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Integrative adaptive management to address interactions between biological invasions and protected area connectivity: a Canadian perspective

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Abstract

Expanding and creating protected area networks has become a central pillar of global conservation planning. In the management and design of protected area networks, we must consider not only the positive aspects of landscape connectivity but also how that connectivity may facilitate the spread of invasive species, a challenge that has become known as the connectivity conundrum. Here, we review key considerations for landscape connectivity planning for protected area networks, focusing on interactions between network connectivity and the management of invasive species. We propose an integrative adaptive management framework for protected area network planning with five main elements, including monitoring, budgeting considerations, risk assessment, inter-organizational coordination, and local engagement. Protected area planners can address the dynamic aspects of the connectivity conundrum through collaborative and integrative adaptive management planning.

Key words: connectivity, conservation, protected areas, invasive species, adaptive management, terrestrial

Introduction

Spatial planning for terrestrial protected areas (hereafter PAs) has been of central importance to the discipline of conservation biology for decades (Noss and Harris 1986) and is increasingly important for guiding conservation decisions at global, regional, and national scales. Protected area planners are faced with the challenge of mitigating human environmental impacts, which continue to cause a steady decline in biodiversity and ecological integrity in and around PAs across the planet (Beyer et al. 2019). Addressing these impacts includes planning for PA ecological connectivity, which is now seen as vital for addressing global environmental change (Liang et al. 2018; Stewart et al. 2019). Connectivity amongst PAs facilitates critical ecological processes such as dispersal, seasonal migrations, and species range shifts resulting from climate change, and in doing so, it can prevent deleterious effects, such as inbreeding and local extinctions, thereby helping to maintain ecosystem integrity (Saura et al. 2019). However, ecological connectivity can also have negative effects such as facilitating the spread of disturbances and invasive species. For example, well-connected PAs can act as corridors for the movement of exotic invasive species, such as the emerald ash borer (*Agrilus planipennis* Fairmaire) or the European fire ant (*Myrmica rubra* L.) (Resasco et al. 2014; Cuddington et al. 2018). Outbreaks of native species such as mountain pine beetles (*Dendroctonous ponderosae* Hopkins; Maguire et al. 2015) and spruce budworms (*Choristoneura occidentalis* Freeman; Drever et al. 2018) can also be facilitated by large contiguous areas of mature coniferous forest. Moreover, the connectivity of anthropogenic disturbances (e.g., road and trail networks, energy infrastructure corridors, and agricultural landscapes) can also facilitate the movement of non-desirable species within and between PAs (Schulze et al. 2018). This can alter predator-prey interactions and facilitate disturbance-mediated species invasions into PAs (Vardarman et al. 2018).

The recently developed United Nations Kunming-Montreal Global Biodiversity Framework reaffirmed targets for having well-connected PAs and for mitigating the spread and impacts of invasive species (UN Environment Program 2022; Targets 2/3 and 6, respectively, of Goal A: 15th Conference of the Parties to the Convention on Biological Diversity). To achieve these targets, PA planners are developing proactive strategies to address the multifaceted challenges of global environmental change (Kullberg et al. 2019; Hilty et al. 2020), including land-use change, climate change (D'Aloia et al. 2019; Hilty et al. 2020), and biological invasions (Schulze et al. 2018; Hilty et al. 2020). However, in planning for PA networks and connectivity, integrative management approaches that account for both the benefits and risks of connectivity will be required. In Canada, the adoption of the Kunming-Montreal Global Biodiversity Framework will lead to the creation of a new suite of national goals and targets for conservation that will be formalized in 2024 (Environment and Climate Change Canada 2023). To achieve the new global and domestic targets, Canada will likely build upon existing initiatives for PA connectivity planning (e.g., the National Program for Ecological Corridors; Parks Canada Agency 2022) and for the mitigation of species invasions (Environment and Climate Change Canada 2016; Beazley et al. 2023). Whether for existing or new initiatives, managers will increasingly need to address these targets in tandem (Beger et al. 2022).

The threat of invasive species in protected areas

The spread of exotic invasive species represents a significant threat to the ecological integrity of PAs around the globe (Schulze et al. 2018). It is well known that invasive species can cause significant reductions in the diversity of native ecosystems as well as impairment of ecosystem functioning (Pyšek et al. 2012). In many cases, landscape alteration or degradation can create opportunities for non-native species to establish and potentially spread throughout a region (Hierro et al. 2006). Conversely, intact ecosystems are typically more resistant to invasion (Beaury et al. 2019), but the degree of resistance is also contingent on the particular characteristics or traits of potential invasive species (Martin and Marks 2006). Indeed, the susceptibility of an ecosystem or PA to biological invasion is not a static property but rather a dynamic and context-dependent spatio-temporal process (Clark and Johnston 2011), demanding an adaptive management response. In Canada, research has been conducted to model the spread of invasive species, and while some local-scale spatial models for invasive species spread have been explicitly focused on PAs (Sy et al. 2009), regional-scale modelling efforts tend not to make explicit linkages to PA management. Furthermore, while invasive species management considerations are embedded into a multitude of policies and strategic frameworks across Canada—including some that focus on PAs (Meloche and Murphy 2006)—integration is lacking across scales and sectors (Smith et al. 2014).

Biological invasions are widely modelled and managed through a stage-based approach (Fig. 1), with optimal management actions recommended for each stage (Richardson et al. 2000). For stage *i* (pre-introduction), managers evaluate the potential pathways for invasion and act to minimize the possibility of transport. For stage *ii* (introduction and establishment), early detection and eradication are prioritized, often involving spatial niche modelling for specific species, which can inform monitoring efforts for vulnerable areas (Václavík et al. 2010). In stage *iii* (spread), the ability to contain spread and/or hinder dispersal is assessed (Mortensen et al. 2009). In stage *iv* (dominance and/or naturalization), the ability to reduce impact and prevent spread to other regions is prioritized, but such efforts are often confounded by a lack of coordination across jurisdictions, land tenure heterogeneity, and/or a lack of management resources (Epanchin-Niell et al. 2010). Managers also contend with the potential for well-connected desirable habitat to allow for the spread of "native invasions" or "overabundant species" (Environment and Climate Change Canada 2010; Wilkerson 2013), which do not necessarily fit the stage-based model of invasion (Nackley et al. 2017). Where non-native invasions tend to act synergistically with other human disturbances, hyper-abundance of native species often arises due to human environmental influence (e.g., resource subsidies, Lamarre et al. 2017) or can take the form of outbreaks (e.g., chronic wasting disease, Nobert et al. 2016; spruce budworm, Senf et al. 2017). These varied ecological possibilities present a major challenge for PA managers and the broader field of PA connectivity planning.

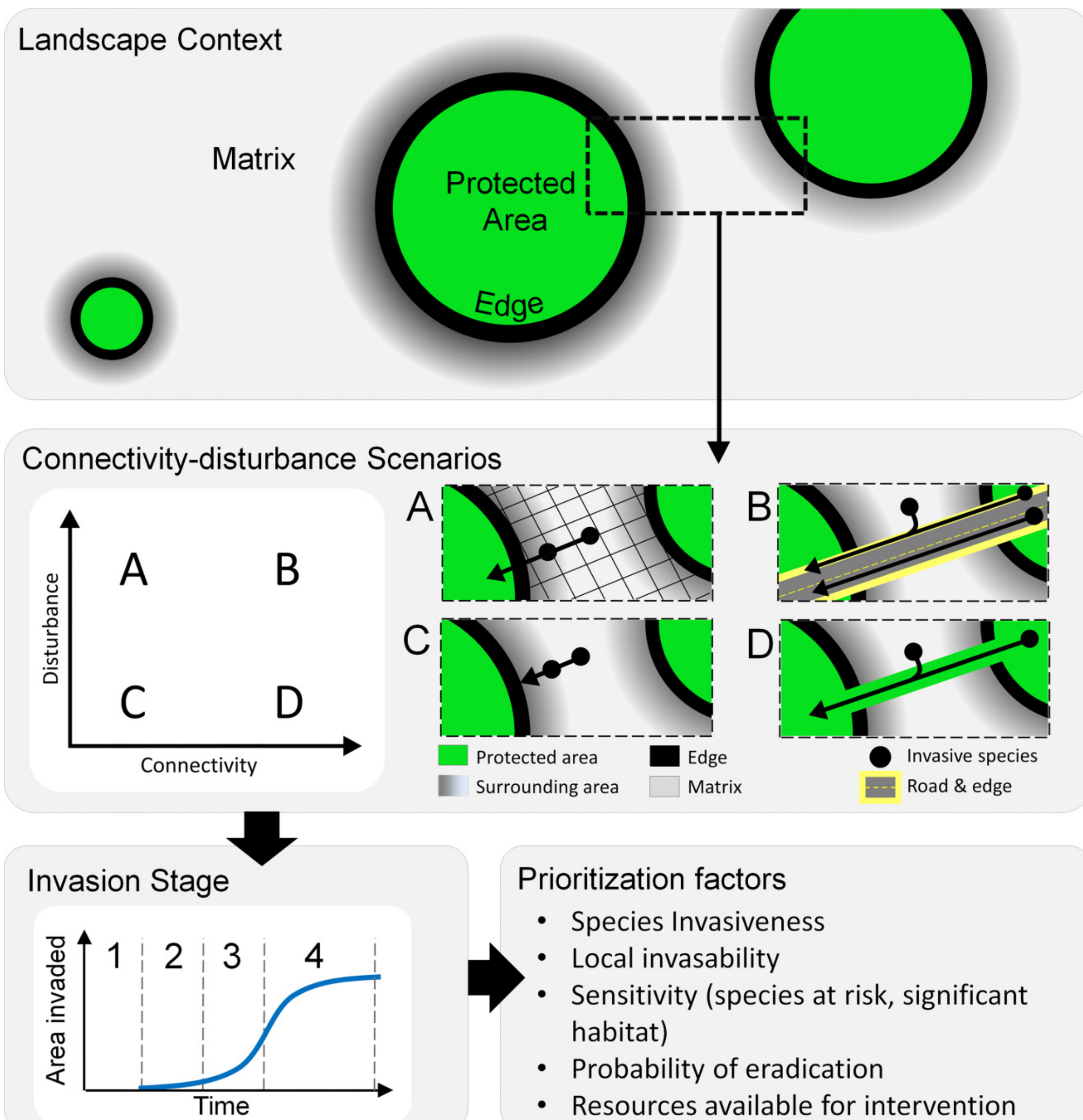
Variation in the movement of desirable and undesirable species across natural and anthropogenic landscape elements leads to a "connectivity conundrum", requiring PA planners to consider the positive and negative consequences of connectivity (Simberloff and Cox 1987; Hilty et al. 2020; Beger et al. 2022; Silva et al. 2023) and trade-offs in spatial conservation planning. Here, we elaborate on the confounding factors surrounding PA network planning and propose a framework to support such planning that recognizes variation in ecological interactions and the multifaceted nature of landscape connectivity. We argue for the importance of integrative adaptive management practices to address this complexity, including monitoring, human resource considerations, risk assessment, inter-organizational coordination, and local engagement. In the coming years in Canada, protected and conserved area planners will be developing and implementing new landscape connectivity and PA network projects and will simultaneously need to grapple with the management of invasive species. Below, we provide a synthetic perspective on these subjects that we hope can inform PA connectivity planning in Canada.

Confounding factors for protected area network planning

Anthropogenic contexts for protected area connectivity

The manner in which different forms and scales of human land-use activity affect biodiversity is highly variable (Decker et al. 2017). For example, intensive agriculture and/or urbanization typically have a direct negative effect on biodiversity (Newbold et al. 2015). These landscape processes tend to also be associated with the increased prevalence of non-native and invasive species (Cadotte et al. 2017), which often spill over into PAs (Padmanaba et al. 2017). Given that biological invasions can be facilitated by direct human transport or often act synergistically with other human disturbances, PAs located in areas with high-to-moderate human population density face the highest probability of invasion (Chapman et al. 2020). However, the presence of non-native invasive species in remote PAs has also been increasingly observed (Sanderson et al. 2012). Protected areas located in regions with high-to-moderate human population density tend to house a greater number of threatened species and generally have a high degree of biodiversity compared to more remote PAs (Kraus and Hebb 2020). These PAs are also differentially subjected to external pressures such as sound and light from anthropogenic sources and chemical pollution runoff, as well as internal pressures such as the transportation and hospitality infrastructure created to support PA visitation (Jones et al. 2018). In

Fig. 1. Protected area invasion scenarios based on different forms of landscape connectivity and disturbance. The top panel depicts the variable nature of invasion risk associated with the positioning of an invasive species relative to a protected species. The middle panel depicts simplified connectivity-disturbance scenarios between two protected areas, noting also the potential invasion risk associated with each scenario. Scenario A illustrates a hypothetical low-connectivity/high-disturbance case where a disturbance-dependent invasive species is able to spread across a disturbed landscape (shown as hatched lines) and invade a protected area. Scenario B shows the case where an adjoining road between two protected areas creates a high degree of both anthropogenic connectivity and disturbance, facilitating the spread of invasive species via road transportation (e.g., stowaways or intentional transport) as well as through road edges (i.e., establishment and spread opportunities for invasive species). Scenario C depicts a low-connectivity/low-disturbance scenario where a disturbance-dependent invader is subject to resistance across the landscape through an intact ecosystem in the matrix, the protected area edge, and/or the protected area itself (i.e., "diversity-resistance"). Scenario D depicts a high-connectivity/low-disturbance scenario where a corridor of desirable habitat may also facilitate the spread of invaders that are not dependent on disturbance for establishment. The bottom-left panel depicts the stage-based conceptualization of the invasion process (i: pre-introduction, ii: establishment, iii: spread, iv: dominance) and the invasion curve. Invasive species can be present at different stages of the invasion process in the matrix, the area surrounding a protected area, or within the protected area itself. Each of these possibilities differentially informs focal management action. The bottom-right panel notes some of the primary factors considered in management prioritization and decision support modelling.



intensively farmed or urbanized landscapes, the availability of desirable habitat is extremely reduced (Wilson et al. 2016). Remnant habitat patches can act as stepping stones, both for species of conservation interest and/or invasive species, as they disperse or are transported between larger and more intact habitats or PAs (Saura et al. 2014). Conversely, fragmentation that impedes the movement of desired species can also reduce the spread of an invasive species that has specific habitat requirements (e.g., apple snail, *Pomacea canaliculata* Lamarck, in wetland habitats; Pierre et al. 2017).

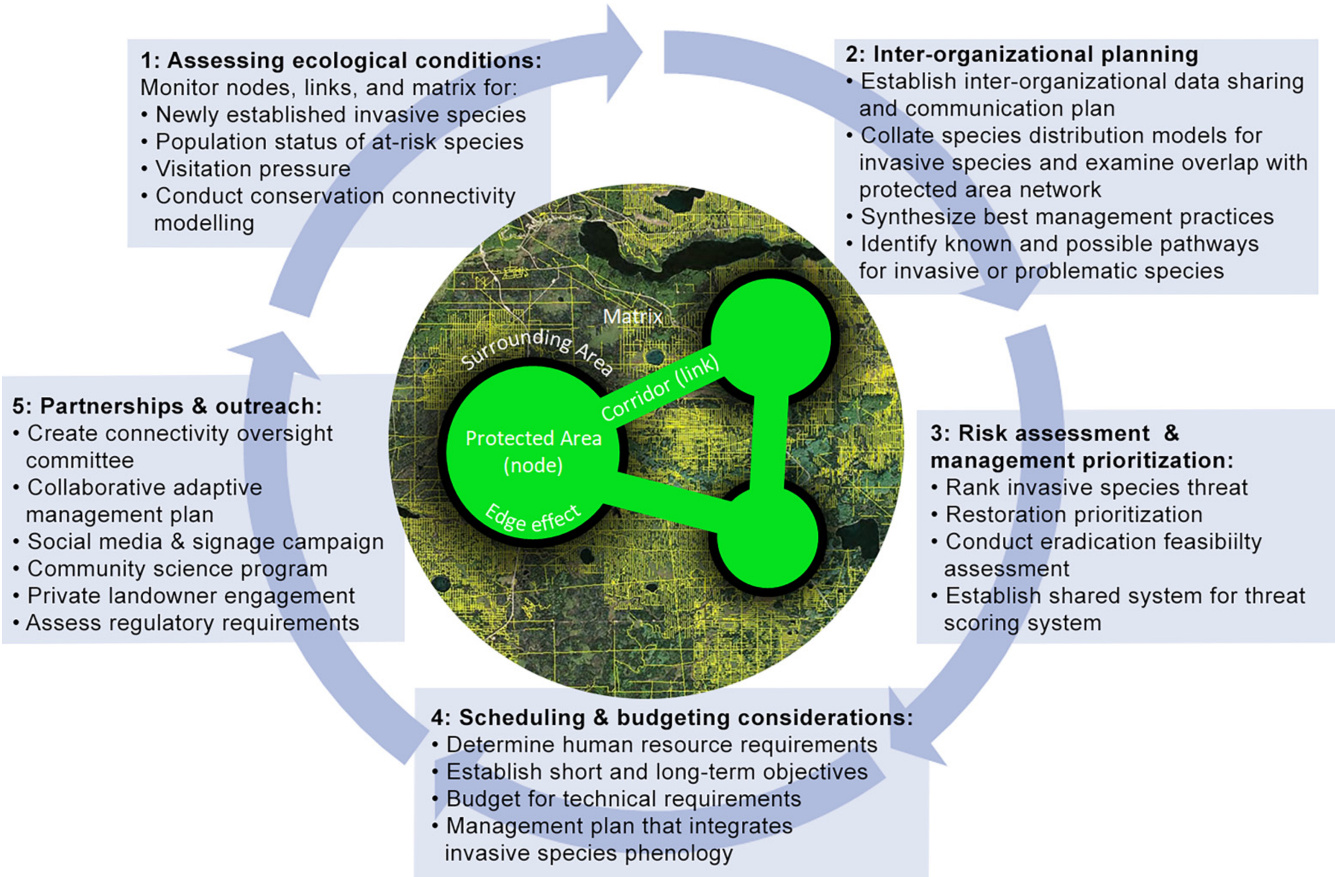
Transportation corridors in and around PAs can have a dual effect of reducing habitat connectivity and impeding the movement of some organisms (Trombulak and Frissell 2000), while also facilitating the spread and establishment of non-native invasive species by creating a well-connected *disturbed* landscape that many invasive species are able to exploit (With 2002; Riitters et al. 2018). Indeed, studies have documented how the connectivity and disturbed conditions created by road networks can facilitate the spread of invasive species beyond the direct vehicular transport of non-native species (e.g., Muthukrishnan et al. 2018). These types of invasions are a product of the interaction between anthropogenic disturbance and connectivity across the landscape, where both factors are explicitly and spatially linked (Fig. 1). Collision mortality risks increase with traffic density, but the impact of smaller rural roads used for forestry, mining, and other resource extraction activities can also be substantial. Invasive species can be transported by users of rural roads into otherwise undisturbed habitats (Trombulak and Frissell 2000), and disturbed road edges create opportunities for disturbance exploiting invasives to thrive and spread along roads and into intact areas (e.g., Japanese knotweed, *Fallopia japonica*, Dauer and Jongejans 2013; *Phragmites australis* (Cav.) Trin. Ex Steud., Sciance et al. 2016). Resource roads also alter behaviour, movement, and mortality risks for native species such as wolves, bears, and woodland caribou, which can, in turn, alter trophic dynamics and population viability (Mumma et al. 2018; Dickie et al. 2020; Proctor et al. 2020; Whittington et al. 2022). Thus, even sparsely populated rural areas can be surprisingly altered. Resource roads and other resource extraction activities are not consistently mapped (Poley et al. 2022), so global, national, and continental analyses do not fully capture the intensity and extent of these disturbances. Even so, in some areas, large tracts of intact land do remain to facilitate the movement and migration of wide-ranging species and connectivity among PAs (Belote et al. 2017; Hirsh-Pearson et al. 2022; Hughes et al. 2023; Pither et al. 2023).

Variation in edge effects across protected areas and corridor linkages

Edge effects refer to the environmental conditions that arise at the boundary of different ecosystems or land-use types (Didham 2010). Typically, edge effects are assessed through a conservation lens as products of anthropogenic landscape fragmentation and disturbance (Harper and Macdonald 2002). The relative significance of edge effects in PA planning varies in relation to the type of ecosystem within a PA, specific conservation objectives (e.g., planning for species at risk, connectivity planning), as well as the composition of the matrix (Fig. 1). For instance, a PA consisting of mostly forest habitat that is surrounded by farmland or an urbanized landscape (e.g., Rouge National Urban Park in Toronto, Canada) will be subject to edge effects at the margins of intact forest habitat (e.g., due to variation in micro-climate, light regime, seed dispersal, and colonization; Matlack 1993). Many invasive plant or arthropod species possess traits that allow them to take advantage of edge effects, readily dispersing along forest edges and establishing populations (Dillon et al. 2018). But many of these species that are able to colonize such disturbed habitats are limited in their ability to spread to intact habitats (Foxcroft et al. 2011). Yet, it can also be the case that an invasive species is able to establish itself in a disturbed edge environment and then spread to intact habitats, which is also a concern for the creation of new ecological corridors where edges and early successional habitats can allow for the establishment and spread of invasive species into PAs (Wilkerson 2013). This can occur due to an invader occupying an empty niche in the intact ecosystem and perhaps also possessing a fitness advantage that allows them to outcompete native species and exert impacts on the system (MacDougall et al. 2009). *Vincetoxicum rossicum* (Kleopow) Babar., an invasive plant species in Rouge National Urban Park, is an example of an invader that has been able to colonize disturbed edge habitat and spread to intact habitat in the PA and throughout the broader region (Sodhi et al. 2019). Similarly, *P. australis* has colonized disturbed edge habitats across Canada—adjacent to both natural and anthropogenic landscape features—and has also spread and become dominant in areas of significant conservation value (Jung et al. 2017).

For PA connectivity considerations, the potentially deleterious impacts of edge effects are of concern when planning for the creation and/or restoration of stepping-stone habitat patches or conservation corridors in fragmented landscapes. In these cases, managers are interested in whether disturbed corridors or patch edges can facilitate the spread of invasive species to valuable conservation land. A conservation corridor may consist of a wide stretch of relatively intact habitat that connects larger PAs, in which case, edge effects may be of minimal concern. Alternatively, a corridor could also consist of a newly restored habitat (i.e., early successional), a patchy and fragmented landscape with multiple land-use types and habitats, or a combination of these (Yu et al. 2012). In the case of a new conservation corridor where a large amount of land will undergo ecological restoration, monitoring can be prioritized during the early stages of restoration because a young system is often most susceptible to invasion (Fig. 2, #1; Yannelli et al. 2017). It is often the case that invasive species removal is the first step of restoration projects (Perry et al. 2017), where such efforts aim to optimize resistance to invasion (Funk et al. 2008).

Fig. 2. Building on existing best practices in invasive species and protected area management, we propose an integrative adaptive management framework for protected area network planning that addresses the interaction between these two conservation objectives. The center image depicts the spatial context for a hypothetical PA network, including the PAs (nodes), corridors (links), the matrix, and the potential for edge effects.



An integrative adaptive management framework addressing interactions between biological invasions and protected area connectivity

Protected areas around the globe are already dealing with biodiversity decline caused by anthropogenic disturbances and invasive species (Jones et al. 2018; Leberger et al. 2020). To address these dynamic challenges, individual PAs typically use adaptive management frameworks, and we argue that these approaches can be applied to the planning and management of PA connectivity initiatives in a manner that addresses the connectivity conundrum. We propose a framework with five main elements, ranging from assessing the current ecological condition to budgeting and developing partnerships.

Assessing ecological conditions

Canadian PAs are often governed by an adaptive management approach, where the status of the PA and management effectiveness are evaluated using ecological indicators and quantitative targets and thresholds (Wright et al. 2017). The key component of adaptive management for PAs is that ecosystem monitoring is carried out on a regular basis so that values for indicators can be assessed in relation to previous years and/or baseline conditions (Fig. 2, #1). With respect to the introduction and spread of invasive species in PAs and PA networks, ecosystem monitoring within an adaptive management program can allow for the identification and possible eradication of recently established invasive species and can also allow managers to evaluate the effectiveness of control methods (Rout et al. 2017). When resources permit, PA managers may apply an active adaptive management approach to gauge the relative effectiveness of multiple types of interventions for the control of abundant invasive species (e.g., physical removal, chemical control, and biological control) (Giljohann et al. 2011) or to examine the potential of different types of connectivity (e.g., stepping stones, intact corridors, and restored habitat corridor) to minimize the rate of spread across a PA connectivity project (Travers et al. 2021).

Monitoring is perhaps the most fundamental aspect of invasive species management. Goals include detecting newly established invaders, characterizing invader distribution and rate of spread, and assessing the effectiveness of different control measures (Foxcroft et al. 2017). However, a systematic monitoring approach for invasive species management does incur a significant financial cost to conservation managers, but the cost of managing well-established invasive species can be crippling (Moodley et al. 2022). Early detection of invasive species via ecological monitoring also maximizes the potential for eradication (Rejmánek and Pitcairn 2002).

With respect to monitoring the establishment and spread of invasive species and/or overabundant native species (Environment and Climate Change Canada 2010) between PAs or from unprotected land into PAs, different management considerations arise from conditions in the matrix between PAs, in the area surrounding a PA, or within the PA itself (Fig. 1). In planning for PA networks and/or connectivity between PAs, managers are faced with multiple possible scenarios and scales of invasion risk. For instance, PA managers may need to assess the risk associated with a specific invasive species that has yet to establish and develop a plan for proactive management actions (i.e., stages *i* and *ii*: pre-introduction and establishment; Fig. 1). It could also be the case that an invasive species is newly established and spreading in either a nearby PA or in the surrounding matrix. In this case, managers may need to work with regional stakeholders to coordinate monitoring and/or the application of control measures (i.e., stage *iii*: spread, Figs. 1 and 2, #5; e.g., Downey et al. 2010). For example, *P. australis* has dispersed across much of eastern North America, becoming common in both PAs and landscape corridors (natural and anthropogenic). Despite emergent bio-control options for *P. australis* management (Blossey et al. 2020) and the existence of inter-organizational and inter-national task forces (Great Lakes Phragmites Collaborative n.d.), it is most likely the case that *P. australis* will remain a significant challenge for ecosystem managers well into the future (Quirion et al. 2018). In this case, faced with a triage scenario, ecosystem and PA managers across the region are prioritizing the conservation of threatened species habitat (Markle et al. 2018).

Inter-organizational planning

The multi-scale and inter-jurisdictional nature of PA connectivity planning has spurred collaborative planning to identify opportunities to improve connectivity for conservation (Lemieux et al. 2021). Inter-organizational collaboration is also a common characteristic of invasive species management and risk assessment (Emilson and Stastny 2019), but the complexity of the issue often hinders effective intervention (Fantle-Lepczyk et al. 2022). Nevertheless, there are clear but unrealized synergies between the organizational structures involved in PA connectivity planning and invasive species management (Fig. 2, #2 and 5). Addressing the connectivity conundrum will require inter-organizational coordination that integrates connectivity for conservation, assessment of invasion risk, and public engagement (Bixler et al. 2016). For example, in the case of PA connectivity planning, local-scale land-use and management practices, both at the "node" scale (Häkkilä et al. 2018) and the "link" scale (corridors and matrix: Newmark et al. 2023), influence the quality and integrity of a larger PA network (Fig. 2). Such interactions can sometimes be complicated by the existence of multiple forms of land tenure and/or conflicting land-use practices across a proposed connectivity corridor or PA network (Mansourian et al. 2019; Hilty et al. 2020). These governance challenges that emerge in multi-actor and multi-scale interactions for PA planning are also pervasive in the practice of invasive species management (Estévez et al. 2015). However, the national-scale adoption and implementation of the Post-2020 Global Biodiversity Framework should promote data sharing and potentially spur the development of a national invasive species database (UN Environment Program, 2023; Fig. 2, #2 and 5), as has been proposed for the United States (Wallace et al. 2020). In Canada, organizations such as the Invasive Species Centre, the Canadian Council on Invasive Species, the National Indigenous Guardians Network, and a multitude of other regional partnerships are well positioned to establish working groups but are also faced with the hurdle of inadequate resource availability (Canadian Council on Invasive Species 2023). The integration of invasive species risk assessment with PA connectivity planning can provide a necessary proactive perspective to guide restoration efforts, land securement, and ecosystem monitoring.

Risk assessment and management prioritization

Effectively integrating invasive species risk assessment into PA connectivity planning initiatives will benefit from the consideration of predictive invasive species distribution models (SDMs). Species distribution models are widely used in conservation and ecology to predict biological responses to future environments (Lawler et al. 2011). Many SDM analyses are focused on species of conservation concern (Austin 2007), but there is an increasing interest in potential future distributions of invasive species (Srivastava 2019). For connectivity planning, SDMs can be developed to predict the risk of invasion into and across potential connectivity corridors by integrating a suite of ecological parameters (Stewart-Koster et al. 2015; Urziceanu et al. 2022). Species distribution models can also be synthesized with risk assessment frameworks to guide proactive monitoring efforts and management intervention strategies (Booy et al. 2017; Srivastava 2019). Some management plans account for the invasion stage, the spatial distribution of an invader, and dispersal predictions that may improve management effectiveness (Fournier and Turgeon 2017), sometimes emphasizing the probability of eradication to prioritize the timing of intervention efforts (Booy et al. 2017). For example, the recent establishment of the invasive spotted lanternfly (*Lycorma delicatula* White) in both North America and other locations around the globe has motivated several analyses involving SDMs (Jung et al. 2017; Wakie et al. 2020) and evaluations of potential control measures (Leach et al. 2019). In these and other examples, climatic niche information has been used to project the potential future distribution of a species (Wakie et al. 2020).

For a more thorough assessment of the risk of dispersal to PAs, natural areas, and agricultural lands, potential conservation corridor managers can also consider (1) the distribution and connectivity of primary host species; (2) the spatial overlap between the predicted climatic niche and the distribution of potential host species (e.g., there are thought to be more than 60 for spotted lantern fly; Lee et al. 2019); (3) the life-history traits of the focal species (dispersal ability, reproductive cycle, and phenology; Muthukrishnan et al. 2018); (4) the potential for human transport (direct or indirect); and (5) the risk to threatened or commercially important species (Andersen et al. 2004). Spatially explicit predictive risk assessments grounded in an understanding of a species biology are often necessary to improve predictions and the effectiveness of management (e.g., hemlock wooly adelgid (*Adelges tsugae* Annand) Liang et al. 2014, and Asian long-horned beetle (*Anoplophora glabripennis* Motschulsky; Favaro et al. 2015; Fig. 2, #2–4).

Scheduling and budgeting considerations

Protected area managers contend with an enormous array of management objectives (e.g., planning ecological restoration work, working with research scientists, planning an annual budget, or determining staffing requirements for a busy field season). In Canada, government funding for the management of PAs has historically been inadequate (Canadian Parks and Wilderness Society 2021) and has been documented at federal and provincial levels (Office of the Auditor General of Canada 2008; Office of the Auditor General of Ontario 2020). More recently, there has been a surge in government funding for conservation science and management to support Canada's adoption of the 2030 Global Biodiversity Framework from the United Nations Convention on Biological Diversity, which includes targets for PA connectivity (Government of Canada 2021) and support for invasive species management (Invasive Species Centre 2023). This recent focus on the need to make progress in PA connectivity and invasive species management arrives at a critical time where many PA managers are contending with increasing anthropogenic pressures and climate change impacts.

Many decision-support tools have been developed for invasive species management that integrate biophysical parameters and management scenarios. Typically, these are species-specific endeavours that integrate rates of spread and phenology of a given invasive species and also often include budgeting and scheduling scenarios to determine optimal long-term management strategies (Adams and Setterfield 2015). However, such approaches rarely consider the "connectivity conundrum" (Ashton et al. 2020; Saffariha et al. 2023, but see Minor and Gardner 2011). These modelling exercises focus on determining optimal timing and extent of ecological monitoring (Bonneau et al. 2018), expenditure on efforts focused on eradication (Adams and Setterfield 2015), and generally assessing the cost of labour and other resources required to carry out the work within a management cycle (Baker et al. 2017). In many cases, these integrative models are complex and may be difficult to implement, so a "science-practice gap" remains (Thompson et al. 2021). Developing more useful decision support tools may require a more collaborative approach that directly involves managers at various stages of the development process (Bodner et al. 2021). Collaborative development can take time, but it can also yield significant returns on investment for evidence-based management strategies (Hanley and Roberts 2019).

Partnerships and outreach

Recent analysis has revealed that the vast majority of PAs lack effective approaches for prioritizing the management of invasive species (Forner et al. 2022). Further, it is rarely the case that invasive species management plans are assembled using input from multiple stakeholders and rights holders to determine conservation priorities (Shackleton et al. 2019). Given the complex, multi-scale nature of biological invasions, effective prioritization of monitoring efforts and/or the application of control measures should benefit from extensive public engagement and collaboration (Crowley et al. 2017). There are examples of management frameworks that include stakeholder input, public perception, and expert opinion, where these considerations are integrated to form consensus opinion on the potential impact of an invader, specifically their potential impacts on biodiversity, ecosystem services, and public safety (Gaertner et al. 2017; Van Poorten and Beck 2021). Potgieter et al. (2018) developed a decision support model for the management of invasive species in Cape Town, South Africa, where these impact factors were assigned weighted values following consultation with stakeholder input and expert opinion. Outputs from this model included a spatially explicit characterization of invasion risk, site sensitivity, and optimal management action. Depending on the scale of PA connectivity planning, a decision support model may need to be structured in a way that integrates multiple actors to appropriately gauge both risk and effective management actions (Fig. 2, #5). In this regard, a generalized decision support framework that synthesizes considerations for both connectivity for conservation and invasive species management would be a welcome addition to the next national-scale biodiversity framework.

It is often the case that human movement into and within PAs acts as a primary driver of biological invasions (Guimarães Silva et al. 2020). As such, many ecosystem managers around the world have sought to improve their communications and public engagement methods in hopes of minimizing this invasion pathway (Lukács and Valkó 2021). These types of initiatives often involve a combination of zoning and PA signage, where human movement is regulated within a PA (Vardarman et al. 2018). Other strategies include engaging the broader public in the region of the PA to incentivize invasive species management (Drescher et al. 2019), accessing community science for early detection (Bonnet et al. 2020), and educational programming (Bravo-Vargas et al. 2019). Public engagement and inclusive approaches to PA management are now recognized as vital components of effective invasive species management practices in and around PAs (Shackleton et al. 2019). This is also true for PA connectivity planning, where community science, private land restoration, and adherence to planning policies all require buy-in from the public to improve the probability of success (Ban et al. 2013). Community science can also provide effective low-cost ecological monitoring in and around PAs (Binley et al. 2021) and contribute to regional PA connectivity planning to mitigate the potential for invasive species to disperse between PAs.

Concluding remarks

In addition to growing national commitments for protected area expansion, effective planning for the connectivity of PA networks and subsequent implementation will be critical in addressing dynamic ecological change in the coming decades (Hilty et al. 2020; UN Environment Program 2022). Central to these PA connectivity considerations (e.g., Targets 2 and 3) are the current and future spread and impacts of invasive species on native ecosystems and PAs (Shulze et al. 2018). The need to facilitate the movement of some species and impede others leads to connectivity conundrums. In Canada, this is of particular concern in the south of the country, where landscapes are highly fragmented and there is a disproportionate concentration of species of conservation concern (Kraus and Hebb 2020). We propose an integrative adaptive management framework and highlight actions that can help address these conundrums in short- and long-term PA planning. Hence, to improve their resistance to invasion, the management and design of PA networks need to focus not only on corridors but also on the PAs themselves as well.

Central to our perspective is the need for collaborative adaptive management for landscape connectivity considerations in PA network planning. However, we also acknowledge that PA managers are often resource-limited and, in many cases, are operating in a state of conservation triage (Coad et al. 2019; Dietz et al. 2021). Robust ecological monitoring and proactive risk assessments can inform both prospects for improved connectivity as well as the threat of species invasions. Further, the complexity of spatial planning for PA networks calls for effective engagement with regional partners (e.g., managers, land owners, Indigenous communities, scientists, and government agencies) and PA patrons. Anthropogenic disturbances, including human movement, act as both the drivers of biological invasions and impediments to conservation connectivity. Protected area planners can address these dynamic aspects of the connectivity conundrum through collaborative and integrative adaptive management planning.

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The authors declare there are no competing interests.

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