatic IAS (Jerde et al. 2013; Guan et al. 2019). Efforts should also be made to ensure that anthropogenic migration corridors (e.g., from climate change related assisted mitigation initiatives) do not inadvertently contribute to the spread of IAS (St-Laurent et al. 2018). Return on investment models can be used to demonstrate the value of forward-thinking when preparing for future biosecurity threats (Leung et al. 2014).

Anticipate conflict

As Canada updates its biosecurity policy to meet future conditions, it is important to recognize that some changes could cause tensions (Crowley et al. 2017). Conflict should be anticipated and mitigated to prevent disagreements from damaging relationships and IAS management outcomes.

Table 4. Future interacting stressors.

Category	Stressor	Mechanism	Mitigating Factors
Global population rise	Anthropogenic disturbance	• Increased probability of IAS spread (With 2002) • Increased IAS colonization success (Marvier et al. 2004)	• Improved resilience, e.g., through maintenance of biodiversity (Folke et al. 2004) • Protected area creation and support for Indigenous land management initiatives (Schuster et al. 2019)
	Increased shipping volume	• Increased opportunities for invasion by IAS (Sardain et al. 2019)	• Regulations on imports (e.g., ISPM 15, Leung et al. 2014)
	Increase in deliberate Introductions	• IAS introduction to meet wood demands (Zobel et al. 1987)	• Native wood products and alternatives (Smyth et al. 2017)
Climate change	Changes to habitat suitability	• Poleward migration (e.g., from US) of IAS due to climate change (Hellmann et al. 2008) • Increased IAS establishment risk (Goldsmit et al. 2018; but see Della Venezia et al. 2018)	• Improved border surveillance (Yemshanov et al. 2019), reducing emissions (Paris Agreement, UNFCCC) • Targeted regulation of tropical species, e.g., through pet trade (Lockwood et al. 2019)
	Shorter shipping routes due to melting arctic ice	• Greater survival rates of hitchhiking IAS via shipping (Pyke et al. 2008)	• Creation of global biofouling policy (Davidson et al. 2016), improved ballast water management in arctic regions (Goldsmit et al. 2019)
	Increase in deliberate introductions	• IAS introduction to meet carbon sequestration and erosion control demands (Pyke et al. 2008) • Assisted migration campaigns (McLachlan et al. 2007)	• Native tree alternatives (Ennos et al. 2019), wetland restoration (Gallant et al. 2020) • Risk assessments prior to assisted migration (St-Laurent et al. 2018)

Note: Future alterations to the environment and global economy will impact invasive alien species (IAS) risk, and therefore the demand for biosecurity measures. Major mediators of future IAS threats are outlined, along with suggestions for mitigation. In this table, the stressors are defined as the ultimate cause of increased IAS risk, while the mechanism is how each stressor impacts risk. Stressors are grouped into those arising primarily from human population growth or climate change, though we acknowledge the inherent synergy in these forms of global change (He and Silliman 2019).

Implementation of new policies should be handled with transparency and coupled with public education campaigns such as signage, advertisements, and school community science programs. Neglecting to educate the public about the value of an initiative can ultimately result in its failure, regardless of its validity, as well as inhibit their engagement in community science. Additionally, policy makers should be aware of conflicting perspectives regarding eradication of some IAS among Indigenous Peoples (Bhattacharyya and Larson 2014) and should therefore prioritize bilateral communication to achieve positive outcomes for all parties. Scientists and policy makers must recognize that without the support of stakeholders, rightsholders, Indigenous Peoples, and the general public, implementation of biosecurity protocols is unlikely to be successful.

Conclusion

Biosecurity and IAS management can be daunting, given their extensive scales, costs, and other obstacles. Furthermore, the rewards of successful biosecurity efforts may be easily overlooked, as successful efforts prevent changes in biodiversity. As evidenced in how Canada has addressed IAS threats to date, the federal government has the potential to form and coordinate highly effective prevention efforts and may be able to help coordinate management of established IAS (which is typically the responsibility of provincial and territorial governments). This is especially true for threats that have yet to be established in the country, as the prevention of novel IAS yields far more substantial results than attempts to control established threats across the country. In summary, the long-term benefits—namely of biodiversity conserved and economic damage mitigated—justify short-term costs of effective proactive IAS management in Canada. Lastly, the success or failure of future management efforts will have ramifications for future endeavours, public trust and support, and willingness for further economic investments. While historical biosecurity efforts have generally been less proactive and yielded mixed results, Canada has undergone considerable progress in IAS management over the last few decades. However, there is significant room for improvement, and Canada must continue striving to maintain this momentum in a time of unprecedented global change. Finally, we hope that this analysis may also provide valuable insight for other jurisdictions that struggle with similar IAS management challenges.

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Author contributions

EJH, SJC, and JRB conceived and designed the study. CHR, EJH, JDG, SP, AMM, SJC, and JRB drafted or revised the manuscript.

Competing interests

The authors have declared that no competing interests exist.

Data availability statement

All relevant data are within the paper.

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