WILDLIFE CROSSING INFRASTRUCTURE FOR A GREEN RECOVERY: EMERGING OPPORTUNITIES FOR INNOVATION IN POST- COVID-19 RECOVERY EFFORTS

VICTORIA BLAKE
2022

IMAGE SOURCE: PEXELS, BY TOMÁŠ MALÍK

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Master of Planning
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ABSTRACT

While roads are an essential part of modern life, they fragment habitats and landscapes. The effectiveness of wildlife crossing infrastructure (WCI) in reducing wildlife-vehicle collisions and reconnecting landscapes across roads are well documented in scientific literature, along with many other co-benefits. However, WCI projects are not implemented on a national scale in the US or Canada, in part due to lack of funding prioritization. This study undertook a thematic review of the US and Canadian infrastructure and spending plans to identify emerging opportunities for landscape connectivity and green infrastructure projects. The potential for co-locating WCI with active transportation uses was then explored in greater detail through an integrative literature review. WCI projects can contribute to national goals of climate resilience, economic recovery, and closing the infrastructure gap. However, positioning projects for funding will require strategic communication of the co-benefits of connected landscapes that align with national funding goals.

Key words: wildlife crossing infrastructure, active transportation, resilience, biodiversity, landscape connectivity

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SECTION ONE

INTRODUCTION

IMAGE SOURCE: PEXELS, BY BRETT SAYLES

1.1 STUDY RATIONALE

Landscape connectivity is a concept derived from the field of landscape ecology that recognizes the critical importance of linkages across the natural environment for the health and survival of animals, insects, plants, and ecosystems. As originally defined, landscape connectivity is "the degree to which the landscape facilitates or impedes movement among resource patches" (Taylor *et al.*, 1993). Landscape fragmentation refers to the breaking of these critical linkages, both through natural occurrences (cliffs, streams, *etc.*) or through human activity (roads, fences, *etc.*) which subdivides habitats into insular fragments (Wilcox & Murphy, 1985). The increasing fragmentation of landscapes from human activity reduces the ability of ecosystems to absorb and respond to change (Oliver *et al.*, 2013; Thrush *et al.*, 2008) . For animals, their habitats are likely to shift as climate change impacts temperatures, rainfall, food sources, and land cover. Connected landscapes promote resilience by allowing space for species to adapt to change (Lister *et al.*, 2015; Oliver *et al.*, 2013; Thrush *et al.*, 2008).

Rapid urbanization and road building fragments landscapes on scales far beyond natural fragmentation (Wilcox & Murphy, 1985). While roads are an essential part of modern life, they act as a barrier to connected habitats and landscapes (Forman & Alexander, 1998; Trombulak & Frissell, 2000). One of the most visible symptoms of this are wildlife-vehicle collisions (WVC) which are both costly and a threat to human and ecosystem health. In the US, WVC cost the country more than $8 billion annually (M. Huijser *et al.*, 2009). Due to the high cost, governments and insurance companies have an interest in reducing WVC and thus the associated personal injury and property damage (Huijser *et al.*, 2008). Ecologists, planners, and conservationists also have an interest in reducing WVC to reconnect landscapes, promote biodiversity, and maintain ecosystem health and wellbeing (Lister, 2019; Morecroft *et al.*, 2012). Along with appropriate wildlife fencing, wildlife crossing infrastructure (WCI) has been proven to reduce WVC by more than 90% (Andis *et al.*, 2017; Clevenger *et al.*, 2009; Clevenger & Waltho, 2000; Huijser *et al.*, 2016) while increasing habitat connectivity and contributing to resilient landscapes (Barrueto & Clevenger, 2014; Clevenger, 2005; Crooks & Sanjayan, 2006). Although there are well-documented benefits of using WCI to reconnect habitats, widespread implementation has been challenging due to barriers including lack of funding, interdisciplinary collaboration and poor cost-benefit analysis (Huijser *et al.*, 2008; Kociolek, 2014; Kociolek *et al.*, 2015; Lister *et al.*, 2015). The amount of scientific literature

Figure 1 (above)
Wildlife crossing structure rendering submitted as part of the ARC International Wildlife Crossing Infrastructure Design Competition in 2010. Image from Olin Studio.

on the subject has grown considerably in the last 10 years, and innovative methods of collaboration have arisen such as co-laboratories [1], design competitions, and transdisciplinary partnerships through ARC Solutions [2] (Lister, 2015).

Both US and Canadian governments have made significant investments in infrastructure to aid in recovery from the COVID-19 pandemic. WCI offers many co-benefits and achieves many of the broad policy goals within Canadian economic recovery spending yet are largely left out of recovery spending plans (Department of Finance Canada, 2021; Infrastructure Canada, 2018). This is in contrast to the United States, who has committed $350 million for dedicated to a pilot program for WCI implementation, and explicitly included WCI in several existing infrastructure programs (United States Government Office of Management and Budget, 2021; U.S. Senate Committee on Environment and Public Works, 2021). Broadly, federal recovery plans and budgets in the US and Canada detail an emphasis on reducing greenhouse gas (GHG) emissions, increasing resilience of the natural and built environment, climate change mitigation and adaptation, disaster preparedness, and promoting community health and wellbeing. WCI is often perceived to be prohibitively expensive to implement (Huijser *et al.*, 2008; Kociolek, 2014); however, positioning WCI projects with other initiatives that achieve compatible co-benefits can also create more favourable cost-benefit analysis and increase the likelihood of funding allocation. Therefore, there is a need to explore the potential for co-location of WCI as a way to strategically position projects for funding opportunities, while ensuring that the ecological function is not compromised.

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1 Summaries of previous co-laboratories are available on the Ecological Design Lab website, including the methods and workshop outcomes: https://ecologicaldesignlab.ca/project/safe-passage-towards-an-integrated-planning-approach-to-landscape-connectivity/

2 ARC Solutions is a not-for-profit interdisciplinary partnership working to facilitate new thinking, new methods, new materials, and new solutions for wildlife crossing structures. Their primary goal is to ensure safe passage for both humans and animals on and across our roads. ARC does this through supporting the study, design, and construction of wildlife crossing structures throughout North America.

1.2 RESEARCH QUESTION AND OBJECTIVES

There is currently a critical juncture for WCI projects to be broadly implemented to contribute to climate resilience while supporting an economic recovery from the COVID-19 pandemic. New funding opportunities are emerging for projects that can increase safety, improve transportation, support biodiversity, and increase climate resilience through national infrastructure and spending programs. To capitalize on this funding, WCI must be positioned in a way that speaks both to its direct ecological benefits as well as the co-benefits relating to cultural and ecosystem services to increase political traction. However, the degree to which the co-benefits can be achieved without compromising the ecological benefits is a fine line that must be navigated carefully. Through this research the following question has been addressed :

> *What opportunities are emerging across the US and Canada to promote landscape connectivity and climate resilience through the deployment of wildlife crossing infrastructure within the context of COVID-19 green recovery strategies?*

Emerging opportunities are expected to relate to creating more cost-effective infrastructure to increase the feasibility of implementation. This is expected to be derived from the highlighting and emphasis of various co-benefits of landscape connectivity infrastructure, while ensuring that trade-offs to promote the co-benefits do not significantly compromise the primary ecological function.

In the current policy framework in the US and Canada, mitigation measures to reconnect landscapes and reduce WVCs typically are only implemented during the development of major road infrastructure projects. They usually are called for in the mitigation section of a project's environmental impact assessment that indicates that the project may impact a species at risk, or a species that poses a safety risk to motorists. The siloed nature of governance and decision making makes implementation of innovative, cross-discipline projects challenging (Dale, 2001; Lister *et al.*, 2015). The governance and decision making related to WCI is a broad, transdisciplinary endeavor that requires collaboration across silos towards integrated, cohesive action (Dale, 2001; Lister *et al.*, 2015; Newell *et al.*, 2022).

Climate resilient infrastructure projects are poised to take on new importance as federal governments look ahead to mitigate impacts from climate change and spur economic development in the wake of COVID-19.[3] The research question was crafted to explore the opportunities emerging from the most recent federal budgets and infrastructure plans for the US and Canada for green infrastructure, landscape connectivity and WCI.

3 See, for example, the 2019 Green New Deal proposed in the US, or the Build Back Better Plan released by the Government of Canada in 2020 (H. RES. 109 Green New Deal, 2019; Government of Canada, 2020).

1.3 PROJECT STRUCTURE

This paper begins in **Section 2** by summarizing key literature related to several concepts critical to the context of landscape connectivity and green infrastructure investments. This starts with contextualizing the current climate emergency with regard to infrastructure, resilience and biodiversity . The review includes a brief summary of available Indigenous knowledge on the aforementioned topics that reflect Indigenous relational ontology and epistemology, while acknowledging the historic and ongoing exclusion of Indigenous work in the academic literature. The relationship between landscape connectivity, fragmentation, and ecosystem services is then detailed as it relates to climate resilient infrastructure. This is followed by a discussion of road ecology, and the role of WCI in mitigating the impacts of roads on ecosystems. The costs and benefits of wildlife crossing infrastructure are then discussed, including significant monitoring work completed to date, as well as common barriers and jurisdictional considerations when examining green infrastructure.

The methods for this research are outlined in **Section 3**. I begin by situating the research as part of the Safe Passages work underway within the Ecological Design Lab . I then outline the methods used in the thematic review of current federal infrastructure and budget plans for the US and Canada. Drawing on conclusions from this thematic review, I discuss the process employed to undertake the integrative literature review of identified emerging opportunities.

Section 4 details the major thematic findings of federal infrastructure and spending plans, which provide the basis for the integrative literature review in the proceeding section.

The integrative literature review is summarized in **Section 5** and identifies key emerging opportunities that require further analysis. The focus of the analysis is on the emerging opportunity of co-locating WCI with active transportation uses, such as pedestrians and cyclists.

The paper concludes in **Section 6** with a closing discussion of recommendations that can help position green infrastructure moving forward, and recommended areas of focus for future research.

SECTION TWO

CONTEXT

IMAGE SOURCE: PEXELS, BY ERIK MCLEAN

2.1 CLIMATE CHANGE AND BIODIVERSITY LOSS EMERGENCY

Scholars have declared that earth has now entered the Anthropocene, where the main driver of ecological change is human activity (Crutzen, 2002; Ellis, 2018; Steffen *et al.*, 2015). We can clearly observe the wide-reaching impacts of human activity on the natural world, including climate change, biodiversity loss, land degradation, and ocean acidification (Intergovernmental Panel on Climate Change, 2022; Pörtner, Hans-Otto *et al.*, 2021). Many scholars and organizations have sounded the alarm that planetary boundaries have already been exceeded (Intergovernmental Panel on Climate Change, 2022; Steffen *et al.*, 2015). Biodiversity loss is also accelerating across the globe, with a projected loss of over one million species in the next decade (IPBES, 2019; Pörtner, Hans-Otto *et al.*, 2021). World leaders have signaled their intention to tackle climate change, with many leaders gathering at the 26th Conference of the Parties (COP26) to accelerate global action to meet the goals laid out in the Paris Agreement and the UN Framework Convention on Climate Change (United Nations, 2021).

In their 6th Assessment Report, the Intergovernmental Panel on Climate Change (IPCC) places strong emphasis on the interconnectedness of climate change, biodiversity and ecosystems (Intergovernmental Panel on Climate Change, 2022). As shown in **Figure 3**, there is an intricate relationship between biodiversity loss and and climate change. Globally, widespread disruption from climate change is already being observed with 1.1 degrees Celsius of warming (**Figure 2**). The global targets set out at COP26 aims to limit warming to 2 degrees Celsius, however even if rapid adaptation occurs we will still experience severe climate change impacts and biodiversity loss over the next decade (Intergovernmental

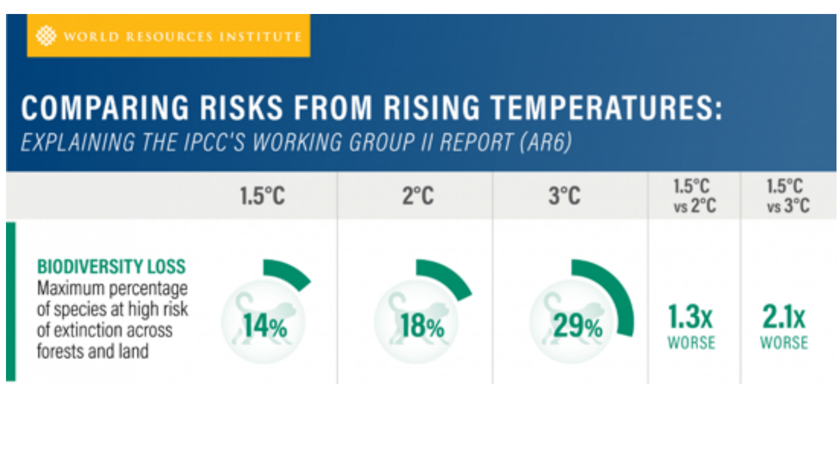


Figure 2 (right)
Risk of biodiversity loss at projected levels of global warming. Image from (Levin *et al.*, 2022).

Panel on Climate Change, 2022; United Nations, 2021). Ecosystems are increasingly vulnerable to climate change, with resilience being eroded through land-use changes, habitat fragmentation, pollution, and species exploitation.

Rapid urbanization and road building presents an acute challenge for climate change adaptation, biodiversity, and connected landscapes. The infrastructure needed to support and connect humans in the Anthropocene has led to fragmentation and degradation of the natural environment, which in turn reduces biodiversity and ecological function globally (Trombulak & Frissell, 2000). Healthy ecological function through reconnecting landscapes can offer resilience to climate change and biodiversity by allowing for free movement of various species to allow for the symbiotic relationships that maintain strong ecosystems (Crooks & Sanjayan, 2006; Lister *et al.*, 2015).

Coupled with the imminent threats arising from climate change, both the US and Canada are experiencing issues related to aging infrastructure that is increasingly vulnerable to disruption during extreme weather events. A major infrastructure boom occurred in the post-war period due to increased growth and government spending (Wylie, 1996). Much of the infrastructure built during this time is nearing the end of its service life and is in need of repair or replacement (ACEC *et al.*, 2019). At this critical juncture, governments acknowledge that there is a need to rehabilitate and support resilient infrastructure as an avenue to recover from economic downturns and adapt to climate change. There is also a need to reconnect and remediate ecosystems that have been weakened as a result of human activity to support the natural environment so that it can support us.

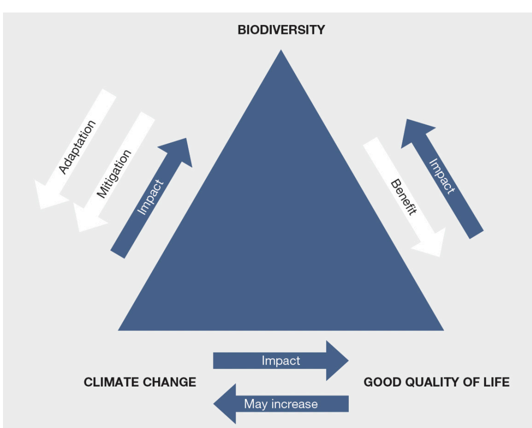


Figure 3 (left)
Relationship between climate change, biodiversity, and good quality of life. Blue arrows represent threats, and white arrows represent opportunities. Image from (Pörtner, Hans-Otto *et al.*, 2021)

DEFINING RESILIENCE

Resilience refers to the ability of an ecosystem to absorb and respond to change (Holling, 1973; Lister, 2016). The concept is derived from the field of systems ecology and challenges the long-held western beliefs of equilibrium, stability and predictability of the natural world (Holling, 1973). Taken further, the term can also be expanded to include the ability of systems to transform and adapt to changing conditions. Designing for resilience incorporates designs that anticipate changing conditions to create safe-to-fail, rather than fail-safe, systems (Lister, 2016).

2.2 INDIGENOUS KNOWLEDGE

Indigenous communities in Canada and the US are the keepers of extensive knowledge of the natural world that is essential to address climate change adaptation and resilience. Central to the Indigenous worldview and land relations is a reciprocity between human and non-human kin (Johnson *et al.*, 2021; Kimmerer, 2015; Makoons Geniusz, 2009). The relational ontology and unique epistemology of Indigenous people has historically been, and continues to be, excluded from western literature and colonial decision making, and as such is not well represented in the literature base (Johnson *et al.*, 2021). The IPCC has recognized the need for western and colonial knowledge systems to include Indigenous knowledge, and decolonize the research and knowledge systems (IPCC, 2022). Decolonization of the colonial literature and knowledge systems requires a deep respect, acknowledgement and empowerment of Indigenous knowledge, worldviews, and human-environment relations (Petzold *et al.*, 2020).

Governance and funding for infrastructure, conservation, and climate change has excluded Indigenous scholars and knowledge from the decision-making process (Johnson *et al.*, 2021). In contrast with extractive colonial philosophies, Indigenous communities' relational ontology includes a responsibility towards places, ecosystems, and species. This core difference in relationships can lead to misrepresentation and extractive interactions when western researchers and academics attempt to interpret and repackage the knowledge (Johnson *et al.*, 2021; Kimmerer, 2015). When Indigenous knowledge is co-opted in this way by non-Indigenous scholars, it does not acknowledge the structural colonial roots to these issues and often minimizes the agency of Indigenous communities

(Johnson *et al.*, 2021; Petzold *et al.*, 2020). Indigenous scholars have critiqued the dominant view of responding and adapting to climate change as merely a scientific or economic problem, while ignoring the social, cultural, and relational implications of measures (Johnson *et al.*, 2021; Makoons Geniusz, 2009).

Landscape connectivity plans and projects often intersect with traditional territories of Indigenous communities. Indigenous knowledge and ways of knowing however have not typically been valued in developing the projects, and if they are it can be superficial and be forced to conform to colonial systems of power and knowledge. Indigenous communities have contributed to landscape connectivity and habitat restoration work, with recent examples including the Blackfeet Nation Animal Vehicle Collision Reduction Master Plan (Fairbank *et al.*, 2019) and the conservation efforts by West Moberly First Nations and Saulteau First Nations to recover the population of Klinse-Za caribou (Lamb *et al.*, 2022). There is still significant work to be done to decolonize planning, ecology, and the power systems that enable this work (Johnson *et al.*, 2021; Petzold *et al.*, 2020). This is a key gap that will be explored in recommendations for future work in Section 6.

2.3 LANDSCAPE CONNECTIVITY AND FRAGMENTATION

Humans are not separate from ecosystems. We live within and shape ecosystems, and we need support from the natural world as it does from us. As such, we derive benefits from ecosystems that are resilient, diverse, and function well. There is a substantial literature base that has explored the relationship between connected landscapes and the ability of species to survive and thrive (e.g. Oliver *et al.*, 2013; Thrush *et al.*, 2008). To this end, connected landscapes contribute to resilient ecosystems that are better able to respond to changes. The definition of "landscape connectivity" for the purpose of this study draws from the definition by Taylor *et al.* (1993). Landscape connectivity can therefore be defined as the degree to which the landscape and its biotic, abiotic and anthropogenic features facilitates or impedes the movement of organisms between habitat patches (Taylor *et al.*, 1993).

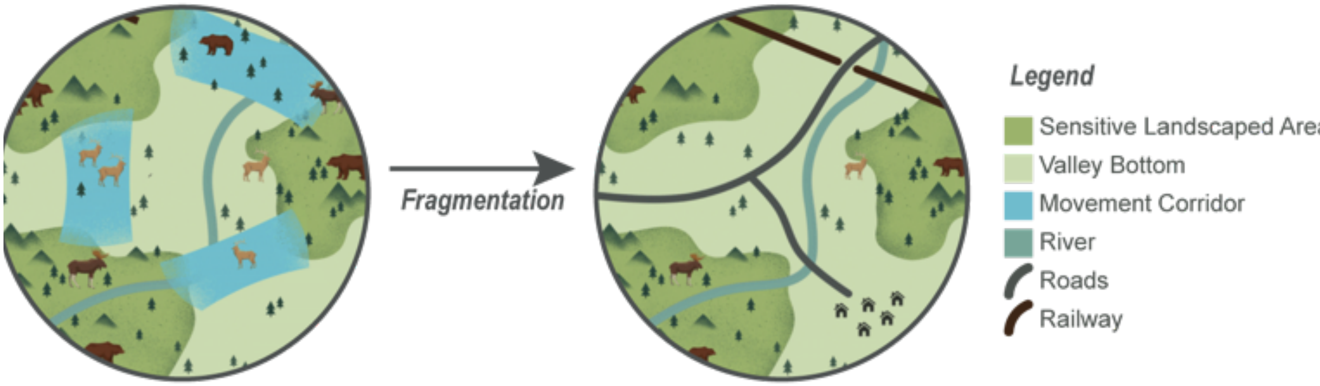


Figure 4 (above)
Landscape fragmentation from road construction can decrease habitat area and reduce wildlife movement. Fragmentation leads to isolation across habitat patches. Image adapted from Wildsight, by Bailey Repp.

The antithesis of connected landscapes are fragmented landscapes. Landscapes can be fragmented in many ways, both by natural processes and anthropogenic influences (Wilcox & Murphy, 1985). Natural processes may include bodies of water, topography, and land cover, whereas anthropogenic fragmentation occurs through the construction of barriers such as roads, settlements, walls, fences, and changes in land uses. Fragmentation impacts species differently depending on a variety of factors; however, the overarching impacts include a reduction in resilience to respond to changing habitat conditions, disease, and genetic diversity. This ultimately results in decreased biodiversity in fragmented landscapes (Wilcox & Murphy, 1985).

While there are well-studied benefits of connected landscapes and many costs associated with fragmented landscapes, the specific value of both can be difficult to quantify and integrate into decision making (Huijser *et al.*, 2009). Humans depend deeply on natural ecosystems for the provision of clean air, water, food, shelter, spiritual fulfilment, recreation, among many other services (Grunewald & Bastian, 2015). These functions are incredibly valuable to society yet are often overlooked in typical public service provision. The term Ecosystem Services was coined in reference to these essential functions in an attempt to properly quantify their value (Grunewald & Bastian, 2015; Norgaard, 2010). Biodiversity is a key underpinning of the provision of ecosystem services and is foundational to the long-term resilience of these services (Watson *et al.*, 2005).

The discourse around ecosystem services attempts to value the services provided by healthy ecosystem function in economic terms. The aim is to better communicate and account for the value of nature for policy and decision-makers to encourage funds to be allocated towards biodiversity conservation and habitat restoration, among other goals. Through this discourse, it is clear that ecosystem services are valuable to communities, and key to the good function of cities, economies and society. While the discussion of ecosystem services can be useful in encouraging investment, framing intricate ecosystems as a service provided solely for human benefit continues the centering of human needs over other non-human lives. Taken without nuance, the framing ecosystems as a service for human benefit has the potential to detract from the overarching goal of resilience because it does not fundamentally challenge the centring of human needs over all others.

2.4 ROAD ECOLOGY

Roads connect us to one another, they allow for the movement of goods across regions, and they are an essential infrastructure to support an increasingly mobile society. Canada has over one million kilometres of public roads, and over 50,000 bridges (Statistics Canada, 2020). Across North America, a historic lack of infrastructure investment and maintenance means that much of our transportation infrastructure is aging and in a state of disrepair. Statistics Canada has estimated that a quarter of all road and bridge infrastructure in Canada is over 50 years old, with almost 40% of assets in fair or worse condition (ACEC, 2019; Statistics Canada, 2020). Similarly, in the US the American Society of Civil Engineers has graded bridges across the country as C (fair condition, requiring attention) and roads as D (poor condition and generally substandard) (ASCE, 2021).

The road building that has connected humans, goods, and services to one another fragments and degrades ecosystems. By 2050, the world is expected to construct 3-5 million km of new

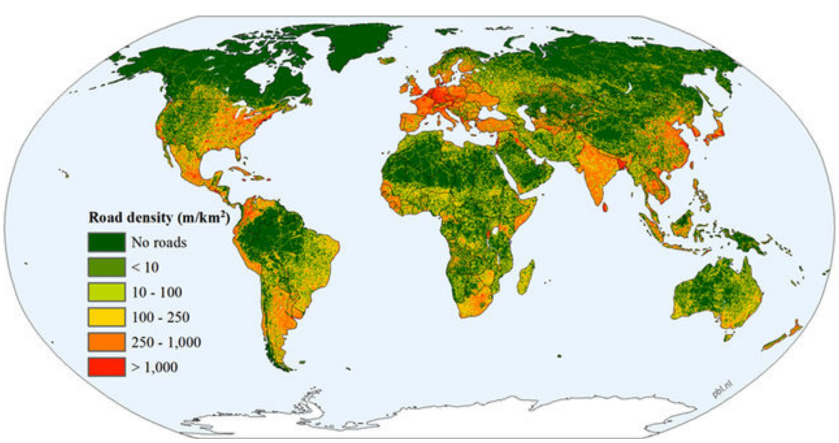


Figure 5 (left)
Global road density, 2018. By 2050, 3 to 5 million kilometers of new roads are projected to be built. Image from (Meijer *et al.*, 2018)

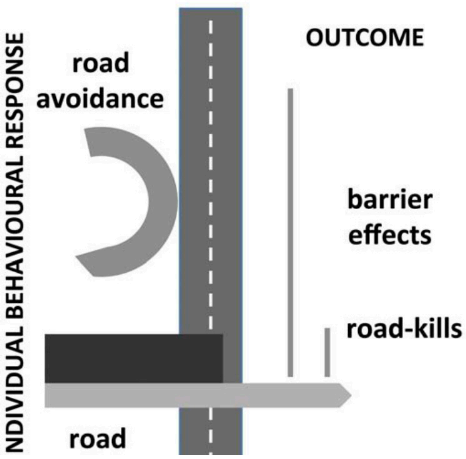


Figure 6 (above)
Wildlife-vehicle collisions and the barrier effect. Image from (Grilo *et al.*, 2012).

roads (Meijer *et al.*, 2018). The impacts of roads on ecosystems have been well documented and far-reaching (Coffin, 2007; Forman & Alexander, 1998; Jackson, 2000; van der Ree *et al.*, 2011). Animal habitats are fragmented by roads, which causes both a direct loss of habitat and a barrier to wildlife movement. Many species are unable to safely cross roads, leading to WVC. Roads act as a barrier, which animals must choose to avoid crossing which limits their movements, or choose to cross which risks their own safety and the safety of road users (**Figure 6**) (Forman & Alexander, 1998). Barriers, such as roads and highways, also lead to a disruption of the animal social structure, population fragmentation, limited gene pools, road mortality, reduced access to vital habitats, degradation of habitat quality, habitat fragmentation, and ultimately decreased biodiversity (Forman & Alexander, 1998; Jackson, 2000).

The increasing fragmentation of landscapes and habitats from roads has a negative impact on biodiversity and an ecosystem's ability to absorb and respond to changes (Morecroft *et al.*, 2012). If there are disturbances (e.g. invasive species, extreme weather) within a fragmented habitat, species have limited options to adapt to the disturbances. Whereas connected landscapes allow for both species richness and genetic diversity within a given species (Sawaya *et al.*, 2013). Reconnecting landscapes across roads can therefore promote biodiversity and foster resilient landscapes.

Beyond the impacts on ecosystems, the fragmentation of habitats from roads also has direct effects on human health and wellbeing. One of the most visible and economically prominent impacts are the collisions between vehicles and wildlife. In Ontario, Canada's most populous province, one in 17 collisions involves a wild animal which poses a direct threat to human safety (MTO, 2011). Communities also rely heavily on the ecosystem services provided by natural habitats. Forests, wetlands, and other natural assets are integral to the provision of clean air, high-quality drinking water, biodiversity, and spiritual fulfilment (Capaldi *et al.*, 2015; Watson *et al.*, 2005). Safeguarding the essential function provided by ecosystems, in turn, provides resilience for communities and cities. The reconnection of habitats and landscape therefore benefits entire ecosystems, which includes individual and community-level human wellbeing.

Figure 7 (left)
Images from the photographic series, *At Rest* by Emma Kisiel. The series depicts roadkill on American highways, drawing attention to the human impact of roads and vehicles on animals.

2.5 WILDLIFE CROSSING INFRASTRUCTURE

The implementation of wildlife crossing infrastructure has been proven to overcome challenges related to habitat fragmentation. WCI increases gene pools (Sawaya *et al.*, 2013; Soanes *et al.*, 2018), significantly reduces WVC (Clevenger & Waltho, 2005; Rytwinski *et al.*, 2016), and reconnects landscapes through defragmentation (De Montis *et al.*, 2018). There is an extensive body of literature that has been amassed in the past decades from ecologists, biologists, landscape architects, engineers, planners, and other academics that explore the use of wildlife crossing structures to reconnect habitats, reduce collisions, and safeguard biodiversity. The diversity of disciplines demonstrates the need for transdisciplinary collaboration to achieve successful, context-specific design and implementation (Apfelbaum *et al.*, 2012; Hack, 2018; Lister, 2012, 2015).

Figure 8 (below)
A wildlife crossing in Banff National Park in Alberta, Canada. Image from Susan Hagwood, Humane Society of the US.

There are many co-benefits that have been documented in literature beyond the direct benefits of landscape connectivity through implementing WCI. Integrated approaches to landscape connectivity can offer insight into the potential co-benefits, as well as potential trade-offs (Newell *et al.*, 2022). For landscape connectivity projects including WCI, the co-benefits can include benefits relating to green space, transportation, green infrastructure, food and agriculture, energy, and land management (Newell *et al.*, 2022). In this respect, landscape connectivity projects can also realize goals relating to GHG emissions, recreation opportunities, human-nature connection, protection from extreme weather events, and promoting green infrastructure (Newell *et al.*, 2022).

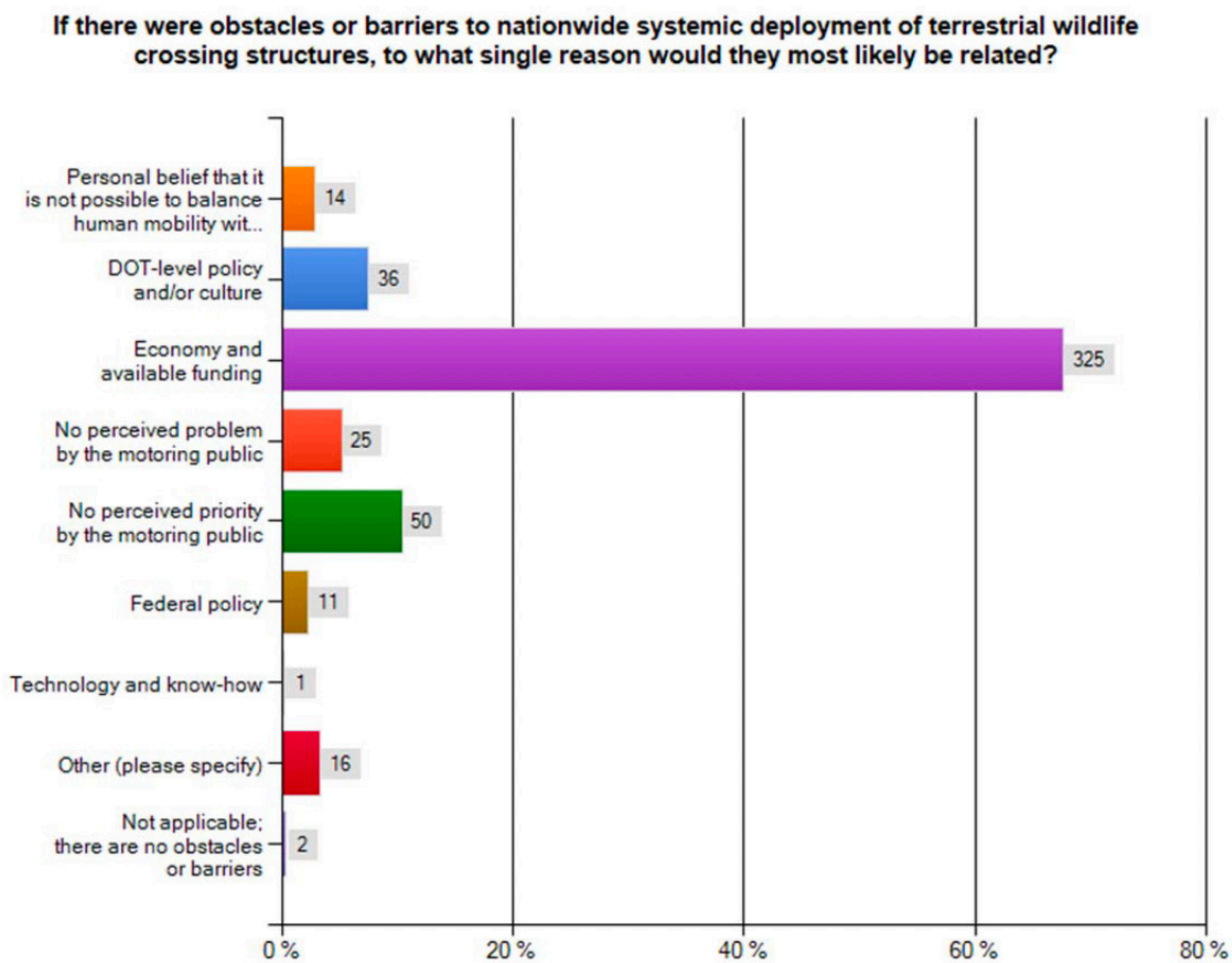
The implementation of WCI is often paired alongside road upgrades and proposed through a form of environmental impact or mitigation framework (for example, Ontario's Environmental Assessment framework). The retrofitting of roads to achieve fewer WVC and better landscape connectivity can be more costly, whereas pairing projects with more traditional capital expenditures can provide cost savings (Healy & Gunson, 2014; Huijser *et al.*, 2009). However, that is not to say that retrofit solutions are not fiscally responsible. In certain "hotspot" areas, WCI may still be feasible when also considering the ecosystem services provided (Huijser *et al.*, 2009). WCI are therefore often thought of as an ancillary cost to constructing or expanding roads, a piece of accessory infrastructure needed so that the ultimate goal of mobility for motorists can be achieved.

A full cost-benefit analysis of WCI is a complex task. Properly quantifying the net present value of crossing infrastructure is important to its viability and widespread implementation. As detailed in Huijser *et al.* (2009), there are costs associated with each WVC. For collisions with animals such as deer and elk, costs include vehicle repair costs, human injury, fatality, towing, accident attendance/investigation, emergency services, disposal of the animal carcass, and the loss of value of the animal to game hunters. For every reduction in WVC, a certain amount of cost savings is realized. This benefit can be compared against the initial capital investment and the maintenance costs over a 75-year service life to evaluate the net present value of the infrastructure (Huijser *et al.*, 2009). However, this evaluation does not account for the broader ecosystem services or sociocultural value that is provided by connected landscapes.

2.6 BARRIERS TO IMPLEMENTATION

Wildlife crossing infrastructure is generally regarded as expensive, and is thought of as a "nice to have" addition rather than an essential infrastructure (Kociolek, 2014). In the US, a 2012 survey concluded that most state transportation organizations do consider the construction of WCI to reconnect landscapes and improve safety (Kociolek, 2014). However, professionals cite the real and perceived costs of wildlife crossing infrastructure as the most common barrier to implementation (Kociolek, 2014). Secondary barriers include a lack of priority by the general public, as well as policy and organizational culture (Kociolek, 2014). The advances in material technology and the ongoing monitoring of existing projects has made strides in making this infrastructure more efficient (Bell *et al.*, 2020) and better understanding the costs and benefits to design more effective WCI (Ahern *et al.*, 2009; Huijser *et al.*, 2009; Marcucci & Jordan, 2013).

Figure 9 (below)
Relative perception of the main barrier to national deployment of wildlife crossing infrastructure. Image from (Kociolek, 2014).



Funding is one of the largest barriers to the widespread implementation of WCI (**Figure 9**). That is not to say that funding is not available, but rather that WCI is not prioritized for funding due to a poor understanding of costs and benefits, or due to the comparative novelty of the infrastructure to decision-makers. In jockeying for funding, there is a natural inclination to co-locate WCI alongside uses that may be more attractive for funding (e.g. active transportation facilities, stormwater management, agricultural uses, wildfire protection infrastructure) to make a better case for the allocation of limited funds (van der Ree & van der Grift, 2015). However, there is a potential for co-location to compromise the function of WCI, with wildlife choosing not to use crossing structures if there is too much human activity (Clevenger & Waltho, 2005). There are some mitigation measures that may be effective, and designers would need to have good familiarity with wildlife behaviour and best practices to achieve success with shared-use crossing structures (Ahern *et al.*, 2009).

The cost-benefit analysis also does not fully address the costs of failing to act now. Given that landscape connectivity is essential to resilience, neglecting to invest in this infrastructure today will inevitably pass the costs down to future generations. This fiscal prudence argument is often applied to debt servicing, however, the costs of inaction on maintenance and essential upgrades also is an important focus of fiscal prudence (Summers & Glaeser, 2021). Similarly, blind spending on infrastructure to contribute to economic recovery can lead to projects that may not deliver the most value to the public. Investment by governments in infrastructure for the sake of recovery alone can be a disservice to the public. Rather, funds should be delivered to create the most value for users of the infrastructure. This further highlights the importance of thorough cost-benefit analysis when positioning WCI projects within budgets.

2.6.1 JURISDICTIONAL CONSIDERATIONS - CANADIAN PERSPECTIVE

As discussed, WCI can foster biodiversity, reconnect landscapes and reduce habitat fragmentation. Therefore, it can be argued that WCI provides ecosystem services to the broader community. Ecosystem services have not been expressly considered in the Canadian constitution, and therefore do not fit squarely into the jurisdiction of one level of government (Constitution Act, 1982). The Constitution lays out specific responsibilities of the federal government (Section 91) and of the provincial governments (Section 92).

In Section 91 of the *Constitution Act*, natural resources are only considered from a resource extraction perspective and are determined to be a matter of provincial jurisdiction. Policies governing natural resource protection are generally developed at the provincial level (Constitution Act, 1982). However, Section 92 specifies that National Parks, navigable waterways, and areas of national interest are the responsibility of the federal governwment (Constitution Act, 1982).

The implementation of specific infrastructure to support ecosystem services and resilience depends heavily on the local context. However, ecosystem services have broad impacts which inevitably lead to spillover and externalities far beyond municipal and even regional borders. The jurisdictional considerations for

WCI can be thought of similarly to roads. Road classification delineates the responsibility of maintenance to governments based on the significance of a particular set of roads to local, provincial, and federal goals. Local governments have full responsibility for locally important routes, whereas regional governments have responsibility for arterial routes that link across regions. Provincial governments then take care of routes of provincial significance, linking together larger regions through major highways. The federal government has limited interest in roads, aside from the Trans-Canada Highways and other federally important transportation routes.

Implementing WCI alongside road projects allows for clear lines across jurisdictional responsibility. Mitigation measures for road upgrades on provincial highways would therefore fall onto the province, whereas mitigation measures on smaller municipal roads would fall onto local governments. Therefore local governments can have a role to play in WCI, particularly for smaller structures of local importance. The need for these would likely arise through an environmental assessment and would be considered as a portion of the total cost of road upgrades. However, if WCI is only considered when a road expansion or upgrade is proposed there is no opportunity to retrofit or construct stand-alone WCI.

SECTION THREE

METHODS

IMAGE SOURCE: PEXELS, BY JOSHUA WORONIECKI

3.1 SAFE PASSAGE RESEARCH PARTNERSHIP

Ryerson's Ecological Design Lab researches the impact landscape barriers have on the connectivity of landscapes. This research has focused primarily on the planning and design of a new generation of wildlife crossing infrastructure in collaboration with ARC Solutions in Alberta, Montana, and California that is capable of safely moving wildlife across roads, connecting them to habitat, and dramatically reducing WVC. At the same time, challenges and opportunities have been investigated to bridge silos and departmental/sectoral divides, enhance collaboration between different agencies, levels of government, and organizations. The project, *Safe Passage: Towards an Integrated Planning Approach for Landscape Connectivity* [1] has a goal to develop an integrated approach to the planning and implementation of WCI to improve landscape connectivity in Canada. This Masters Research Paper is designed to help work towards this goal by building on this with emerging opportunities to explore the intersection of wildlife and human landscape connectivity, and broader goals of climate change resilience and strengthening resilient infrastructure.

3.2 THEMATIC REVIEW: NATIONAL BUDGET AND INFRASTRUCTURE PLANS

A thematic review of the current federal budget and infrastructure plans was conducted to identify potential emerging opportunities within the US and Canada. While infrastructure costs are shared amongst the three levels of government, the scale of federal

1 Safe Passage: Towards an Integrated Planning Approach for Landscape Connectivity seeks proactive solutions to jurisdictional, sociopolitical, and economic barriers to the sustainable implementation of wildlife crossing infrastructure in Canada. The research employs a participatory action research approach, involving collaboration among academics, professional planners, landscape architects, ecologists, and sustainability and policy experts. The partnership has engaged participants through a series of interviews and workshops, or CoLaboratories, and this work has provided valuable insights on the challenges and opportunities for designing, developing, and implementing integrated landscape connectivity planning and policy in Canada.

funding programs set the stage for investments at the state and local levels. A thematic review is a method for identifying, analyzing, organizing, describing, and reporting themes found within a set of information (Nowell *et al.*, 2017). The method was chosen as it is appropriate for highlighting similarities and differences while allowing the flexibility to generate unanticipated insights from the data set. While this is advantageous to discover emerging opportunities, the flexibility of the method can lead to a lack of rigour and trustworthiness of the results.

This method was carried out in three phases. First, the specific budget and infrastructure plan documents were collected and reviewed at a high level to gain familiarity with the data. The following documents were collected:

- Canada Budget 2021
- Canada Investing in Canada Plan
- US Budget 2022
- US Infrastructure Investment and Jobs Act

After this, the table of contents for each document were scanned for relevant sections relating broadly to direct benefits and

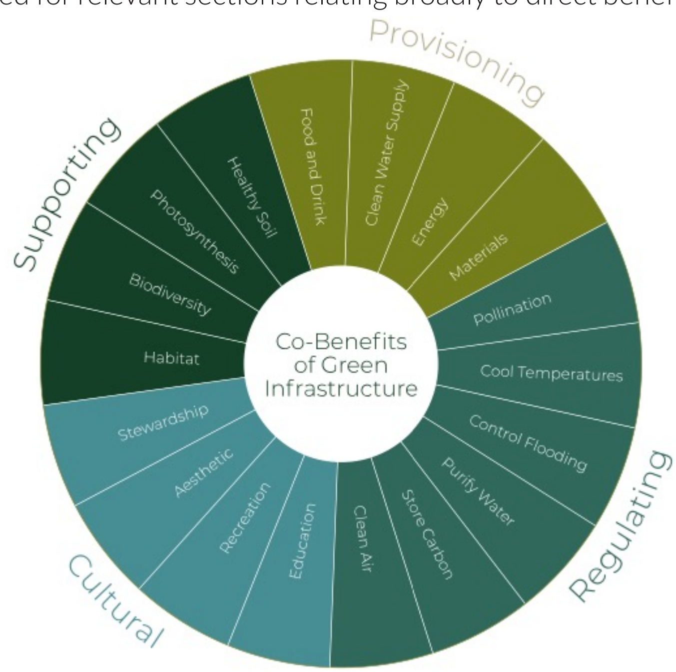


Figure 10 (left)
Various co-benefits of green infrastructure and landscape connectivity projects. Image from (Anderson *et al.*, 2021).

potential co-benefits of WCI. This included topics such as climate change adaptation and mitigation, infrastructure resilience, road and bridge construction, disaster preparedness, recreation, conservation, and ecological protection (Figure 10) (Anderson *et al.*, 2021; Newell *et al.*, 2022). Using the headings identified, a detailed analysis was conducted for each section. Recurring themes were identified across relevant sections, which were then compiled and used to inform the next stage of research. The results of this review are described in Section 4.

3.3 INTEGRATIVE LITERATURE REVIEW: EMERGING OPPORTUNITIES

Using the emerging opportunities identified as part of the thematic review, an integrative literature review was undertaken of an emerging opportunity to deepen the understanding of research conducted on the opportunity to date. An integrative literature review is a method that summarizes past empirical or theoretical literature to provide a more comprehensive understanding of a particular topic of interest (Broome, 2000; Whittemore & Knafl, 2005). While it is an approach primarily used in healthcare and human resource research it is appropriate for the research question because it aims at providing an exhaustive summary of the literature relevant to the research questions at hand. The method is appropriate for a broader research scope and allows for the inclusion of diverse research, which may contain theoretical and methodological literature (Toronto & Remington, 2020).

In total six databases were included in the search for each topic.

- GeoBase
- Scopus
- TRID
- ProQuest Research Library
- Web of Science
- EbscoHost

Publication years were set to the earliest possible year in each database, up to the latest year, which was 2022 at the time the search was performed. The search terms in this study are shown below (adapted from the query developed by Denneboom *et al.*, 2021).

(((wildlife OR fauna OR mammal OR reptile* OR amphibian* OR ungulate* OR carnivore* OR herbivore* OR omnivore*) AND ("crossing structure*" OR underpass* OR overpass* OR culvert*)) OR "wildlife passage*" OR "wildlife bridge*" OR "fauna passage*" OR ecopassage* OR ecoduct* OR "green bridge*" OR "road mitigation") AND (Pedestrian or "Active transportation" or recreation* or trail* or "shared use" or "co-locat*" or colocat*)*

A total of 184 results were found based on this search criteria across the 6 databases, of which 130 were unique results. The results were then filtered for relevance by reviewing the title and abstract of each piece of literature. The selection of the literature to answer the research questions was based on several criteria for inclusion. Studies, reports, and articles were included in the results if they related specifically to wildlife crossing projects and the identified emerging opportunity. Studies that examined wildlife behaviour outside of crossings, or infrastructure projects not focused on wildlife crossing or landscape connectivity were not included. 44 papers were determined to be relevant to the research question at hand based on the review of abstracts.

During the detailed review of each paper, additional papers were added through tracing-back references included in the retrieved literature, while other papers were removed because they were determined to be not relevant or inaccessible. In total, 27 studies formed the basis for answering the research question. Each of the 27 papers were analyzed and mapped to integrate the literature into a comprehensive description of knowledge to date.

SECTION FOUR

GREEN RECOVERY STRATEGIES AND EMERGING OPPORTUNITIES

4

IMAGE SOURCE: PEXELS, BY MHTOORI-COM

4 GREEN RECOVERY STRATEGIES AND EMERGING OPPORTUNITIES

Both US and Canadian governments are poised to make major investments in infrastructure in the coming years to facilitate a green recovery. The major economic disruption due to COVID-19, the growing infrastructure funding gap, and increasingly severe infrastructure damage resulting from climate change necessitates this historic investment in infrastructure. World leaders have also recently come together to signify a renewed urgency in addressing climate change at COP26 (United Nations, 2021). One of the key goals of the conference is to "adapt to protect communities and natural habitats" with a focus on restoring ecosystems and developing resilient infrastructure to respond and adapt to climate change (United Nations, 2021). Promoting resilient, connected landscapes can offer benefits in recovering economically from the COVID-19 pandemic while adapting and responding to climate change.

WCI has several co-benefits relating to resilience and climate change adaptation alongside the increased safety for road users, as discussed in **Section 2.5**. Intuitively, the co-benefits of landscape connectivity projects should position the infrastructure well for investment, particularly at the intersection of economic recovery, rehabilitating aging infrastructure, and responding to the climate emergency. However, the transdisciplinary nature of landscape connectivity projects often is a barrier to implementation, as collaboration is necessary between disciplines that may not often work together (Ahern *et al.*, 2009; Dale, 2001; Lister *et al.*, 2015).

The following sections will outline both Canadian and US approaches to recovery spending through their most recent federal budgets and infrastructure plans. Specifically, opportunities for green infrastructure and landscape connectivity are discussed.

4.1 CANADA

4.1.1 INVESTING IN CANADA PLAN

The *Investing in Canada Plan* was published by Infrastructure Canada in 2016 to allocate federal funding for infrastructure over 12 years (Infrastructure Canada, 2018). One of the programs introduced under this plan is the Investing in Canada Infrastructure Program, which funds projects that fall into four streams: Public Transit, Green Infrastructure, Community Culture and Recreation, and Rural and Northern Communities. During the COVID-19 pandemic, another temporary stream was created called the COVID-19 Resilience stream. The funding structure of this program provides up to 40% of project costs to municipal governments and up to 50% to provincial governments. For municipal projects, the program requires that the province must also contribute 33% of costs (Infrastructure Canada, 2018). To date, this funding has not yet been used to fund WCI projects, and WCI is not explicitly included within any of the streams.

The Green Infrastructure stream allocates $9.2 billion over 10 years, delivered by Infrastructure Canada (Infrastructure Canada, 2018). The stream includes three targeted sub-streams, Climate Change Mitigation; Adaptation, Resilience and Disaster Mitigation; and Environmental Quality. The outcomes identified in these three streams do not focus specifically on increasing biodiversity or landscape connectivity, however, there is a focus on providing natural capacity to mitigate the impacts of climate change. Although WCI projects could fit within the scope of the Green Infrastructure Stream, projects are typically related to water-wastewater treatment, flood protection, and green energy projects. To be eligible, projects within this stream would require a direct link to GHG reductions and climate change adaptation (Infrastructure Canada, 2018). As discussed in **Section 2.3**, there is a significant literature base linking landscape connectivity projects with ecosystem resilience and natural capacity to adapt to climate change. Additionally, if projects are co-located with low-impact human uses such as active transportation they may be able to demonstrate overall GHG emission reductions. Canadian funding opportunities also include climate related charity groups that support GHG emission reduction research, including the Transition Accelerator (Transition Accelerator, n.d.).

The Public Transit stream aims to improve the capacity of public transit, improve quality and safety of existing transit infrastructure, and improve access to public transit. Allocation of funding is calculated based on ridership and population served (Infrastructure Canada, 2018). Landscape connectivity projects that increase connectivity to public transit infrastructure could be considered in this stream, however the ridership and users would have to be high to be competitive for funding. Key co-benefits of landscape connectivity and WCI projects that need to be emphasized would therefore include the value of active transportation, and enhancement of human mobility.

The Community, Culture and Recreation stream delivers $1.3 billion over 10 years, delivered by Infrastructure Canada. Under this stream, projects should include those that enhance or create new cultural opportunities, community capacity and recreational facilities (Infrastructure Canada, 2018). Landscape connectivity projects that emphasize the co-benefits of low-impact recreational activities, such as hiking and biking, may be able to position themselves to secure funding from this stream. Landscape connectivity and connecting humans to nature has broad health and wellbeing benefits that may also be highlighted to position projects within this stream.

The Rural and Northern Infrastructure stream is broad, but all projects should serve rural and northern communities. Goals generally include improvements to transportation infrastructure, increasing access to food, internet, and energy, and improved health and education facilities (Infrastructure Canada, 2018). Depending on the location of landscape connectivity projects, they may be eligible for this stream. Key co-benefits to emphasize would include increased road safety, health and wellbeing benefits, and the mitigation of habitat fragmentation from new road construction.

Lastly, the COVID-10 Resilience stream was introduced in 2020 to assist communities in recovering and adapting to the COVID-19 pandemic. The eligible initiatives largely cover health care capacity and building retrofits to improve safety. Active transportation projects (including parks, trails, foot bridges, bike lanes and multi-use paths), and natural infrastructure to increase climate change resilience are also included in this temporary funding allocation. Funding for this stream requires project construction to be completed by the end of 2023 (Infrastructure Canada, 2018). This signifies a renewed interest in overall community resilience, including ecosystem resilience.

The *Investing in Canada Plan* also lays the groundwork for three funds that are relevant to landscape connectivity projects, the Natural Infrastructure Fund, the National Trade Corridor Fund, and the Disaster Mitigation and Adaptation Fund (Infrastructure Canada, 2018). The goals, objectives and key themes relating to each fund is described in the following paragraphs.

The $200 million Natural Infrastructure Fund supports projects that use natural or hybrid approaches to protect the natural environment, support healthy and resilient communities, contribute to economic growth, and improve access to nature for Canadians. As part of this fund, up to $120 million will be invested in large natural infrastructure projects (Infrastructure Canada, 2018).

The National Trade Corridor Fund supports new technologies and innovation to address transportation challenges and recognizes the value of having resilient transportation infrastructure for trade. This fund allocates $2 billion over 11 years delivered by Transport Canada (Infrastructure Canada, 2018).

The Disaster Mitigation and Adaptation Fund focuses on both constructed infrastructure and natural infrastructure projects that result in increased infrastructure capacity to withstand and adapt to climate change impacts and climate-related disasters. The goal of this fund is to invest in large scale adaptation, resilience and disaster mitigation projects that may span multiple jurisdictions. This fund allocates $2 billion over 10 years, delivered by Infrastructure Canada (Infrastructure Canada, 2018).

The *Investing in Canada Plan* is the guiding document in allocating federal funds for infrastructure in Canada. The plan puts specific focus on GHG emission reduction, increased safety and mobility, social, cultural, and recreational infrastructure, and climate change adaptation. It is key to highlight the co-benefits related to the areas of focus in positioning landscape connectivity projects. The funding structure required motivated provincial, municipal, and Indigenous partnership to realize landscape connectivity infrastructure projects.

4.1.2 CURRENT FEDERAL BUDGET

In Canada, COVID-19 recovery spending to date has focused largely on health care improvements and direct assistance to businesses. That said, the federal government has continued their efforts to improve Canadian infrastructure, through previously committed funding allocation based on the *Investing in Canada Plan* developed by Infrastructure Canada (described in detailed in **Section 4.1.1**). *Budget 2021* lays out five key priorities for spending: Job Creation, Small Business and Growth, Women and Early Learning and Child Care, Climate Action and a Green Economy, and Young Canadians. Within these themes, *Budget 2021* includes several categories of infrastructure-related funding planned for the coming years, with a clear emphasis on developing resilient green infrastructure (Department of Finance Canada, 2021).

A key target included in *Budget 2021* is an increased conservation target to hit 25 percent protected by 2025, which includes funding committed through the Nature Legacy Initiative (Department of Finance Canada, 2021). This target is accompanied by a new $2.3 billion of investment over five years to several federal ministries responsible for conservation (Environment and Climate Change Canada, Parks Canada, and the Department of Fisheries and Oceans). These funds are earmarked for projects that provide nature conservation and protect species at risk (Department of Finance Canada, 2021). WCI targeted for species at risk would be well-suited for projects under this funding priority.

There is a continued emphasis on national trade corridors, including a new investment of $1.9 billion over four years to the National Trade Corridors Fund, discussed in **Section 4.1.1** (Department of Finance Canada, 2021). This signifies an ongoing commitment to enhancing the reliability, safety, and resilience of federally significant transportation corridors. Landscape connectivity and WCI projects are well positioned to be funded as part of this initiative when emphasizing the increased safety for drivers and increased natural capacity to respond to climate change.

The budget commits $200M over three years to Infrastructure Canada to develop a Natural Infrastructure Fund, as discussed in **Section 4.1.1**, to support green infrastructure projects (Department of Finance Canada, 2021; Infrastructure Canada, 2018). While this was introduced in the 2018 *Investing in Canada Plan*, this initiative was previously unfunded.

There is a new emphasis within this year's budget on Indigenous communities and infrastructure that extends beyond funding allocated to communities to support immediate issues, such as eliminating boil-water advisories. *Budget 2021* committed a new $4.3 billion to the Indigenous Community Infrastructure Fund (Department of Finance Canada, 2021). This fund is dedicated to finance needs identified by Indigenous communities and could include projects that protect the natural environment and reconnect ecosystems. The allocation of funding to adapt to climate change focuses on relationships with Indigenous communities and earmarks specific funding for rural, remote, and northern projects.

As part of the recovery from COVID-19, there is recognition of a need for jobs and growth. *Budget 2021* recognizes that infrastructure investments are important to job creation and economic wellbeing. The budget allocates funding to conduct a national infrastructure assessment, which will likely lead to coordinated efforts to rehabilitate and replace identified aging infrastructure (Department of Finance Canada, 2021). Landscape connectivity and WCI projects are not mentioned in this program, however they could be integrated as part of rehabilitation measures. Communicating co-benefits relating to resilient and future-ready infrastructure would help position landscape connectivity projects for these types of projects.

The current Canadian Federal budget generally aligns with the infrastructure plans laid out in the *Investing in Canada Plan* developed prior to the COVID-19 pandemic. However, new funding is committed to various funds that show a renewed commitment to certain infrastructure priorities. These include increased conservation and species protection goals, creating resilient national transportation infrastructure, natural infrastructure, partnerships with Indigenous communities, and infrastructure investment to promote job creation.

4.2 UNITED STATES INFRASTRUCTURE ACT AND FEDERAL BUDGET

The United States government has recently passed a historic infrastructure spending bill, the *US Infrastructure and Jobs Act*, committing upwards of one trillion dollars to build and repair infrastructure in the country (US Sentate, 2021). The Act includes an additional $550 billion of new spending, above what Congress has already planned to spend over the next eight years (Sprunt *et al.*, 2021). The act and current federal budget are in close alignment as they have been passed together in the same year. As such, they have been reviewed and discussed together.

A portion of the newly allocated budget is dedicated to increasing road safety and resilience through rehabilitation of key infrastructure. There is $190 billion committed over 10 years for the repair of 10 major bridges and 10,000 minor bridges, and for the modernization of 20,000 miles of roads (US OMB, 2021). These initiatives aim to directly address the infrastructure gap and bring infrastructure into a state of good repair. Linking road expansion and bridge rehabilitation with mitigation measures to reconnect landscapes can achieve goals related to climate change, conservation, and wellbeing. As with Canadian spending initiatives, highlighting co-benefits such as resilience, climate change adaptation and biodiversity can position landscape connectivity projects for funding.

In contrast with Canadian plans and budgets, the *US Infrastructure and Jobs Act* explicitly includes WCI as eligible for two existing infrastructure programs (i.e. the Surface Transportation Block Grant Program and the Nationally Significant Freight and Highway Projects), and one new program (i.e. the Bridge Investment Program) (US Sentate, 2021). The Surface Transportation Block Program will see funding allocated to State governments, who will have the authority to prioritize and fund projects put forth by local/regional governments, transportation agencies, tribes, and other public organizations. Federal projects are administered by the Secretary of State, and applicants can include local, state, and other public organizations (US Sentate, 2021).

The Act authorizes and allocates $350 million over 5 years to a pilot project to reduce WVC, stating that the reduction in WVC is in the public interest because of the danger posed to humans and animals and because the costs associated with WVC are estimated to be over 8 trillion dollars annually (US Sentate, 2021). The pilot program will evaluate prospective projects primarily based on the ability of the project to reduce WVC, as well as the ability of the project to accomplish several secondary goals. These include:

- Leveraging public-private partnerships, and other private investors in the project
- Supporting economic development
- Improving visitation opportunities
- The use of innovative technologies
- Educational and outreach programs
- Ongoing monitoring and research opportunities

The Act has also allocated funds to a study to update the 2008 WVC Reduction Study by Huijser *et al.*. This is a historic investment in WCI and marks an understanding of the importance of safe passage in mitigating the impacts of climate change on ecosystems, humans, and transportation infrastructure.

These initiatives are reflected in the current US Budget, where the government has laid out key spending priorities for the coming years (US OMB, 2021). These include themes such as transportation equity, climate resilience, disaster preparedness, supporting Indigenous communities in addressing climate change, a focus on conservation and surface transportation in rural America, increasing active transportation, and rehabilitating aging infrastructure (i.e. bridges, culverts, and roads) (US OMB, 2021).

SECTION FIVE

CO-LOCATION OF ACTIVE TRANSPORTATION AND WILDLIFE CROSSING INFRASTRUCTURE

IMAGE SOURCE: PEXELS, BY ALI-KAZAL ALI-KAZAL

5 CO-LOCATION OF ACTIVE TRANSPORTATION AND WILDLIFE CROSSING INFRASTRUCTURE

The plans and budgets reviewed in Section 4 place significant emphasis on the need for green infrastructure. Within the programs identified, there are several requirements that shape the green infrastructure to be prioritized. In this sense, projects may be better positioned to receive successful funding if they achieve the metrics outlined in the plans and budgets as co-benefits. These include reducing overall GHG emissions, increasing the country's disaster preparedness and promoting community health and wellbeing.

While landscape connectivity projects are important to ecosystem health, human health and wellbeing, communicating and accounting for the co-benefits within the narrow scope of fiscal programs and infrastructure initiatives is often cited as a barrier to implementation (Anderson *et al.*, 2021; Keeley *et al.*, 2018). As identified in Section 4, there are emerging opportunities within funding programs to integrate landscape connectivity projects with active transportation uses. This is intuitively appealing when positioning landscape connectivity infrastructure for investment, as active transportation can be directly tied with lowered GHG emissions and public health (Frank *et al.*, 2010). However, human activity can have adverse impacts on the ecological function of WCI and may compromise the function for certain target species altogether. Extensive research has been conducted to understand

Figure 11 (right)
Many species use wildlife crossing infrastructure. Some target species may be less sensitive to human activity than others. Image from Tony Clevenger via ARC Solutions.

the effectiveness of WCI for target species and WVC reduction (**Section 2.5**), and the impacts of human activity on animal habituation, habitats, and species wellbeing separately. However, less research has been conducted on the impacts of human activity on wildlife crossings specifically. This is an emerging area of research, and as such there is a need to survey the work done to date and identify gaps to be filled to better position landscape connectivity initiatives well for funding opportunities.

Co-locating WCI alongside other uses can be used as a strategy to stack the benefits of many green infrastructures within one project. The co-location can strengthen and highlight co-benefits that are realized within green infrastructure projects. Beyond active transportation and recreation, there may also be opportunities in co-locating landscape connectivity with flood protection and stormwater management initiatives. Co-locating WCI can create more cost-effective structures, and position projects for broader funding opportunities (McGuire *et al.*, 2020). Newer and more innovative technologies, construction materials, and flexible standards may also offer new opportunities for the widespread implementation of landscape connectivity initiatives (Bell *et al.*, 2020).

Using the methods explained in **Section 3.3**, a total of 27 pieces of literature were reviewed that related the function of WCI to human activity and influence. The dataset included journal articles, book chapters and conference proceedings. The earliest data is from 2000, with the most recent works from 2021. Roughly half of the dataset (14 papers) consisted of empirical field studies, and half of the data included other methods including case studies, meta-analyses, and exploratory research (12 papers). **Figure 12** and **Figure 13** depict the descriptive statistics of the data collected. A full summary of the literature is included in **Table 1**. Empirical field studies have largely been conducted on WCI located in Banff National Park in Alberta, Canada. There is therefore much more robust information available for the target species present within this park (i.e. deer, elk, cougars, wolfs, *etc.*) than for species native to other locations. North American research is also represented significantly in the dataset, with fewer studies collected from Asia and Europe. No studies were collected from Africa, Oceania, or South America.

Figure 12 (right)
Geographic distribution of reviewed literature.

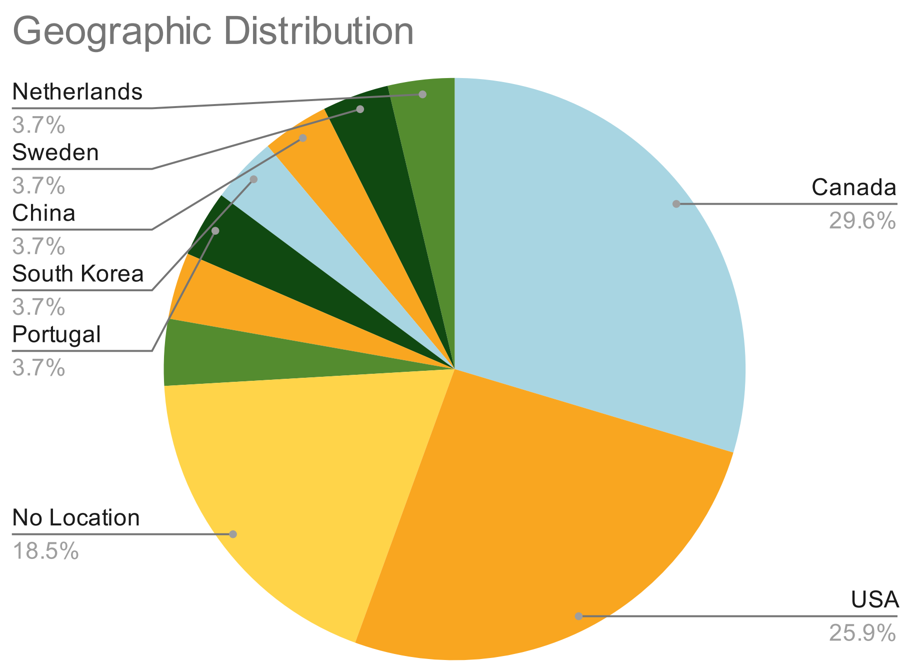


Figure 13 (right)
Distribution of publication date of reviewed literature.

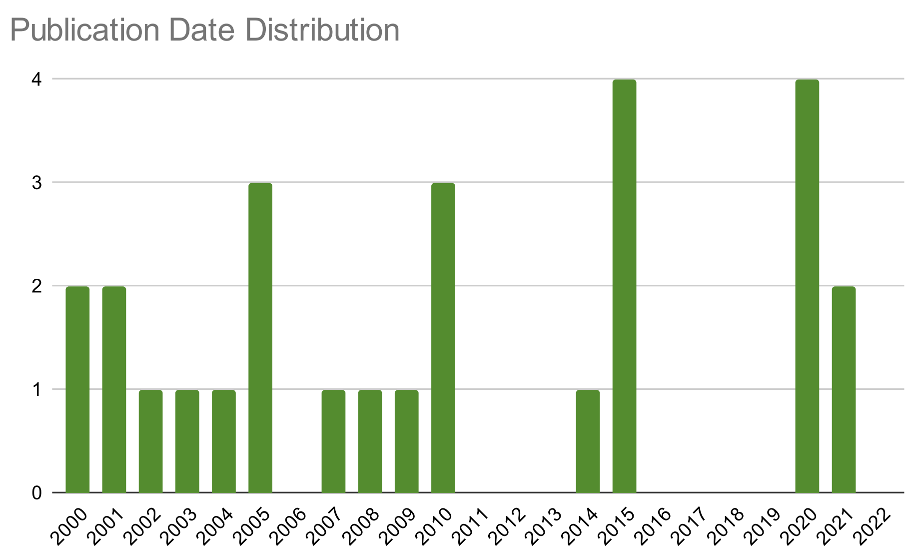


Table 1
Full list of literature reviewed as part of the integrative literature review.

Year	Author(s)	Title
2009	Ahern, Jack; Jennings, Lee; Fenstermacher, Beth; Warren, Paige; Charney, Noah; Jackson, Scott; Mullin, John; Kotval, Zenia; Brena, Sergio; Civjan, Scott; Carr, Ethan	Issues and Methods for Transdisciplinary Planning of Combined Wildlife and Pedestrian Highway Crossings
2020	Asari, Yushin; Noro, Misako; Yamada, Yoshiki; Maruyama, Ryuichi	Overpasses intended for human use can be crossed by middle and large-size mammals
2014	Barrueto, M., Ford, A.T., Clevenger, A.P.	Anthropogenic effects on activity patterns of wildlife at crossing structures
2005	Brodziewska, Jadwiga	Wildlife tunnels and fauna bridges in Poland: past, present and future, 1997-2013
2020	Caldwell, Molly R.; Klip, J. Mario K.	Wildlife Interactions within Highway Underpasses
2003	Clevenger, Anthony P; Waltho, N; New York State Department of Transportation; Federal Highway Administration	Long-term, year-round monitoring of wildlife crossing structures and the importance of temporal and spatial variability in performance studies
2000	Clevenger, Anthony P; Waltho, Nigel	Factors influencing the effectiveness of wildlife underpasses in Banff National Park, Alberta, Canada
2005	Clevenger, Anthony P; Waltho, Nigel	Performance indices to identify attributes of highway crossing structures facilitating movement of large mammals
2021	Denneboom, Dror, AviBar-Massadab, Assaf Shwartz	Factors affecting usage of crossing structures by wildlife – A systematic review and meta-analysis
2000	Duggar C.F., Jr., Corven, J.A.	Design of the Cross Florida Greenway land bridge over I-75 using precast Florida u-beams
2010	Gartshore, Geoffrey; Thompson, Gillian; Harrington, Alex; Cox, Charlotte; Scott, Martin; Craig, Brian; Jongerden, Paula; Levick, Rick; North Carolina State University, Raleigh	Long Point World Biosphere Reserve Causeway Improvement Plan, Port Rowan Ontario: Benefits for Wildlife Movement, Species at Risk, Traffic and Pedestrian Safety
2005	Gartshore, R Geoffrey; Rook, Robert I; North Carolina State University, Raleigh	Bayview Avenue Extension, Richmond Hill, Ontario, Canada Habitat Creation and Wildlife Crossings in a Contentious Environmental Setting: A Case Study
2001	Gloyne, Claire, Clevenger, Anthony	Cougar Puma concolor use of wildlife crossing structures on the Trans-Canada highway in Banff National Park, Alberta
2008	Grilo, Clara, John A. Bissonette, Margarida Santos-Reis	Response of carnivores to existing highway culverts and underpasses: implications for road planning and mitigation
2010	Helldin, Jan Olof; Folkeson, Lennart; Göransson, Görgen; Van der Grift, Edgar; Henningsson, Marianne; Herrmann, Mathias; Kjellander, Petter; Kunc, Hansjoerg; Nilsson, Mats E; Pouwels, Rogier; Seiler, Andreas; Sjölund, Anders; North Carolina State University, Raleigh	Similar Impacts, Similar Solutions? The Effects of Transport Infrastructure on Outdoor Recreation and Wildlife
2015	Huh, Y.-S., Hur, Y.-A., Yoon, S.-Y., Widawati, E., Son, Y.	Challenges and tasks of ecobridges in Seoul based on the ecobridge-use behavior survey: In the case of ecobridges in Dongjak-gu and Gwanak-gu
2010	Humble, L., Furtado, G.	Innovation in interchange design - Golden Hill to West Portal
2020	Liu, Zheng; Lin, Yanliu; De Meulder, Bruno; Wang, Shifu	Heterogeneous landscapes of urban greenways in Shenzhen: Traffic impact, corridor width and land use.
2015	Murphy-Mariscal, Michelle L.; Barrows, Cameron W.; Allen, Michael F.	Native Wildlife Use of Highway Underpasses In A Desert Environment

Table 1 (continued)
Full list of literature reviewed as part of the integrative literature review.

Year	Author(s)	Title
2004	Ng, SJ; Dole, JW; Sauvajot, RM; Riley, SPD; Valone, TJ	Use of highway undercrossings by wildlife in southern California
2007	Olsson, Mattias	Effectiveness of a highway overpass to promote landscape connectivity and movement of moose and roe deer in Sweden
2001	Phillips et al	Mitigating disturbance of migrating mule deer caused by cyclists and pedestrians at a highway underpass near Vail, Colorado
2021	Serieys, Laurel E.K.; Rogan, Matthew S.; Matsushima, Stephani S.; Wilmers, Christopher C.	Road-crossings, vegetative cover, land use and poisons interact to influence corridor effectiveness.
2020	Sijtsma, F.J., van der Veen, E., van Hinsberg, A., Pouwels, R., Bekker, R., van Dijk, R.E., Grutters, M., Klaassen, R., Krijn, M., Mouissie, M., Wymenga, E.	Ecological impact and cost-effectiveness of wildlife crossings in a highly fragmented landscape: a multi-method approach
2015	Smith, D. J., van der Ree, R., & Rosell, C.	Wildlife Crossing Structures: An Effective Strategy to Restore or Maintain Wildlife Connectivity Across Roads
2002	Tigas, Lourraine A.; Van Vuren, Dirk H.; Sauvajot, Raymond M.	Behavioral responses of bobcats and coyotes to habitat fragmentation and corridors in an urban environment
2015	Van Der Ree, R., Van Der Grift, E.A.	Recreational Co-Use of Wildlife Crossing Structures

5.1 COSTS AND BENEFITS

As discussed in **Section 2.6**, infrastructure projects typically undergo extensive cost-benefit analysis to determine priority and feasibility since projects are funded by public dollars. Politicians, decision makers, and the public at large all have an interest in spending funds efficiently and to deliver the most value to stakeholders. Similarly, the mitigation of hazards associated with infrastructure projects are also considered in accounting for costs and benefits of this infrastructure.

Often the translation of research into practice comes in accounting for the specific costs and benefits (effectiveness) of infrastructure projects and mitigation measures. As is clear from national level plans and priorities (**Section 4**), there is currently a focus to prioritize funding to reduce GHG emissions, promote a multimodal transportation system, and encourage community well-being. Therefore, when accounting for costs and benefits amongst different mitigation strategies, ones that demonstrate GHG emission reduction and increased health and wellbeing would be positioned better within funding initiatives. This requires a great deal of transdisciplinary collaboration to communicate benefits across disciplines which can be challenging, as noted by Ahern *et al.* (2009) in their development of a multi-use wildlife crossing project in Massachusetts.

The Netherlands is a leader in landscape connectivity infrastructure, in spite of the fact that the country has the densest road network in Europe (Eurostat, 2018; van der Grift, 2005). The state has developed a specific defragmentation policy that has led to the implementation of 479 structures ranging in scale from large overpass structures to small culverts (Sijtsma *et al.*, 2020). While the case study in Massachusetts (Ahern *et al.*, 2009) discusses the specific challenges in designing shared use structures, Sijtsma *et al.* (2020) evaluated a large, national dataset to determine the average costs and ecological connectivity performance of different forms of WCI. Their findings, in alignment with the considerations in Massachusetts, show that shared-use crossing structures deliver moderate connectivity benefits but do so for lower costs. Sijtsma *et al.* (2020) conclude that twice as many shared use crossings could be implemented for an equivalent cost to single-use crossings. There is a trade-off highlighted in the literature between a single project with high ecological function, and many projects with slightly reduced ecological function. Similarly, there are trade-offs between usage by wildlife, and the potential for human-wildlife conflict, particularly with large predator species.

A similar trade-off is demonstrated in Shenzhen, China with respect to the urban greenway system (Liu *et al.*, 2020). There was a limited regard for ecology when designing and implementing the network of green corridors. The active transportation functions were over emphasized, and as such they offer very little ecological value to the city. Only 15% of greenways in Shenzhen are considered ecological greenways, and even so, no monitoring has been conducted to determine the effectiveness of these measures in reconnecting landscapes (Liu *et al.*, 2020).

5.2 METRIC AND PERFORMANCE EVALUATION

The effectiveness of landscape connectivity projects is central to the discussion of costs and benefits. The values of researchers and funding agencies are often revealed in choosing which metrics equate to effectiveness. All empirical field studies collected as part of this study evaluated the effectiveness of the infrastructure by the number of crossings events by either one target species, or for a group of species (for example, Caldwell & Klip, 2020; Clevenger & Waltho, 2005; Gloyne & Clevenger, 2001). In previous systematic reviews of crossing structures, authors have raised issues with this metric for evaluating crossing structures (Denneboom *et al.*, 2021). When only counting crossings using cameras and tracks, the study is not able report the number of approaches, which can be important in evaluating the degree to which WCI effectively reconnect landscapes. If animals are approaching structures and not successfully crossing, this is an important piece of information in determining the effectiveness of reconnecting landscapes (Denneboom *et al.*, 2021). Studies conducted in Banff National Park address this partially through the use of predictive modelling, comparing the observed number of crossings to a calculated predicted number of crossings (Clevenger & Waltho, 2000). Other studies have addressed this as well, by comparing crossing activity with activity recorded in nearby habitats at randomly selected locations within 300m of a crossing (Andis *et al.*, 2017).

The target species is also important in evaluating the effectiveness of WCI. It stands to reason that because many species have preference for certain conditions when traveling across landscapes, different species will respond differently to various structural aspects of WCS. In planning and designing crossings, there is often a focus on a specific species, which some authors have noted are primarily large, charismatic animals such as deer, elk, lynx, bears and bobcats, among others (Newell *et al.*, 2022). Because of this, monitoring studies often are narrowly focused on the target species and the predators or prey of that species, which may not fully indicate the degree of connectivity offered.

Similarly, the presence of human activity and human disturbance can be measured in a variety of ways. Nine empirical studies measured human activity as a count by the number of crossings by humans over the monitoring period (i.e. whether humans were permitted on the structure or not). Within these, only three studies from Banff National Park accounted for different types of human activity (i.e. pedestrians, cyclists, and horseback riders) through the use of indices (Clevenger & Waltho, 2000, 2003, 2005). One study in Colorado (Phillips *et al.*, 2001) used human activity as a controlled variable through the use of both visual barriers, and researchers set to start and stop human crossings when deer were approaching. In this study, the objective was to evaluate the impact of specific human activity on deer crossing behaviour across an underpass (Phillips *et al.*, 2001). With a limited base of literature on shared use crossings, care should be taken when generalizing findings when different measures of human activity are employed. It is often the case that human activity variables are confounded with other variables including age of structure, proximity to towns, and traffic volumes (Clevenger & Waltho, 2005).

5.3 HUMAN DISTURBANCE

Human activity and disturbance has been shown to impact the performance of WCI, however the relationship is complex and relates to many other elements of WCI such as the level of animal habituation, the types of species studied, and structural attributes of the infrastructure (Clevenger & Waltho, 2005).

Species respond differently to the presence of human activity, and the degree to which human activity impacts animal behaviour varies greatly. Clevenger & Waltho (2000) observed through several studies in Banff National Park that in areas of high human activity, the age of crossing structures is very important in predicting the likelihood of use by wildlife. They postulated that over the 12-year life of the crossing infrastructure, animals had become habituated to human activity and avoided crossings with high levels of activity. In subsequent studies, the authors found that for newer structures the structural attributes of WCS were of more importance than the degree of human activity (Clevenger & Waltho, 2003, 2005). This is expanded on in Barrueto, Ford and Clevenger (2014) in which the authors concluded that the design of structures can buffer the impacts of human activity to a certain extent. While all species showed some impact from human use, certain species (deer, elk, coyotes, and black bears) were only sensitive to specific types of activity. Large carnivores (wolves, grizzly bears, cougars), on the other hand, were sensitive to all types of human activity. When examining the activity of cougars specifically, Gloyne and Clevenger (2001) suggest that when other options are not available, cougars practice mutual avoidance with humans to reduce interactions. In this case, the most important predictor of crossing use was the quality of habitat adjacent to the crossing infrastructure (Gloyne & Clevenger, 2001).

Bobcats and coyotes in California are the subject of five empirical studies reviewed as part of this paper (Caldwell & Klip, 2020; Murphy-Mariscal *et al.*, 2015; Ng *et al.*, 2004; Serieys *et al.*, 2021; Tigas *et al.*, 2002). These species exist within a highly fragmented landscape with a high degree of human activity (Tigas *et al.*, 2002). The activity pattern of both species has adjusted over time to show some spatial and temporal avoidance of heavy human activity. Caldwell & Klip (2020) concluded that predator-prey interactions are important in this highly fragmented ecosystem. Findings indicate that predator species (coyotes) exhibited spatial avoidance of human activity and used crossings with high human activity less than ones with lower activity. At the same time, prey species such as mule deer, quail, and rodents favoured crossings with higher levels of human activity. Conversely, Ng *et al.* (2004) found that in the absence of purpose-built crossing structures, coyote crossings were highly correlated with human activity due to high rates of habituation.

Human disturbance may impact habitat generalists and habitat specialists differently. A monitoring study in Portugal found that habitat generalists have higher avoidance of human activity, when human activity is broadly defined to include traffic volume, foot traffic, and distance to roads and cities (Grilo *et al.*, 2008). For example, deer living in a suburban area are expected to react differently to human use than species who have habituated less. Therefore, the target species for connectivity is important in the design of large scale WCI and especially so for shared use crossings.

5.4 MITIGATION MEASURES

Few studies have tested mitigation strategies to reduce the impact of human activity on wildlife behaviour. A study conducted in Vail, Colorado concluded that rigid visual barriers such as fences may be effective in promoting crossing by deer (Phillips *et al.*, 2001). The same study determined that flexible curtain barriers are less effective in mitigating the impacts. In this study, the crossing structure itself was not shared use, but the road above the crossing structure had trails alongside it (Phillips *et al.*, 2001). Likewise, for smaller amphibians, a case study in Long Point, Canada has shown success with small fencing and visual barrier to reduce human disturbance (Gartshore *et al.*, 2010).

Figure 14 (above)
Renderings of a wildlife crossing structure from the ARC International Wildlife Crossing Infrastructure Design Competition held in 2010. Image from Landshape, Zwarta and Jansma Architects via ARC Solutions.

Urban wildlife, referring to mostly smaller rodents and birds, responds much differently to human disturbance, and as such, mitigation measures may work differently. In Seoul, eco-corridors have been installed across the city to promote biodiversity and landscape connectivity (Huh *et al.*, 2015). All of these corridors are shared use, and many have visual barriers present to separate humans and wildlife (Huh *et al.*, 2015). In a user-survey study, several small rodents and birds were observed to be using the crossings alongside human use (Huh *et al.*, 2015). Better connectivity for these urban structures requires better surface treatment and tree planting in order to create a more appealing environment for wildlife (Huh *et al.*, 2015). Similar findings are present in a monitoring study in Hokkaido, Japan (Asari *et al.*, 2019). The authors recorded crossing events on bridges designed for human use (Asari *et al.*, 2019). Findings suggested that four animals used the bridges: raccoons, foxes, raccoon dogs, and sika deer (Asari *et al.*, 2019). Similar to Huh *et al.* (2015), the ground cover and presence of plantings influences wildlife use of bridges in Hokkaido (Asari *et al.*, 2019). Further research is required to understand the connectivity value for urban wildlife in shared use structures due to differences in habituation to human activity.

The long-term monitoring of WCI in Banff provide valuable insight into possible mitigation of human disturbance for wildlife. Clevenger and Waltho (2005) discuss that managing the degree and intensity of human use may be able to reduce disturbance for certain target species. When structures have moderate to low human activity (i.e. 2-3 human crossings per month on average), structural factors are much more important in predicting the use of crossing structures (Clevenger & Waltho, 2005). From these conclusions, it may be possible to allow for light-touch human activity on select crossings without rendering the crossing ineffective for the target species.

S E C T I O N S I X

CONCLUSION

IMAGE SOURCE: PEXELS, BY THOMAS SHOCKEY

6 CONCLUSION

Landscape connectivity is an integral element in promoting sustainable, resilient ecosystems that can adapt to the changing climate. At this moment, federal governments in Canada and the US have committed significant efforts to an economic recovery from the COVID-19 pandemic using infrastructure investments to promote climate change mitigation and adaptation.

The federal plans and budgets lay out the high-level priorities of governments, which largely include repairing and rehabilitating aging roads, bridges and culverts, green infrastructure opportunities, reductions in GHG emissions, and increased community health and wellbeing. Canadian budgets and infrastructure plans do not explicitly include WCI, however landscape connectivity projects could be eligible for green infrastructure, conservation, and recreation initiatives. The co-benefits of WCI projects will need to be highlighted, analysed and strategically communicated to position well for funding opportunities. Conversely, the US has announced dedicated funding towards projects that reduce WVC and have expanded existing programs to include WCI and other natural infrastructure. This signifies a new commitment to and a duty of care by federal governments to mitigate the impacts of roads on ecosystems and create safer roads for humans and non-humans alike. Canadian governments and policymakers should look to innovative funding opportunities created in the US. This program specifically allows for WCI projects to be built as standalone projects and does not require road upgrades to identify the need for mitigation measures. Similarly, Canadian governments should plan to integrate WCI projects into infrastructure rehabilitation efforts as part of a green recovery.

A key emerging opportunity identified through the review of the plans and budgets is the potential to co-locate landscape connectivity infrastructure alongside active transportation uses. Through the integrative literature review, it can be concluded that there may be opportunities for co-location provided that the human use is closely managed in the context of the target species for which crossing infrastructure is intended and designed. Of particular interest is the potential for shared use when target species are either common or less sensitive to humans such as e.g. white tailed deer or other prey species that may use human activity as protection from predators that avoid human activity. Similarly, urban and

Figure 15 (left)
A small wildlife crossing bridge made from fiber reinforced polymer in the Netherlands. Image by Rob Ament, Western Transportation Institute.

peri-urban environments where wildlife have a degree of habituation may offer opportunities for co-location. The use of temporary, modular, and low-cost prototype solutions to test various methods to lessen the impacts of human use would contribute to the development of successful shared use crossing structures.

While there is significant literature on mitigation of human impact on wildlife generally, there is limited literature on measures to mitigate human use within WCI specifically. Additional research into this emerging opportunity should include the evaluation of mitigation techniques, such as limiting human use to specific times of day, temporal zoning (i.e. closures during important breeding or migration periods), or visual barriers. Further research would also be required to determine the degree to which ecological function is reduced by the amount of human activity, especially broken down further into various types of human activity. There is likely a threshold where the intensity of human activity impacts ecological function too negatively, and therefore the project would not successfully reconnect landscapes. Future research should also include species beyond those found in California and Banff National Park. Current research, especially empirical field studies, are largely limited to these locations and little data is available for wildlife local to other areas.

The shared use of crossing structures can create more economically feasible projects, while positioning projects well for existing funding opportunities. However, the fact that there must be a direct human benefit within a project to push it to implementation is, in itself, problematic. There is a larger sociocultural shift that must occur within decision-making structures that values non-human life, ecosystems, and the natural world more generally. This is an area of focus that Indigenous scholars are thought leaders.

The valuable contributions from Indigenous scholars in climate change mitigation, adaptation, and conservation actively works towards decolonizing these disciplines. Colonial knowledge systems require an expanded conception of valid ontologies and epistemologies to move forward with Indigenous communities. Funding and partnership opportunities led by Indigenous communities can also create opportunities to promote ecosystem health and wellbeing. Further research by Indigenous scholars and communities that reflect Indigenous ontology and epistemology within conservation and landscape connectivity disciplines will progress decolonization.

In Canada and the US, governments are grappling with ongoing impacts of climate change which include increasing biodiversity loss, while recovering economically from the COVID-19 pandemic. It is a critical time to reconnect landscapes across the country. Doing so will help create resilient landscapes that are able to survive, respond and adapt to climate change while also creating opportunities for economic growth through infrastructure investment. Co-locating WCI with active transportation uses may offer new opportunities for funding, so long as projects appropriately manage the trade-off between human use and ecological function. While these opportunities can capitalize on funding opportunities present now, a larger shift is necessary for governments and decision makers to place value on ecosystem function and non-human life.

Figure 16 (left)
Wildlife crossing structures. (A) Crossing in Banff National Park, Alberta Canada. Image from Allie Banting, Parks Canada. (B) Rendering of crossing structure for Highway 9, Colorado. Image from Post Independent. (C) Wildlife crossing structure rendering submitted as part of the ARC International Wildlife Crossing Infrastructure Design Competition in 2010. Image from Olin Studio.

SECTION SEVEN

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IMAGE SOURCE: PEXELS, BY SNAPWIRE

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