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Review

The application of assisted migration as a climate change adaptation tactic: An evidence map and synthesis

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ABSTRACT

Assisted migration entails the human assisted movement of individuals to more climatically-suitable areas within or outside of their current species range to help species respond to climate change. To better understand the potential for assisted migration to benefit species threatened by climate change, we conducted an evidence synthesis to map examples where assisted migration has been implemented around the world. With this mapping exercise, we collate and describe the quantity and key characteristics of the available evidence base, including the taxa, species conservation status, locations, and contexts relating to the use of this conservation tactic. Findings from this exercise highlight that assisted migration has been implemented very few times as a conservation tactic, though assisted migration has been conducted experimentally (for research purposes) and inadvertently (e.g., for reforestation) much more frequently. Assisted migration was most common for plants (particularly trees), followed by birds, and was rarely implemented for other taxa. Our review highlights the need for more research on assisted migration, with particular emphasis on understanding the population- and community-level outcomes of these actions. Our discussion focuses on the potential for assisted migration of Canadian species but will be informative to those considering assisted migration in other jurisdictions.

1. Introduction

Climate change is resulting in increasingly rapid shifts in temperature and weather patterns around the globe (IPCC, 2022). Although the impacts of climate change vary across spatial scales, a general pattern of warming is being experienced worldwide, with particularly rapid warming occurring at the highest latitudes (Jansen et al., 2020). Precipitation patterns are also being impacted by climate change, and it is generally expected that drier areas will become drier while wetter areas will become wetter (Donat et al., 2017). Further, the frequency and severity of extreme weather events (e.g., floods, droughts, hurricanes, blizzards) are expected to increase (Ummenhofer and Meehl, 2017). These changes in climate are altering the suitability of habitat to species adapted to local environmental conditions. Indeed, there are various taxa of flora and fauna that are at risk of local extinction near their trailing-edge range limits (Wiens, 2016; Gilbert et al., 2020). Given the current and anticipated impacts of climate change on native species within their respective ranges, various conservation approaches have been suggested, including protected areas (Thomas and Gillingham, 2015; Melillo et al., 2016), management for habitat connectivity (Hannah, 2011), and conservation genetics (Franks and Hoffmann, 2012), among others. Recently, there has been considerable discussion of 'assisted migration' and the potential it has as a conservation tool to mitigate the impacts of climate change on species (Loss et al., 2011; Aitken and Whitlock, 2013; Gallagher et al., 2015; Butt et al., 2021).

Assisted migration describes the human-assisted movement of representatives of a species or population harmed by climate change to an area outside the indigenous range of that unit where it would be predicted to move as climate changes, were it not for anthropogenic dispersal barriers or lack of time (Hällfors et al., 2014). Assisted

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migration centers on the concept of an ‘adaptational lag’ (i.e., that species or populations are not adapting fast enough to the climatic changes occurring in their environment), and that certain species or population units lack the dispersal capacity to establish on habitat becoming more ‘suitable’ as the climate changes (Schloss et al., 2012; Fréjaville et al., 2020). In the context of climate change adaptation, assisted migration applies to the translocation of individuals beyond species ranges (called assisted species migration, assisted colonization or assisted range expansion), as well as the translocation of individuals within species ranges (called assisted gene flow or assisted population migration) away from rapidly changing areas (e.g., trailing-edge ranges) to more suitable habitat within their range (e.g., cooler areas), thereby improving the ability of recipient populations to adapt to changing climatic conditions. Assisted migration is variously referred to as assisted conservation translocation, and managed relocation, among other terms; Hällfors et al., 2014).

The literature is rife with discussion and debate over the risks and benefits of assisted migration as a conservation intervention (see Benomar et al., 2022). Numerous authors have highlighted the possible ecological and genetic risks associated with assisted migration including negative consequences to the source population/ecosystem, translocated individuals, and recipient ecosystems (Ricciardi and Simberloff, 2009; Seddon et al., 2009; Hewitt et al., 2011; Bucharova, 2017). Indeed, much of the concern over assisted migration (beyond species ranges) stems from the broad literature, and well-grounded understanding of the impacts of invasive species on native ecosystems (Lunt et al., 2013; Loss et al., 2011), as well as the disruption of relationships among species (e.g., symbioses; Gallien and Carboni, 2017). Discussion of genetic risks of assisted migration within range have largely focused on outbreeding depression due to disruption of coadapted gene complexes (Aitken and Whitlock, 2013; Keller et al., 2000; Weeks et al., 2011), or the disruption of adaptation to non-climatic environmental factors (e.g., soil or water characteristics) as well as disruption of coadaptation of populations (e.g., plants and mycorrhizal communities; Bucharova, 2017). Further, substantial ethical concerns have been raised within the literature, including generational considerations, interspecies equity, ethics of neo-acclimatization, sentience-based ethics, ecological ethics (Minteer and Collins, 2010; Albrecht et al., 2013), and how Traditional knowledge and other worldviews factor into decision-making around assisted migration (Pelai et al., 2021). In contrast, arguments to support this conservation tactic have been crafted from ecological (overcoming fragmented landscapes, assisting species with poor dispersal, preventing biodiversity loss), genetic (promoting rapid adaptation of populations to new conditions, maintaining genetic integrity; Aitken and Whitlock, 2013; Ledig and Kitzmiller, 1992), and ethical perspectives (Gray et al., 2011; Hewitt et al., 2011; Thomas, 2011). Polarizing perspectives on this tactic have likely limited its implementation by decision-makers, and few instances exist where it has been used from a climate change adaptation perspective (discussed in Williams and Dumroese, 2013; Hewitt et al., 2011; Butt et al., 2021).

The current and forecasted impacts of climate change on ecosystems is well documented (e.g. Prowse et al., 2009). Canada, as a country with diverse ecosystems (including grassland, forest, desert, marine, freshwater, tundra, Arctic) that span a vast latitudinal range, stands to suffer potentially severe and wide-ranging impacts from climate change on its flora and fauna (Price et al., 2013; Poesch et al., 2016; Bush and Lemmen, 2019). In a horizon scan of issues likely to impact Canadian protected areas, survey respondents identified the emerging effects of climate change on protected area design, planning, and management as one of four major issues (Dietz et al., 2021). Moreover, a recent synthesis of key information needs to move from knowledge to action for biodiversity conservation in Canada identified targeted research on planning and management relevant to climate adaptation as one such need (Buxton et al., 2021). Of particular interest to Parks Canada (federal department managing National Parks) is the potential for protected areas to serve as recipient locations for assisted migration initiatives. Protected areas may serve as ideal locations for assisted migration given that protected areas typically offer higher quality habitat and fewer threats to organisms (e.g. harvest, development; Worboys et al., 2005).

To better understand the potential for assisted migration as a conservation and adaptation tactic to benefit Canadian species threatened by climate change, we conducted an evidence synthesis to map examples where assisted migration has been implemented globally. With this mapping exercise, we collate and describe the quantity and key characteristics of the available evidence base pertaining to this conservation tactic, including the taxa, species' conservation status, locations, use of protected areas, monitoring indicators, and contexts. To provide support to Parks Canada, our discussion focuses on the potential for assisted migration of Canadian species within or outside of natural species ranges, but will be widely applicable to those considering assisted migration regardless of location or jurisdiction.

2. Methods

2.1. Searching for articles

Searches were conducted in January 2022 for commercially published and gray literature in three bibliographic databases [ISI Web of Science Core Collection (WoSCC), Federal Science Library (FSL; Canada), Science.gov] and one search engine (Google Scholar; first 200 results sorted by relevance). Search strings included the term ‘climate’ and various synonyms for assisted migration (combined using the Boolean operator OR) but were modified depending on the search functionality of different databases or the search engine. Search terms were limited to English, though no language, geographic, date, or document type restrictions were applied during the search (full search strings and details on search settings and restrictions can be found in Additional File 1). Search results were exported into Microsoft Excel and duplicates were removed between the four sets of results.

A call for evidence was prepared that included a brief description of the aim of the synthesis, the type of evidence being searched for, and contact information. The call for evidence was distributed on social media (e.g., Twitter, Facebook) in January and February of 2022 and by the Advisory Team to relevant networks and colleagues. A final search was conducted in the IUCN ‘Global conservation translocation perspectives: 2021. Case studies from around the globe’ (Soorae, 2021). Also, the reference section of 72 relevant reviews identified during the initial search was screened for articles potentially missed during the search.

2.2. Screening and eligibility

Articles (including those suggested during calls for literature, supplemental searches, and identified in Soorae, 2021) were screened at two stages: (i) title and abstract, and (ii) full-text. Full texts of articles included at title and abstract screening were obtained using the Carleton University library subscriptions or interlibrary loans when not available open access. Full texts were obtained for all articles eligible for inclusion.

Eligible articles included those describing a human-assisted movement of individuals of a species in response to climate change, as well as articles describing studies where human-assisted movements were interpreted in the context of climate change (e.g., provenance studies) even if that was not the original intent. Studies describing simulated assisted migration, perspectives on assisted migration, or translocations not pertaining to climate change were not eligible and were excluded from this review (e.g., Gallagher et al., 2015; Sullivan et al., 2015). Additionally, reviews were excluded but if on topic, bibliographies were searched for relevant articles that were not captured by our search strategy (see Additional File 2 for a complete list of relevant reviews). Only assisted migration studies conducted in natural settings were included (e.g., studies in greenhouses and growth chambers such as Lu and Man, 2011; Lazarus and McGill, 2014; Seidel et al., 2019; Inoue et al., 2020 were excluded). Further, articles applying a climatic treatment were excluded (e.g., watering vs. drought, shade vs. unshaded), unless a suitable control was included, and results could be extracted specifically for the control. All populations and outcomes from anywhere in the world were eligible for inclusion. A small number of articles that could only be found in Spanish were translated using Google Translate before screening. No other articles were identified in languages other than English and Spanish. For a full list of articles excluded at full-text screening see Additional File 3.

2.3. Data extraction

After full-text screening, 97 articles were eligible for inclusion and underwent data extraction. Within an individual article, data were extracted at the species-level (hereby considered a 'study'), meaning data pertaining to various release sites, outcomes, and years were aggregated. In a small number of articles, assisted migration trials occurring over multiple years were considered separately for the same species (treated as separate studies) when outcome data could be interpreted separately (i.e., Yang et al., 2015; Skikne et al., 2020). Where two articles contained overlapping data or focused on the same assisted migration study, only the more complete of the two was included (e.g., Bert et al., 2020 instead of Sinclair et al., 2015). The following variables were extracted for each study: bibliographic information, taxa, species, common name (as reported in the article), conservation status (as reported in the article), year(s) that assisted migration was implemented, a qualitative description of the assisted migration undertaken, region, biome, whether release sites were protected areas, whether release sites were within the species range, operational context, response variable(s) considered, assessment date, summary of findings, indirect impacts to non-target taxa, and the institution/sector undertaking the assisted migration (see Table 1). Where applicable, summary statistics are reported across studies, and variation between studies is discussed through narrative synthesis. The distribution and frequency of the evidence base was also compiled into structured heatmaps showing linkages between investigations of assisted migration inside and outside of protected areas (grouped by their assessment duration) (columns) related to taxa and operational context (rows). A separate heat map was made investigating the distribution of assisted migration studies conducted within vs. outside species ranges. The aim of this heatmap was to describe the distribution of research

Table 1
Extracted variables, descriptions, and considerations for data extraction.

Extracted information	Description	Considerations
Bibliographic information	Authors, title, year, journal, volume, issue, pages, DOI	–
Taxa	Broadly categorized into plant, insect, coral, fish, reptile, mammal	–
Species	Common name, Latin name	As reported in the article
Conservation status	Species conservation status	The conservation status was extracted as reported within papers (which comprised various types of regional, national, and international classifications). If no conservation status was reported in the article, Not Reported (NR) was indicated.
Year	Year that assisted migration was undertaken	Multiple years are reported when assisted migration occurred across years
Assisted migration description	Description of the source and release locations	Descriptions vary (e.g., transfer distance, climatic distance, regional descriptions)
Region	Province/Territory/State, Country	–
Biome	The biome where the study took place	Biomes were described as forest, grassland, freshwater, marine, wetland
Protected area	Whether the release site was within a protected area	Various types of protected areas were reported (e.g., national forest, parks, refuges). Protected status was assigned as reported in the article
Range	Whether the release site was within the species range	Introductions outside of a species' range were reported as described in the article, and where not available, were inferred from published distributions. If the study included introductions both within and outside a species' range, it was considered as 'outside' for the purpose of analysis.
Operational context	Studies were classified by type as 'assisted migration', 'experimental assisted migration', or 'inadvertent assisted migration'. The 'assisted migration' classification identifies studies that moved species to a location as part of a conservation/management effort related to climate change. The 'experimental assisted migration' classification includes studies that sought to investigate the response of species to various climates and generally included movements to both warmer and cooler climates (e.g., reciprocal transplants). These studies often involved some level of influence over translocated species such as containment within forest plots, experimental treatments, etc. Studies classified as 'inadvertent assisted migration' included species movements that were conducted for other purposes initially (e.g., forestry-related movements), but were interpreted post-hoc in the context of climate change.	–
Management outcomes	Description of the variables assessed for each assisted migration study	–
Assessment duration	The elapsed time between assisted migration and assessment of outcomes	Where a range of years was reported in the study, the mid-point of that range was recorded
Findings	Principal findings of each study were extracted, regardless of the response variable used within the study. Generally, findings were extracted as-written within the article	–
Indirect impacts	Impacts described to non-target taxa	–
Institution/sector	The institutions/sectors involved in the assisted migration were inferred by the author list, unless otherwise specified in the text. We did not consider foreign government co-authors as an indication of 'government' involvement in the translocation. It was assumed large-scale, international assisted migration was conducted by governments even if not reported specifically.	–

effort (i.e., identify knowledge clusters and gaps), rather than quantify or validate the outcomes of this conservation tactic. See Additional File 4 for the database of literature reviewed.

3. Results

Searches returned 1309 individual records from Web of Science Core Collections (788 articles), FSL (131), Science.gov (190), and Google Scholar (200). Removal of duplicates resulted in 1000 unique articles. After screening all unique articles for eligibility (first at title and abstract, and then at full-text), our study identified 204 studies from 97 articles where assisted migration was conducted or interpreted in the context of climate change. Most of these studies were experimental (n = 127) or involved an inadvertent assisted migration event (n = 71; e.g., forestry-related study). In contrast, very few studies explicitly documented the implementation of assisted migration as part of a conservation/management effort or conservation tactic (n = 6; Box 1). Assisted migration (including experimental and inadvertent instances) was undertaken on 143 unique species, which included both plants and animals of various taxa (see Fig. 1). Trees (n = 127 studies) and other vascular plants (n = 45) were most commonly moved, particularly the families of Pinaceae (n = 57) and Fagaceae (n = 29). Movements were most common among the genera *Pinus* (n = 33) and *Quercus* (n = 24), followed by *Picea* (n = 9), *Pseudotsuga* (n = 7), and *Populus* (n = 6). Although various conservation lists were used to assign conservation status (i.e., regional, national, international lists), 13 % (27/204) of studies reported some form of at-risk status for the study species, which ranged from ‘least concern’ (e.g., *Fraxinus uhdei*) to ‘critically-endangered’ (e.g., *Euryodendron excelsum*) as recommended by the IUCN.

Within the scope of this review assisted migration studies have been implemented from 1889 to 2018, with a median date of 2010. The scale of assisted migration varied greatly, ranging from the movements of butterflies (*Melanargia galathea, Thymelicus sylvestris*) 35 km outside of their native range (Willis et al., 2009), to the international movements of black spruce (*Picea mariana*) seeds from hundreds of provenances (Yang et al., 2015). Most assisted migration movements occurred in North America (n = 129), followed by Europe (n = 54), Oceania (n = 14), then Asia (n = 7). Movements were most common in the USA (n = 75), Canada (n = 33), and Mexico (n = 29). Movements occurred most frequently in forests (n = 146), followed by grasslands (n = 26), islands (n = 13), wetlands (n = 4), marine (n = 2), freshwater (n = 2), and other systems (n = 11; e.g., dunes, alpine, sagebrush, agricultural fields; Fig. 1). Approximately 29 % of movements involved release of species into a protected area (which varied in type of protection; see breakdown of studies in Fig. 2). Most movements were within (n = 131) rather than outside (n = 73) species ranges (Fig. 3). Academic institutions were most often involved with assisted migration (n = 139), followed by governments (n = 88), and less frequently NGOs (n = 5), or industry (n = 4). In many cases (n = 54), more than one sector was involved with the assisted migration. For some historical and inadvertent assisted migration events, it was not clear exactly who was responsible for the assisted migration.

Almost all assessments of assisted migration (n = 193) involved individual-level outcomes, with most reporting survival (n = 143) and/or growth (n = 127), while emergence (n = 10), and germination (n = 8) were also reported for some plant species. Population or community-level outcomes (e.g., population growth, abundance) were infrequently reported (n = 11). Only four studies quantified impacts of assisted migration on non-target taxa within the recipient community (Box 2A/B). Assessment intervals following assisted migration ranged from <1 year to 98 years, with a median assessment interval of 2 years (see Box 2C for a longer-term example).

The distribution and frequency of studies investigating assisted migration inside and outside of protected areas (grouped by their assessment duration) in relation to the taxa and operational context was explored via a visual heatmap (Fig. 2). The heatmap highlights significant knowledge gaps across all taxa other than trees and a small cluster of experimental releases in other plants. Inadvertent assisted migration in trees had large variation in assessment duration including several longer-term studies, while when done in the context of experimental release, most tree studies lasted 1–5 years. Regardless of being in a protected area or not, studies on plants other than trees did not extend beyond 10 years in the case of experimental releases, and not beyond 5 years for assisted migration or inadvertent assisted migration. All bird studies included lasted 1–5 years and had almost equal frequencies in representation within and outside of protected areas. All studies on coral, fish, insects, and mammals occurred within protected areas while the single reptile study occurred outside of a protected area.

4. Discussion

Across the literature there appears to be notable hesitancy to implement assisted migration for the purposes of conservation, which may be due to the potential unknowns and risks associated with this activity (Ricciardi and Simberloff, 2009; Sandler, 2010; Rivera et al., 2021). Further, societal support for assisted migration is found to vary based on value-based and policy-strategic considerations at least as much as varied understandings of technical issues (Neff and Larson, 2014). For instance, in Australia the public is more likely to support actions that mitigate proximal threats rather than assisted migration (Hancock and Gallagher, 2014). The acceptance of assisted migration appears to depend on whether movements are within or outside of a species' range (Peterson St-Laurent et al., 2018; Peterson St-Laurent et al., 2021). Despite hesitancy around the tactic, humans have a long history of relocating plants and animals for a variety of reasons (e.g., agriculture, horticulture, forestry, pet trade; Van der Veken et al., 2008). Further, Indigenous peoples have been translocating species for millennia (Silcock, 2018; Rayne et al., 2020). As such, it is somewhat surprising that assisted migration for the purpose of conservation has been subject to so much controversy (Hewitt et al., 2011).

We reviewed the assisted migration literature and found 204 examples where species were subject to ‘assisted migration’. A diverse array of studies was discovered, spanning species of different taxa and conservation status (though most involved plants and species not at-risk). The scale and extent of assisted migrations were vast, from the intercontinental movements of tree species (e.g., Niemczyk et al., 2021), to the movements of cloud forest tree species up a single mountain (e.g., Garcia-Hernandez et al., 2019). Implementation of assisted migration in a conservation/management context was rare (6 studies), though many more assisted migrations have occurred experimentally (e.g., Evans et al., 2016; Martín-Alcón et al., 2016) and many translocations have happened inadvertently that allow researchers to gain insights into assisted migration (e.g., St. Clair et al., 2020; Steiner et al., 2021). Although we did not quantify or validate the outcomes of this conservation tactic, as this was a mapping exercise only, overall, the outcomes of assisted migration on target species were generally considered positive by study authors. However, very little evidence existed to quantify impacts at the population- or community-level, or at the socio-cultural level. Below we discuss the major findings of our evidence synthesis.

4.1. Implications for assisted migration in Canada

Assisted migration is gaining increasing attention as a potential conservation tactic within Canada (Coristine and Kerr, 2011; Dietz et al., 2021; Pedlar et al., 2021). Most assisted migration studies have pertained to trees and other plants that have a long history of movements related to forestry and agriculture (e.g., *Pinus*, *Picea*, and *Quercus* spp). The limited migration capacity of these sessile organisms and reduced ability to keep up with changing climates make them relevant candidates for assisted migration (Sáenz-Romero et al., 2016). According to Natural Resources Canada, assisted migration of trees can be subdivided into three categories: assisted population migration (within a species

Box 1
Brief case studies highlighting all investigations describing an assisted migration study conducted for the purpose of conservation or management, rather than for experimentation or some other purpose (See Ren et al., 2016a,b; Widhalm et al., 2020; Willis et al., 2009).

Camellia changii is an endemic and rare small tree species in China with an extremely narrow range. The wild population has ~1000 individuals remaining, with human removal and climate change among threats to the species. As a conservation measure for the species, 45 individuals were grafted to a related species and were planted back into their source location or at the Tianxin Nature Reserve, located 390 km north of the only remnant wild population (Ren et al. 2016a). After two years, they found 100% survival at both sites and few signs of reproductive consequences for the introduced population. Further, pollinators of several species were frequently observed visiting the flowers in the introduced area. Although the assessment period was short, this study suggests positive outcomes associated with this particular assisted migration effort.

Manglietia longipedunculata is a tree listed as Critically-Endangered by the IUCN with a sole population in the Nankunshan Nature Reserve in South China. Emerged and grafted seedlings from the species were introduced into two sites. The first site was the existing site, while the second was the Tianxin Nature Reserve located 202 km north, which allowed researchers to buffer against potential climate change impacts. After 5 years, survival was high for grafted seedlings (96%), and moderate for emerged seedlings (64%), but was lower than that of individuals introduced within their existing range (Ren et al. 2016b).

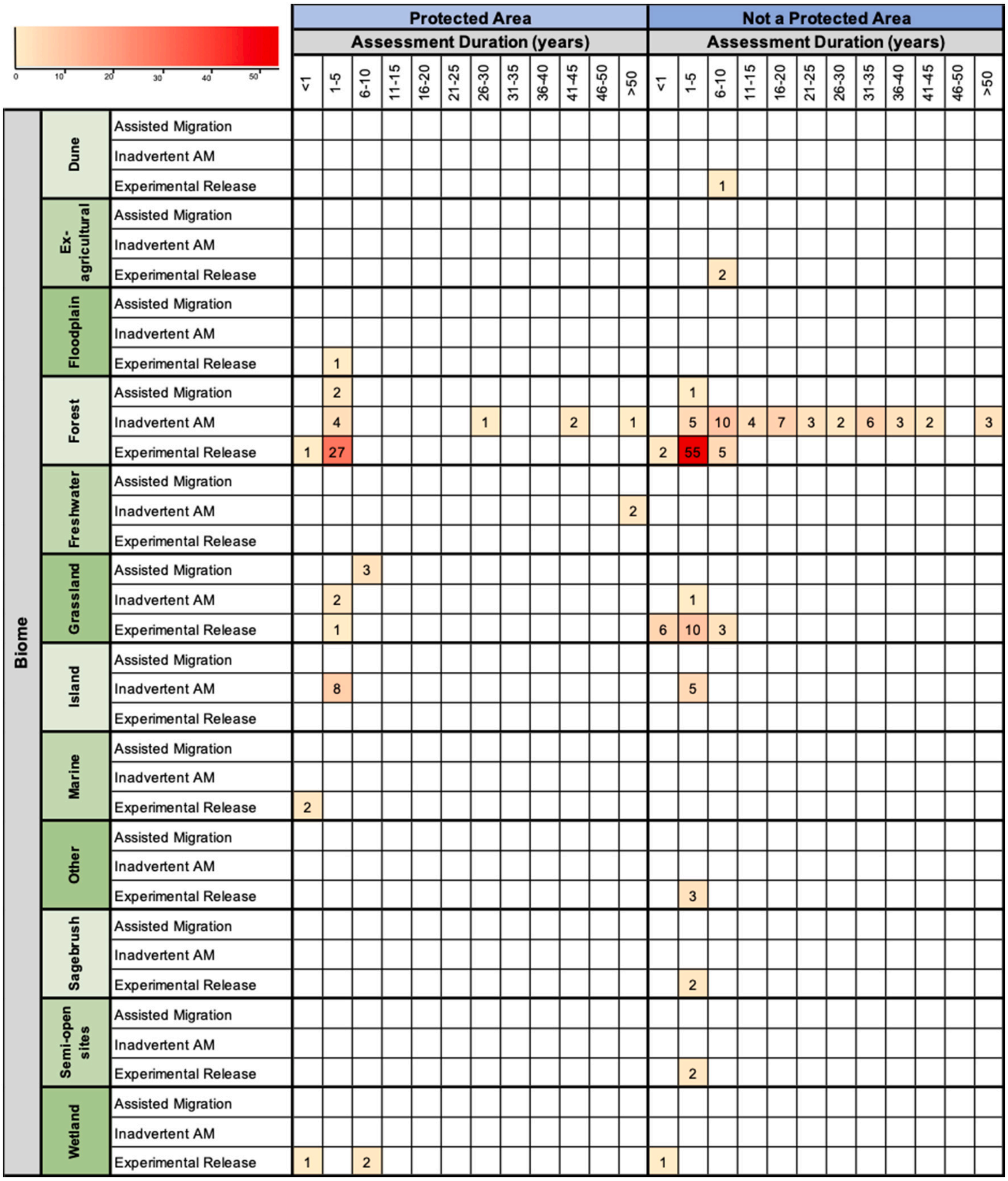
In 2000, assisted migration was conducted for two butterfly species in northern England; the marbled white (*Melanargia galathea*) and small skipper (*Thymelicus sylvestris*). Individuals from both species were introduced into grassland sites 35 km (*T. sylvestris*) and 65 km (*M. galathea*) outside of their current range, with site selection based on species-climate models (Willis et al. 2009). Both introduced populations grew and expanded their respective range over 6 years, suggesting a positive outcome of this conservation measure.

Oberthür's grizzled skipper butterfly (*Pyrgus armoricanus*) has low dispersal ability and a status of Endangered on the Red List of Sweden. To learn more about its expansion dynamics, a small number of individuals were introduced to six previously uninhabited sites about 70 km beyond their northern range limit in southern Sweden, as well as six other sites within the range. After 8 years of monitoring, introduced individuals survived at two sites north of the current range limit. Reproduction and expansion at one of those sites eventually led to the establishment of a viable metapopulation (Widhalm et al. 2020).

The Florida Torreya (*Torreya taxifolia*) is an Endangered tree located in the southeastern US. A Citizen Science group known as the Torreya Guardians was formed in the early 2000s with the goal of protecting the species. They argued the species would survive best in a cooler climate and took advantage of a legal exception to the Endangered Species Act which allowed them to implement their own assisted migration project outside established institutions. Seeds and seedlings were moved from Florida (and South Carolina) to North Carolina, and later Wisconsin, Michigan, and New Hampshire. After about a decade of implementation, the Florida Torreyahas thrived in some states, while in other states with cooler climates, the tree manages to survive, but is having more trouble growing than in warmer places. Although this assisted migration was criticized for its lack of scientific planning prior to implementation, it has turned out to be an interesting, uncontrolled experiment.

range), assisted range expansion (just outside a species range), and assisted long-distance migration (far outside a species established range; Natural Resources Canada, 2020). In most cases, interventions have focused on assisted population migration, which may constitute a less risky approach, particularly for trees (Pedlar et al., 2012). Although the broader ecological impacts were rarely evaluated by studies in our review (but see Box 2A and B), insights from the invasive species literature suggest plants have relatively low risk of intracontinental invasions, and that AM may be particularly useful for the taxa (Mueller and Hellmann, 2008). Trees can also serve as foundation species which can provide ecosystem integrity for a multitude of dependent species during different stages of their life-cycle (Kreyling et al., 2011).

Canada (and the rest of the world) has a long history of conducting assisted migration for forestry purposes (Williams and Dumroese, 2013). Indeed, many studies have been conducted to evaluate the relative performance of various provenances in different climatic regions. In some cases, provenances sampled from warmer climatic zones have demonstrated greater performance than local ones (Pedlar et al., 2021). Some of the most positive Canadian examples include White spruce (*Picea glauca*) movements from Ontario to Quebec during the 1980s. The results revealed that provenances originating from south-central Ontario and southwestern Quebec (close to the southern edge of the species' natural distribution), demonstrated superior growth in more northern environments compared to local populations and performed much

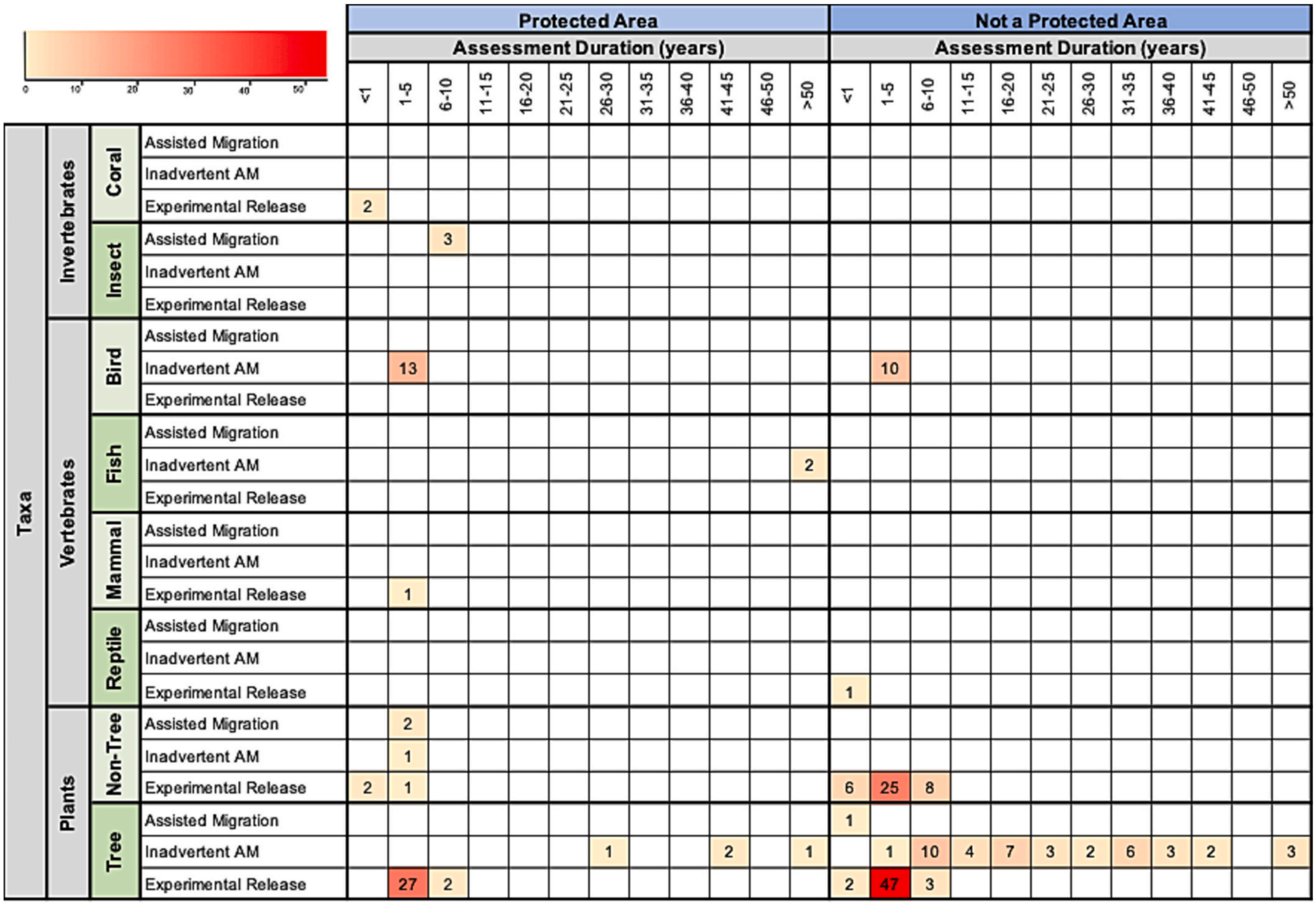


Biome		Protected Area												Not a Protected Area											
		Assessment Duration (years)												Assessment Duration (years)											
		<1	1-5	6-10	11-15	16-20	21-25	26-30	31-35	36-40	41-45	46-50	>50	<1	1-5	6-10	11-15	16-20	21-25	26-30	31-35	36-40	41-45	46-50	>50
Dune	Assisted Migration																								
	Inadvertent AM																								
	Experimental Release															1									
Ex-agricultural	Assisted Migration																								
	Inadvertent AM																								
	Experimental Release															2									
Floodplain	Assisted Migration																								
	Inadvertent AM																								
	Experimental Release		1																						
Forest	Assisted Migration		2												1										
	Inadvertent AM		4					1			2		1		5	10	4	7	3	2	6	3	2		3
	Experimental Release	1	27											2	55	5									
Freshwater	Assisted Migration																								
	Inadvertent AM												2												
	Experimental Release																								
Grassland	Assisted Migration			3																					
	Inadvertent AM		2												1										
	Experimental Release		1											6	10	3									
Island	Assisted Migration																								
	Inadvertent AM		8												5										
	Experimental Release																								
Marine	Assisted Migration																								
	Inadvertent AM																								
	Experimental Release	2																							
Other	Assisted Migration																								
	Inadvertent AM																								
	Experimental Release														3										
Sagebrush	Assisted Migration																								
	Inadvertent AM																								
	Experimental Release														2										
Semi-open sites	Assisted Migration																								
	Inadvertent AM																								
	Experimental Release														2										
Wetland	Assisted Migration																								
	Inadvertent AM																								
	Experimental Release	1		2										1											

Fig. 1. Distribution and frequency of studies examining assisted migration inside and outside of a protected area (grouped by biome and operational context) in relation to the number of assessment years. In this matrix of counts, darker coloured cells indicate a higher frequency of occurrence of the evidence, while lighter colours indicate a lower occurrence.

better than cold-adapted populations from western Canada and Alaska (Lu et al., 2014). As such, the dogma that 'local is best' with respect to seed origins has been challenged by climate change (Breed et al., 2018), and reforestation strategies are shifting in light of uncertain future climate conditions (Gray and Hamann, 2011; Hajjar et al., 2014). Indeed, the British Columbia government has changed their seed source guidelines for forestry to only allow seeds to be chosen based on appropriate (future) climate conditions, and not because they are local (Government of British Columbia, 2022), with similar policies being implemented in Ontario (Ministry of Natural Resources and Forestry, 2020). In contrast, Red alder (*Alnus rubra*) appear to perform sub-optimally when planted in different climatic regions, emphasizing that assisted migration will not be equally successful for all tree species (Porter et al., 2013).

Canada has an immense – and growing – area of protected habitat (UNEP-WCMC, 2022), and there is potential to consider assisted migration within existing protected area management strategies (Loss et al., 2011), particularly given evidence for and projections of shifting bioclimatic envelopes (Cheung et al., 2008; Rose and Burton, 2009). Indeed, there are many examples worldwide where conservation translocations have occurred in protected areas (Langridge et al., 2020), though in most cases these translocations have not been specifically related to abating climate change threats to biodiversity. The assisted migration of the endangered plant *Camellia changii* (see Box 1) provides a positive example of the use of assisted migration as a conservation tactic for plants within protected areas. Individuals were grafted and



Protected Area – Assessment Duration (years)

Group	Taxon	Context	<1	1-5	6-10	11-15	16-20	21-25	26-30	31-35	36-40	41-45	46-50	>50
Invertebrates	Coral	Assisted Migration												
Invertebrates	Coral	Inadvertent AM												
Invertebrates	Coral	Experimental Release	2											
Invertebrates	Insect	Assisted Migration			3									
Invertebrates	Insect	Inadvertent AM												
Invertebrates	Insect	Experimental Release												
Vertebrates	Bird	Assisted Migration												
Vertebrates	Bird	Inadvertent AM		13										
Vertebrates	Bird	Experimental Release												
Vertebrates	Fish	Assisted Migration												
Vertebrates	Fish	Inadvertent AM												2
Vertebrates	Fish	Experimental Release												
Vertebrates	Mammal	Assisted Migration												
Vertebrates	Mammal	Inadvertent AM												
Vertebrates	Mammal	Experimental Release		1										
Vertebrates	Reptile	Assisted Migration												
Vertebrates	Reptile	Inadvertent AM												
Vertebrates	Reptile	Experimental Release												
Plants	Non-Tree	Assisted Migration		2										
Plants	Non-Tree	Inadvertent AM		1										
Plants	Non-Tree	Experimental Release	2	1										
Plants	Tree	Assisted Migration												
Plants	Tree	Inadvertent AM							1			2		1
Plants	Tree	Experimental Release		27	2									

Not a Protected Area – Assessment Duration (years)

Group	Taxon	Context	<1	1-5	6-10	11-15	16-20	21-25	26-30	31-35	36-40	41-45	46-50	>50
Invertebrates	Coral	Assisted Migration												
Invertebrates	Coral	Inadvertent AM												
Invertebrates	Coral	Experimental Release												
Invertebrates	Insect	Assisted Migration												
Invertebrates	Insect	Inadvertent AM												
Invertebrates	Insect	Experimental Release												
Vertebrates	Bird	Assisted Migration												
Vertebrates	Bird	Inadvertent AM		10										
Vertebrates	Bird	Experimental Release												
Vertebrates	Fish	Assisted Migration												
Vertebrates	Fish	Inadvertent AM												
Vertebrates	Fish	Experimental Release												
Vertebrates	Mammal	Assisted Migration												
Vertebrates	Mammal	Inadvertent AM												
Vertebrates	Mammal	Experimental Release												
Vertebrates	Reptile	Assisted Migration												
Vertebrates	Reptile	Inadvertent AM												
Vertebrates	Reptile	Experimental Release	1											
Plants	Non-Tree	Assisted Migration												
Plants	Non-Tree	Inadvertent AM												
Plants	Non-Tree	Experimental Release	6	25	8									
Plants	Tree	Assisted Migration	1											
Plants	Tree	Inadvertent AM		1	10	4	7	3	2	6	3	2		3
Plants	Tree	Experimental Release	2	47	3									

Fig. 2. Distribution and frequency of studies examining assisted migration inside and outside of a protected area (grouped by taxa and operational context) in relation to the number of assessment years. In this matrix of counts, darker coloured cells indicate a higher frequency of occurrence of the evidence, while lighter colours indicate a lower occurrence.

transplanted into the Tianxin Nature Reserve, China, located 390 km beyond the species northern range limit. Findings suggested that *C. changii* 'graft hybrids' subject to the out-of-range conservation introduction did not suffer a decline in reproductive success compared to translocation within its range (Ren et al., 2016a). Indeed, the restricted harvest, reduced human access/development, and higher habitat quality within protected areas (Worboys et al., 2005), among other factors, may increase the success of assisted migration efforts in these spaces.

4.2. Knowledge gaps

There are key limitations of the data that preclude risk-averse decision-making around the use of assisted migration. For one, very few studies quantified population-level outcomes (e.g., abundance, population growth), or whole ecosystem implications and outcomes, and instead focused on individual-level fitness outcomes (e.g., survival, growth). While these outcomes are important, it is difficult to relate them to potential broader scale ecological (and evolutionary) consequences of assisted migration. The lack of population-level outcomes reported likely relates to the experimental design of most studies, and the factors influencing experimental design (e.g., time, human and financial resources, equipment, travel and access to experimental sites, permitting, ecological risk, etc.). Transplanted individuals (generally plants) were often contained (e.g., in transects, cleared plots) and the intent of the studies, in such cases, was typically to inform or validate, rather than actually implement assisted migration as a conservation tactic (e.g., Marsico and Hellmann, 2009). For example, in one study, turtles introduced in southern Australia were recaptured at the end of the study period and returned to the Perth Zoo (Bouma et al., 2020). As such, the conditions and opportunity to allow population growth were often not provided, restricting the ability for researchers to quantify it, diminishing the evidence for the efficacy and importance of assisted migration as a long-term conservation tactic. Further, very few studies (~2 %) quantified impacts to non-target species (but see Box 2A). Even among the handful of studies that implemented assisted migration for the purpose of conservation (rather than experimentation), only one documented any form of indirect impacts to non-target species (i.e. pollinators; Ren et al., 2016a). Given the potential community-level risks associated with assisted migration (Ricciardi and Simberloff, 2009), this paucity of information precludes effective decision-making and has likely limited implementation of assisted migration. Nonetheless, some information on ecological impacts of this conservation tactic can be gleaned from the broader conservation translocation literature. For instance, in a review of US conservation translocations, only one instance led to a loss of biodiversity (Novak et al., 2021). Although assisted migration may involve more drastic species movements than conservation translocation, findings from Novak et al. (2021) provide relevant information for decision-making surrounding assisted migration.

Few studies have documented the long-term outcomes of translocation (discussed in Schwartz and Martin, 2013). Indeed, the median duration of assessment after assisted migration was 2 years (also see Fig. 2). The longest-term data come from long-term provenance trials

Taxa				Within Range	Outside Range
Invertebrates	Coral	Assisted Migration			
		Inadvertent AM			
		Experimental Release		2	
	Insect	Assisted Migration			3
		Inadvertent AM			
		Experimental Release			
Vertebrates	Bird	Assisted Migration			
		Inadvertent AM		18	5
		Experimental Release			
	Fish	Assisted Migration			
		Inadvertent AM			2
		Experimental Release			
	Mammal	Assisted Migration			
		Inadvertent AM			
		Experimental Release		1	
	Reptile	Assisted Migration			
		Inadvertent AM			
		Experimental Release			1
Plants	Non-Tree	Assisted Migration			2
		Inadvertent AM			1
		Experimental Release		24	18
	Tree	Assisted Migration			1
		Inadvertent AM		42	3
		Experimental Release		44	37

Fig. 3. Distribution and frequency of studies examining assisted migration within vs. outside species ranges (grouped by taxa and operational context). In this matrix of counts, darker coloured cells indicate a higher frequency of occurrence of the evidence, while lighter colours indicate a lower occurrence.

with trees (See Box 2C), though these studies were rarely initiated with assisted migration and climate change adaptation in mind. Given that assisted migration is most likely a permanent, irreversible action, evaluation of long-term outcomes among existing case studies is key to informing decision-making. Many ecological interactions may not be apparent during early years following establishment. For instance, poorer survival of certain Douglas Fir provenances was not evident until more than two decades after planting (St. Clair et al., 2020). Overall, it is clear more information on the long-term population- and community-level impacts of assisted migration is needed, in addition to information on socio-cultural and other potential impacts (Pelai et al., 2021).

Our review also found considerable differences in the number of studies conducting assisted migration across taxa, with most examples pertaining to trees and other plants, followed by birds, and a couple of examples for mammals, reptiles, insects, fish, and coral (Fig. 2). Other taxa, e.g., molluscs, non-vascular plants, fungi, lichens, bacteria, and archaea (hydrothermal vents), have received little attention in the assisted migration and conservation translocation literature, leaving unanswered questions about how assisted migration of these organisms could influence ecosystem function. The bias towards trees primarily reflects the extensive efforts around the globe to support forestry practices. Although assisted migration was not at the forefront of these tree movements, researchers have now gone back and retroactively analyzed these movements in the context of climate change (e.g., Pedlar et al., 2021), providing relevance for our review. Further, many conservation translocations can be considered in the context of climate change even if that was not the original intent. Skikne et al. (2020) analyzed conservation translocations of birds in the context of assisted migration, providing us with several relevant avian examples for our review. Indeed, there are likely many more contexts where this could be done. As an example, Novak et al. (2021) conducted a review of translocations in the U.S. and found 1014 taxa that had undergone conservation translocations (across 125 years). Indeed, many of these translocations likely involved northward movements to habitats that species may be predicted to move towards as the climate changes, and therefore could be interpreted in the context of climate change adaptation. Further, an estimated two billion fish across various species are stocked around the world each year (Halverson, 2010). Many of these stocking events serve as individual assisted migration experiments (e.g., those involving poleward movements). Although outside the scope of this mapping exercise, future work could characterize the geographic and climatic transfer distances associated with conservation introductions (as well as other human-assisted movements like fish stocking, use of biological control agents, etc.) and contextualize the findings with respect to assisted migration. The invasive species literature is also well-positioned to inform the use of assisted migration (Mueller and Hellmann, 2008). Indeed, it has been suggested fish and crustaceans have the greatest risk of becoming 'invasive' after assisted migration (though this may relate to their likelihood of being noticed; Mueller and Hellmann, 2008).

4.3. Limitations of the review

This mapping exercise was initiated to provide support to Parks Canada with a collated summary of existing information on assisted migration as a climate change adaptation tactic, and as such the search was inherently biased towards Canadian studies. For instance, while we used three bibliographic databases and a search engine, these sources may have biased search results towards North American studies (e.g., Federal Science Library and Science.gov; Canadian and United States federal government science research). In addition, all authors and Advisory Team members contributing to this evidence synthesis were Canadian. With that said, however, we attempted to mitigate some potential bias, in part, by supplementing the searches by screening relevant reviews and conducting a broad call for evidence to mitigate this risk. Furthermore, while our evidence synthesis included a broad list of search terms describing assisted migration, it may not have captured all studies pertaining to the topic for a few reasons. First, there are several terms used that may vary by jurisdiction and/or taxa and situation (Hällfors et al., 2014) and it is possible some were missed. Second, based on our search string, articles that did not mention climate within the title, abstract, and/or keywords were not captured by our searches, though it is possible some of these articles may still have been relevant in the context of climate change (See Box 3A/B). For instance, running our search string without including the term "climate" yielded an additional 913 articles in WoSCC alone, which combined with other databases may have resulted in an increased number of relevant articles. Finally, only articles that involved human-assisted movements in the context of climate change were screened as eligible for inclusion in this review, however, movements completed in other contexts could also provide information about moving species outside of their range (see Box 3C).

5. Conclusions

This mapping exercise highlights the overall paucity of studies on the implementation of assisted migration for the purpose of conservation, limiting future quantitative synthesis on the effectiveness of this tactic. A key drawback associated with the literature is a lack of knowledge pertaining to population and community-level impacts of assisted migration and we recommend further efforts to address these knowledge gaps moving forward. Potential ecological risks have been described extensively in the literature (McLachlan et al., 2007; Ricciardi and Simberloff, 2009), though more effort must be made to quantify the wider impacts that follow assisted migration where experimental and inadvertent assisted migration have occurred. As suggested by some, assisted migration may be part of an integrated suite of conservation strategies that includes management for habitat connectivity,

Box 2
Examples of community-level (A, B) and long-term (C) impacts associated with assisted migration in Canada (Banting et al., 2021; Illingworth, 1978; Krakowski and Stoehr, 2009; Kranabetter et al., 2012; Montwé et al., 2018).

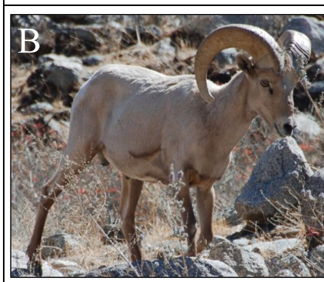
In the late 1960s, Douglas-Fir (*Pseudotsuga menziesii*) were moved throughout southwestern British Columbia as part of a provenance trial established by the British Columbia Ministry of Forests to develop seed transfer rules (primarily for reforestation purposes; Krakowski and Stoehr 2009). Seedlings in the trial were transferred up to 450 km within the natural range of coastal Douglas-fir in a common-garden design. Four decades later, Kranabetter et al. (2012) investigated the influence that specific provenances had on ectomycorrhizal (EMF) communities. They sampled root tips of trees in this field trial and found that species richness did not differ across transfer extent, while Shannon's diversity index declined only slightly. This suggests that Douglas-Fir of various origins can be transferred with minimal impact on the EMF community. However, they did observe significant site-specific differences in the EMF community and suggested that host-fungal interactions should be considered in the development of assisted migration strategies. While this study provides a good example of a community-level assessment that should be undertaken when evaluating the outcomes of assisted migration, it is clear there is a further need to evaluate impacts of species introductions outside of the native range more broadly on some key members of the ecological community (e.g., to other plants, birds, mammals).

In the 1900's, both native (*Oncorhynchus clarkii*) and non-native (*Salvelinus fontinalis*) trout were stocked into high-elevation, fishless, alpine lakes throughout Banff National Park. Persistence of these populations for several decades in these lakes highlights the success of these movements and potential for conserving trout in the face of climate change. To better understand the community-level consequences of trout stocking, Banting et al (2021) compared littoral benthic invertebrate diversity in non-native trout lakes, native trout lakes, and fishless lakes. They found similar levels of invertebrate species richness and diversity across lake types, regardless of whether fish were introduced or not. However, the benthic invertebrate community structure in lakes with fish differed from that of fishless lakes, highlighting the impacts of trout introductions on recipient invertebrate communities.

In 1974, the Illingworth provenance trial was undertaken which involved the range-wide collection of lodgepole pine (*Pinus contorta*) seed sources and subsequent planting in three experimental sites in British Columbia's Southern Interior (Illingworth 1978). Approximately 30 years later, Montwé, et al. (2018) analyzed the growth (tree rings) of these trees and related this to their source location. Until 1992, they found that southern, warm-adapted trees had equal productivity to local trees when transferred northward. However, a spring frost event in 1992 led to a permanent reduction in growth in southern seed sources. The authors conclude that cold adaptation should remain a key consideration when developing seed transfer and assisted migration strategies. Indeed, this study highlights the importance of long-term monitoring, as the first ~15 years of data would have yielded significantly different conclusions than the longer-term 30-year dataset.

Box 3
Examples of the types of conservation translocation studies that were either not identified during searches (A, B) or were screened out (C) due to our inclusion criteria (See DeGregorio et al., 2012; Kuussaari et al., 2015; Wild Sheep Working Group, 2015).

In 2001, 106 Gopher Tortoises (*Gopherus polyphemus*) were translocated from Georgia to the northern limit of their geographic range in South Carolina (DeGregorio et al. 2012). Tortoises were translocated in response to development at their source site and were moved to habitat managed by the U.S. Forest Service. The species was once abundant in the introduced habitat, though at the time of translocation was no longer present. To investigate whether cold winter temperatures would compromise the effectiveness of this Gopher Tortoise translocation, researchers released tortoises with temperature loggers. After two winters of monitoring, they found high survival, with only two juvenile tortoises experiencing mortality during winter months. They concluded that translocation of adult individuals can be successful when tortoises are provided access to suitable refugia at recipient sites. Despite this study providing useful information on the efficacy of assisted migration, the study did not include the word 'climate' in its title, abstract, or keywords, and as such, was not identified within our searches. This example highlights the potential information that could be captured with broader literature search terms.



Since the 1920s, over 15,000 Bighorn sheep (*Ovis canadensis*) translocations have occurred across North America (Wild Sheep Working Group 2015). The source and release sites vary for these movements, though many translocations have been northward to habitats that would seemingly have improved future climatic suitability (i.e., assisted migration). Examples of this include the movement of sheep from Arizona, California, Nevada, and Colorado to northern areas both within and outside the source state. Translocations of Bighorn sheep have been occurring for decades and have resulted in the establishment of self-sustaining populations and expanded ranges of existing populations, emphasizing the value of this conservation tactic. While this study provides useful information on assisted migration, it was only indexed on Google Scholar and lacked an abstract – reducing its likelihood of being screened into our search. As such, further efforts to identify pertinent grey literature could prove useful.

Kuussaari et al. (2015) describe two translocations of the Apollo clouded butterfly (*Parnassius Mnemosyne*) in Southern Finland. The species is threatened, in large part due to the loss of suitable habitat from overgrowth and grazing of natural pastures. In 2000, individuals were moved ~100 km east to two apparently suitable semi-natural grassland sites (both in protected areas) where the species had gone extinct ~50 years earlier. Over 13 years of monitoring at one of the sites, they observed a seemingly viable metapopulation with 11 subpopulations. However, expansion rates were low, and butterflies took 7 years to colonise patches within 200 m of the translocation site. In contrast, the butterfly failed to establish at the other site, seemingly due to fewer host-plants, extensive farmland, and a lack of topographical variation. While this example was excluded as it did not relate to climate change, it could indeed provide useful information on the movement of animals outside of their range.

conservation genetics, and when necessary, movement of species (Loss et al., 2011). While implementation of assisted migration for the purpose of conservation in the face of climate change has been infrequent, the literature still has a wealth of resources available to help guide assisted migration decisions, including methods to identify priority species for introduction (Rout et al., 2013), models to map suitable future habitat (e.g., Palmer and Larson, 2014; Dade et al., 2014), and various decision frameworks and protocols (Abeli et al., 2014; Karasov-Olson et al., 2021).

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data are available as supplementary files

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