NATURE REQUIRES INVESTMENT: APPLYING PRIORITY THREAT MANAGEMENT TO SUPPORT BIODIVERSITY AND CLIMATE TARGETS

Abbey E Camaclang*[1], Aranya Iyer[2], Chris Liang[2], Emily Giles[2], Beatrice Frank[2], Jessica Currie[2], Katherine I Alambo[3], Jennifer Lamoureux[4], Sarah Matchett[5], Tyler Miller[6], D Ryan Norris[7], Mary Ann C Perron[8], Robyn H M Rumney[9], Frederick W Schueler[10], Laura Timms[11], Catherine Paquette[2], Victoria Hemming[1], James Snider[2], and Tara G Martin[1]

* corresponding author: abbey.camaclang@uqconnect.edu.au

[1] Conservation Decisions Lab, Department of Forest and Conservation Sciences, Faculty of Forestry, University of British Columbia, 2424 Main Mall, Vancouver, BC Canada

[2] WWF-Canada, 410 Adelaide St. West, Suite 400, Toronto ON Canada

[3] Ottawa Riverkeeper, 501 Sir George-Etienne Parkway, Suite 300, Ottawa ON Canada

[4] Rideau Valley Conservation Authority, 3889 Rideau Valley Drive, Manotick, ON Canada

[5] Fisheries and Oceans Canada, 867 Lakeshore Road, Burlington, ON Canada

[6] Bruce Peninsula National Park | Fathom Five National Marine Park, Parks Canada Agency, 248 Big Tub Rd., Tobermory ON Canada

[7] Dept of Integrative Biology, University of Guelph, 50 Stone Rd E, Guelph, ON Canada

[8] St Lawrence River Institute, 2 St Lawrence Dr, Cornwall ON Canada

[9] Wildlife Conservation Society Canada, 344 Bloor Street West, Suite 204, Toronto ON Canada

[10] Fragile Inheritance, 6 St Lawrence Street, Bishops Mills Oxford Station, ON Canada

[11] Credit Valley Conservation, 1255 Old Derry Road, Mississauga ON Canada

ABSTRACT

1. Stemming biodiversity loss requires greater investment in conservation and more efficient use of available resources. Prioritizing conservation actions that yield the most biodiversity benefit for the least cost can help maximize return on investment. Actions that have co-benefits for other objectives, such as climate change mitigation, can also help mobilize additional funds for conservation.

2. We used Priority Threat Management to identify actions to secure the greatest number of species groups of conservation concern for the least cost in the Lake Simcoe-Rideau ecoregion, Ontario—one of Canada's biodiversity crisis ecoregions. We also estimated the carbon sequestration benefits of actions related to land protection and restoration.

3. We found that without additional investment in conservation, 13 of 16 species groups were expected to have <50% probability of persistence in this ecoregion by 2050. Implementing all proposed strategies would yield the greatest biodiversity benefits and secure 12 of the 16 species groups with ≥60% probability of persistence, at a cost of $113 million per year over 27 years. In comparison, investing CA$97 million per year in landowner stewardship, habitat protection, and restoration and regeneration strategies could secure ten species groups and improve the probability of persistence of one additional group from 39% to 55%, an increase of >15%.

4. The habitat protection and restoration strategies also deliver direct carbon benefits of around 11.2Mt in avoided CO_2 emissions and 137.6Mt CO_2 in potential sequestration, respectively, thus supporting alignment with climate change mitigation targets and delivering co-benefits that may further justify investment.

5. *Synthesis and applications.* By estimating the costs and demonstrating the expected benefits and potential carbon co-benefits of conservation actions, Priority Threat Management can help maximize return on investment and identify actions that address multiple environmental crises.

KEYWORDS

biodiversity conservation, carbon co-benefits, complementarity, conservation prioritization, cost-effectiveness, nature-based climate solutions, return on investment, species at risk

INTRODUCTION

Inadequate funding for conservation action has been linked to species imperilment and repeated failures to meet global biodiversity targets under the Convention on Biological Diversity (CBD) (McKinney, 2002; Waldron et al., 2013). Left unchecked, the continued loss of biodiversity can amplify the interacting effects of climate change and anthropogenic threats such as land-use changes, potentially leading to abrupt and irreversible ecosystem changes (Turner et al., 2020). It is, therefore, critical that we intensify our efforts to halt and reverse biodiversity loss. To this end, the Kunming-Montreal Global Biodiversity Framework (GBF) outlines a set of ambitious goals and corresponding biodiversity conservation targets. The GBF also includes targets to mobilize financial resources through various mechanisms, including enhancing the effectiveness and efficiency of use of those resources and optimizing co-benefits to address the biodiversity and climate crises simultaneously (Convention on Biological Diversity, 2022).

As a signatory to the CBD, Canada is responsible for implementing the GBF within its borders by developing a national strategy that outlines its biodiversity goals and action plans and securing sufficient funds to achieve those goals. Since 2018, the federal government has mobilized roughly CA$10 billion in investments to support biodiversity and climate goals (Environment and Climate Change Canada, 2023b). Despite these recent investments, however, additional financial resources need to be secured to close Canada's biodiversity finance gap, estimated at around US$15-20 billion per year (Rally Assets & Nature Conservancy of Canada, 2020), or about $20-27 billion per year in 2019 Canadian dollars. At the same time, it is equally important to make the most of currently available resources by maximizing the return on investment—that is, by prioritizing actions that yield the greatest conservation benefit for a given investment level, or that achieve a predetermined conservation goal for the least cost (Boyd et al., 2015; Murdoch et al., 2007).

Conservation return on investment can be improved by taking action at the regional scale, thus benefiting multiple species or ecosystems simultaneously (Kennedy et al., 2016), and by prioritizing actions that maximize biodiversity benefits across a given region for the least cost (Pressey & Bottrill, 2009). In particular, accounting for the complementarity of actions can help minimize costs by reducing duplication of effort, and help ensure that benefits of actions are spread across the suite of target biodiversity features in the region of interest (Chadès et al., 2015; Moilanen, 2008). Considering the potential co-benefits of conservation actions, such as those related to climate change mitigation (Shin et al., 2022) or human well-being (Blicharska et al., 2019), can further maximize the overall benefits to society and the environment.

A variety of decision science tools and frameworks are available to help identify conservation actions that maximize the return on investment (Hemming et al., 2022). One example is Priority Threat Management (PTM), a decision analysis framework developed to identify cost-effective and complementary sets of actions to manage and recover multiple species or other biodiversity features simultaneously across broad regions (Carwardine et al., 2012, 2019). It is a participatory process that brings together diverse groups of experts in the ecology and management of species of conservation concern. PTM also allows for the integration of multiple types of data, including empirically derived data and expert knowledge obtained through a structured elicitation protocol (Martin et al., 2012).

The application of PTM in Canada (Camaclang et al., 2021; Chalifour et al., 2022; Kehoe et al., 2021; Martin et al., 2018; Walsh et al., 2020) and elsewhere (Carwardine et al., 2012; Chadès et al., 2015; Firn et al., 2015; Ponce Reyes et al., 2019; Utami et al., 2020) demonstrates its broad applicability and is leading to positive outcomes for biodiversity through increased investment in priority actions and documented improvements in species recovery (Legge et al., 2011, 2023; Semeniuk, 2018).

Here, we applied PTM to the Lake Simcoe-Rideau ecoregion in Ontario, Canada to identify management strategies that would secure the greatest number of species groups of conservation concern in the region for the least cost. We also estimated the potential co-benefits of proposed strategies for climate change mitigation. The aim was to inform the development of a conservation prospectus that could be used to coordinate actions and establish collaborations among different conservation actors in the region, and aid in securing sufficient investment in conservation action.

The Lake Simcoe-Rideau ecoregion (Fig 1) is highly productive and biodiverse, and encompasses most of Ontario's unique alvar habitats and nearly thirty natural heritage areas designated for their significant biological or ecological importance (Crins et al., 2009). As the second most densely populated ecoregion in Ontario with a high risk of habitat conversion due to development pressure, this ecoregion is also facing high levels of threat, making it one of Canada's conservation crisis ecoregions (Kraus & Hebb, 2020). This region is also expected to be greatly impacted by climate change by mid to late century (2050-2080) (Climate Risk Institute, 2023). A 2021 report by the Auditor General of Ontario concluded that the provincial government is failing to protect species at risk, suggesting that populations will continue to decline (Office of the Auditor General of Ontario, 2021). In recent years, the Ontario government also decreased funding for species at risk and dismantled many biodiversity-focused legislative frameworks and programs, resulting in a reduced ability to act at a pace and scale required for species recovery (Bethlenfalvy & Olive, 2021; Mitchell et al., 2021). Given the scale and urgency of conservation issues in Ontario, there is a need to act strategically and collaboratively to ensure that available resources are invested in actions with the greatest benefits for biodiversity and the recovery of species of conservation concern in the region.

MATERIALS AND METHODS

Expert elicitation

A total of 145 prospective experts—individuals with knowledge of or practical experience with the ecology and management of the species of conservation concern in the Lake Simcoe-Rideau ecoregion—were invited to participate in the PTM process. Of those invited, 28 experts agreed to participate. Experts were from government agencies, conservation authorities, First Nations, conservation non-profit organizations, industry, and research institutions.

Experts participated in a series of five online workshops and a two-day in-person workshop held between May 2022 and January 2023. With the help of several workshop facilitators, experts worked together and refined the spatial extent and temporal scope of the study, identified 133 species of conservation concern in the region (Supporting Information Table A-1), assessed key threats to those species, and developed a list of eight individual and seven combination management strategies to address those threats and their impacts (Table 1; Supporting Information Table A-2). Experts were then asked to provide estimates of feasibility of the proposed actions as well as the annual costs, in 2022 Canadian dollars, of planning and implementing the proposed actions (Table 1). A modified Delphi structured elicitation protocol was used to obtain expert estimates of the conservation benefits of each management strategy (Carwardine et al., 2012; Hemming et al., 2018). Benefit was estimated as the difference between the probability of functional persistence in the region in 2050 with the strategy as well as under the baseline or counterfactual scenario, where functional persistence was defined as having viable, self-sustaining populations that continue to perform their ecological function. See Supporting Information Appendix B for more details about the study region and the expert elicitation process.

Of the 28 experts, 24 attended two or more workshop sessions. Nine experts attended the in-person workshop to provide estimates of the cost and feasibility of actions, while 16 experts provided individual estimates of the conservation benefits of the proposed management strategies.

Cost-effectiveness and complementarity analysis

We used the estimates of the benefit under the most likely scenario to evaluate the cost-effectiveness and the complementarity of management strategies. We calculated the expected benefit of each management strategy as the summed benefit of the strategy across species groups, weighted by the estimated feasibility of the strategy. We then derived a cost-effectiveness (CE) score by dividing the expected benefit by the total cost of the strategy.

To assess the complementarity in the benefits of management strategies, we arranged species into 16 species groups based on similarities in responses to threats and management actions, and assumed that species groups that achieve a probability of persistence equal to or greater than a particular threshold value to be 'secure'. We set this threshold value to 60%, based on the range of estimates for the expected probability of persistence under the proposed management strategies and the preference of the experts for higher probabilities of persistence. We identified the optimal sets of complementary management strategies that could maximize the number of species groups secured while minimizing the cost by solving the integer linear programming problem for a range of budgets (Chadès et al., 2015). The solutions identified are Pareto optimal solutions, representing trade-offs wherein greater benefits can only be achieved by increasing costs (Chadès et al., 2015; Ruzika & Wiecek, 2005).

When the budget is fixed, the solution to implement is typically determined by the budget constraint. However, if the budget is flexible or is yet to be secured, a choice must be made on which of the solutions should be adopted. To help inform this choice, we performed an additional analysis to determine which sets of strategies could maximize both the number of species groups secured with at least 60% probability of persistence and the number of groups that could gain at least 15% probability of persistence above the baseline for the least cost.

See Supporting Information Appendix B for a detailed description of the cost-effectiveness and the complementarity analysis, as well as the methods and results of uncertainty analyses that explored the potential effect of variability in benefit estimates and cost discounting rates on the outputs of the complementarity analysis.

Carbon co-benefits

To examine how candidate management strategies align with climate change mitigation priorities, we estimated the potential carbon co-benefits of management actions with direct and quantifiable benefits, recognizing that indirect or flow-on benefits, such as those from policy changes or behavioural change incentives, are difficult to quantify, and may include higher levels of uncertainty (Carwardine et al., 2019). Actions with direct benefits for climate mitigation, such as avoided CO_2 emissions from habitat protection and long-term sequestration resulting from restoration activities (Drever et al., 2021; Duncanson et al., 2023), were identified and only actions with sufficient geospatial data to refine target areas were assessed. For habitat protection, we calculated potential avoided CO_2 emissions from future land use conversion using a national carbon dataset (Sothe et al., 2022). In the case of restoration, we adapted the approach used in Currie et al. (2023) to estimate the net restorable carbon for target restoration areas, with higher priority applied towards areas used by species of conservation concern considered in the PTM. For a detailed description of the carbon co-benefits analysis and results for specific actions, see Supporting Information, Appendix C.

RESULTS

Expected benefits of management strategies

Under the baseline scenario of “business-as-usual”, 15 of the 16 species groups in the region were expected to have less than 60% probability of functional persistence by 2050 (Fig 2). Only the working landscapes species group, consisting of three species, was predicted to be secure under the baseline scenario with a probability of persistence greater than or equal to 60%. In contrast, if all strategies were to be implemented (i.e., S15), all but the cisco species group were predicted to have greater than 50% probability of persistence and 12 species groups were expected to have a probability of persistence of 60% or higher (Fig 2). None of the species groups were expected to reach a 70% probability of persistence, although the working landscapes species group comes close with a 69% probability of persistence under strategy S15.

Of the individual management strategies, restoration and regeneration (S7) could secure the most species groups (four groups) up to the 60% threshold, while landowner stewardship (S2) was predicted to secure three species groups (Table 2). Overall, strategies S7 and S2 had the highest expected benefits relative to the baseline for all but four species groups (alvar, riverine, turtle, and bat species groups). The alvar species group was expected to benefit most from legislation and policy (S3) or protecting habitat (S4), while riverine and turtle species groups were both expected to benefit most from wildlife-safe crossings (S5). For bats, invasive species and disease management (S6) were expected to be the most beneficial individual strategy.

Of the combined strategies, the combination of all individual strategies (S15) had the highest expected benefit across all species groups (Table 1) and was expected to secure the most species groups (Table 3) but was also estimated to be the most expensive to implement, with an estimated present value (PV) cost of $2.1 billion over 27 years, or $113 million per year in annualized values (Table 1). Combination strategy S11—a combination of strategies S2, S4, and S7—was estimated to be $300 million cheaper (or $16.3 million per year cheaper) than strategy S15, to have the second highest expected benefit (Table 1), and to secure up to 10 species groups (Table 3).

Cost-effective and complementary strategies

The single most cost-effective individual strategy was legislation and policy (S3), followed by human-wildlife management (S1) and industry-targeted policy and practices (S8) (Table 1). The high cost-effectiveness scores for these three strategies were largely driven by their costs—at $27 million, $29 million, and $58 million, respectively, these strategies were estimated to be the least expensive to implement. However, they were expected to have low to moderate expected benefit across all species groups (Table 1) and were not expected to secure any additional species groups to ≥60% probability of persistence beyond what would already be considered secure under the baseline scenario (Table 2). In addition, there are likely additional costs for implementing proposed legislation and policy changes in strategy S3 that were not accounted for in the cost estimates due to the high degree of uncertainty regarding those costs.

The complementarity analysis identified the best sets of strategies for 'securing' the most species groups to at least a 60% probability of persistence for different levels of investment. For lower levels of investment, strategy S5 would be the optimal strategy at a cost of $5 million per year over 27 years (Fig 3), securing the snakes and lizards group in addition to the working landscapes species group that was expected to remain secure under the baseline scenario (Table 3). Given a slightly higher budget of $5.5 million per year, however, it would be optimal to invest instead in strategy S2 (Fig 3), which would secure the artificial structure-dependent and the naturalized open habitat species groups in addition to the working landscapes species group (Table 3). With higher levels of investment, combination strategy S11 would help secure 10 species groups at a cost of $97 million per year over 27 years (Fig 3). Securing additional species groups would require investing $113 million per year to implement strategy S15 (Fig 3). Doing so would help secure 12 out of the 16 species groups (comprising 100 out of the 133 species of conservation concern) in the region (Table 3).

Most of the Pareto-optimal solutions that could maximize the number of species groups secured for the least cost were also expected to maximize the number of species groups that gain >15% in probability of persistence (Fig 3 and Supporting Information Appendix B). In particular, under combination strategy S11, the turtle species group had an expected probability of persistence of 55%, which is below the 60% threshold but still represents a gain of 16% relative to the baseline scenario (Table 2). Similarly, although neither the turtle nor bat species groups were expected to achieve a 60% probability of persistence under combination strategy S15, the expected benefits of S15 for both groups were >15% (Table 2, Supporting Information Fig B-1).

Carbon co-benefits

Of the 48 actions considered in this PTM assessment, only seven actions had direct and quantifiable carbon benefits. Of these, data to calculate carbon co-benefits were available for only four actions: 1) protecting 10% of the ecoregion (S4); 2) restoring 1% of shoreline area (S7); 3) restoring 50 km^2 of wetland and 25 km^2 of areas connecting wetlands (S7); and 4) restoring 1200 km^2 of forest transition zones (S7). We found that protecting habitat (S4) has direct carbon co-benefits equivalent to 11.2 Mt of avoided CO_2 emissions while restoration and regeneration (S7) has direct carbon co-benefits equivalent to 137.6 Mt of CO_2 sequestration (Table 4, Supporting Information Appendix C).

DISCUSSION

Our analysis revealed that without additional investment in conservation, 15 species groups, or 130 out of the 133 species of conservation concern in the Lake Simcoe-Rideau ecoregion, will have <60% probability of persisting with viable, self-sustaining populations that continue to perform their ecological function (i.e., functional persistence) by 2050. Investing $97 million per year over 27 years in the combination of landowner stewardship (S2), protecting habitat (S4), and restoration and regeneration (S7) strategies (i.e., S11) could help secure 10 species groups (88 species) with ≥60% probability of persistence, while implementing the combination of all proposed management strategies (i.e., S15) for $113 million per year could secure 12 species groups (100 species).

However, even with this level of investment, none of the species groups were expected to have ≥70% probability of persistence. The low estimates of the probability of persistence for species of conservation concern in the ecoregion reflect the high level of threats in the area, and are comparable to those for the Fraser River Estuary, British Columbia, Canada (Kehoe et al., 2021)—an area also characterized by high human footprint (Hirsh-Pearson et al., 2022) and high levels of threat from competing demands for space and resources (Kraus & Hebb, 2020). The low expected probabilities of persistence may also be indicative of the inherent difficulty in recovering species that are already at a high risk of extinction, and the current lack of effective management options that adequately address the impact of key historical and ongoing threats to these species groups. For example, the poor status and low potential for recovery of the cisco group, which consists of two cisco species, has been attributed to historical overexploitation and more recent threats of habitat degradation and introduced species (COSEWIC, 2003; Fisheries and Oceans Canada, 2012). Similarly, the four species in the bat group are endangered due to the threat of white-nose syndrome, a rapidly spreading infectious disease that causes mass mortality and for which prevention and treatment has proven challenging (Cheng et al., 2021; Grider et al., 2022).

Uncertainties surrounding the potential impacts of recent policy and legislative changes in Ontario could also have influenced estimates of the expected probability of persistence of species groups. Beginning in 2019, the Ontario provincial government introduced significant changes to the Endangered Species Act (ESA), which led to the delisting of many species at risk and the weakening of previously strong protections under this legislation (Bethlenfalvy & Olive, 2021; Olive & Penton, 2018). More recently, the provincial government introduced Bill 23, the "More Homes Built Faster Act", which made substantial changes to environmental and biodiversity protections in Ontario. Experts noted that these changes to policy and legislation will likely lead to further exacerbation of environmental challenges and greater difficulty in implementing conservation actions, resulting in wide-ranging implications for biodiversity.

These recent changes to environmental and conservation policy were also met with controversy (Jones, 2022; SpearChief-Morris, 2022), fueled partly by Canada's colonial legacy and the provincial government's largely unsuccessful efforts to engage meaningfully and work with Indigenous groups on environmental policy and conservation initiatives (McIntosh, 2023). Indigenous groups in the region were invited to engage with and participate in the PTM assessment, however, many expressed reluctance to participate in the process, in part due to the lack of clarity regarding the views held by participating experts from government agencies about Indigenous-led conservation. For conservation to be successful and grounded in just approaches, it is necessary to ensure that there is engagement, consent and collaboration with the First Nations and Métis communities in the region (Seddon et al., 2021). It is therefore crucial to meaningfully engage and consult with Indigenous groups prior to and throughout the process of implementing the selected priority strategies (Townsend et al., 2020). Future applications of PTM in this region and elsewhere should also allow for sufficient time and resources to build trust and develop relationships with Indigenous groups in the region, and to ensure that the process is inclusive, trauma-informed, and grounded in the principles of respect and reciprocity (Adams et al., 2023).

The complementarity analysis identifies multiple Pareto optimal solutions, representing the trade-off between maximizing benefit and minimizing costs. Choosing a solution that also contributes to other targets, such as the 30% by 2030 protected area and restoration targets of the GBF or national climate change mitigation targets, could further increase the total benefits gained and help secure additional funding and resources for conservation action. In this PTM assessment, protecting habitat (S4) and restoration and regeneration (S7) include actions that have potential direct carbon co-benefits of at least 11.2 Mt CO_2 equivalent in avoided emissions and 137.6 Mt CO_2 emissions equivalent in sequestered carbon, respectively (Supporting Information, Appendix C) and thus could be considered as nature-based climate solutions (NbCS). The potential carbon-co-benefits of S4 and S7 combined could, over time, make up for all of Ontario's greenhouse gas emissions in 2021 (Environment and Climate Change Canada, 2023a). Choosing a solution that includes one or both strategies would help support alignment with climate change mitigation targets, delivering co-benefits that may further justify investment and improve the likelihood of securing additional funding for implementation. Other actions considered in the PTM may also have carbon co-benefits that we were unable to quantify due to their indirect nature, limited data availability, or lack of specificity regarding where, when, and how the action will be implemented.

Many of the actions suggested by experts may also have co-benefits for other environmental and social objectives. For instance, the water quality in the ecoregion could be improved directly by implementing wastewater treatment (S2) or water allocation (S3) actions (Buttle, 2011). The implementation of actions in urban areas (S7), or in recreational activity hotspots (S6) can contribute to long-term urban regeneration, recreation, and overall human and cultural wellbeing (Colléony & Shwartz, 2019). Finally, co-benefits can be generated through the creation of jobs (Gómez Martín et al., 2020; Raymond et al., 2017). Demonstrating and, where possible, quantifying these co-benefits can further support the business case for financing biodiversity conservation, and thus improve the likelihood of uptake and successful implementation.

CONCLUSION

Our analysis revealed that considerable additional investment—$2.1 billion over 27 years—is required to safeguard the future of species of conservation concern in the Lake Simcoe-Rideau ecoregion, Ontario. By estimating the costs and expected benefits of different combinations of strategies, PTM can help maximize the return on investment and make the business case for conservation, which can lead to increased investment and positive outcomes for biodiversity. Identifying and implementing actions with co-benefits for climate change mitigation or other environmental or social objectives can further maximize the return on investment in conservation actions, help secure additional funding for implementation, and contribute to Canada's efforts to meet its commitments to the CBD's Global Biodiversity Framework.

AUTHOR CONTRIBUTIONS

AEC and TGM helped develop the data collection methods and analysis used in this study. EG was responsible for recruiting expert participants and organizing workshops, and AI conducted literature reviews, prepared elicitation materials, and conducted data analysis. AEC also provided technical advice and assistance with workshop organization and data analysis. AEC, AI, EG, BF, JC, and CP facilitated expert elicitation workshops. CL and JC conducted the carbon co-benefits analysis, with assistance and advice from VH, AEC, and TGM. KIA, JL, SM, TM, DRN, MACP, RHMR, FWS, and LT contributed data used in this study. All authors contributed to writing and reviewing the manuscript.

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CONFLICT OF INTEREST STATEMENT

The authors declare that they have no conflicts of interest.

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TABLES

Table 1 Candidate management strategies for the Lake Simcoe-Rideau ecoregion and their estimated benefits, feasibility, costs, and cost-effectiveness (CE) scores. Total costs are in present values, calculated using a 3% discount rate per year over the 27-year time period.

Individual strategies		Number of actions	Total Benefit	Feasibility	Total Expected Benefit	Total Cost (million CA$)	Annualized Cost (million CA$)	CE score	CE rank
S1	Human-wildlife management	6	1029.68	0.55	566.32	28.63	1.56	19.78	2
S2	Landowner stewardship	4	1742.55	0.65	1132.66	100.97	5.51	11.22	4
S3	Legislation and policy	6	2262.89	0.42	950.41	27.48	1.50	34.59	1
S4	Protecting habitat	5	1962.82	0.51	1001.04	1461.94	79.77	0.68	15
S5	Wildlife-safe crossings	4	996.68	0.67	667.77	88.51	4.83	7.54	6
S6	Invasive species and diseases management	7	1546.27	0.44	680.36	96.34	5.26	7.06	7
S7	Restoration and regeneration	8	2212.40	0.62	1371.69	216.58	11.82	6.33	8
S8	Industry-targeted policy and practices	8	1562.47	0.60	937.48	57.63	3.14	16.27	3
Combination strategies									
S9	S5 + S7	12	2331.24	0.64	1492.00	305.09	16.65	4.89	10
S10	S7 + S4	13	2797.16	0.57	1594.38	1678.53	91.59	0.95	13
S11	S7 + S4 + S2	17	3206.14	0.59	1891.62	1779.49	97.10	1.06	11
S12	S3 + S4	11	2774.09	0.47	1303.82	1489.42	81.27	0.88	14
S13	S1 + S7	14	2274.43	0.58	1319.17	245.21	13.38	5.38	9
S14	S2 + S8 + S3	18	2818.12	0.56	1578.15	186.07	10.15	8.48	5
S15	All strategies (S1-S8)	48	3838.57	0.56	2149.60	2078.07	113.39	1.03	12

Table 2 Expected probability of persistence (%) of species groups in the Lake Simcoe-Rideau ecoregion over 27 years under the Baseline scenario (business-as-usual; no additional management) and under each individual and combination strategy.

		Base-line	Individual strategies								Combination strategies						
	Species groups		**S1**	**S2**	**S3**	**S4**	**S5**	**S6**	**S7**	**S8**	**S9**	**S10**	**S11**	**S12**	**S13**	**S14**	**S15**
Expected probability of persistence of species groups	*Alvar species*	40	42	49	51	50	40	43	48	47	49	58	63	57	49	59	64
	Artificial structure-dependent species	48	48	60	53	49	48	48	59	52	60	59	62	55	59	61	63
	Bats	38	39	46	43	43	38	48	43	40	43	46	49	46	44	47	54
	Forest species	45	54	59	55	55	47	54	62	58	62	64	66	59	62	63	66
	Mixed forest species	48	56	55	54	55	52	51	58	55	59	60	62	58	60	60	63
	Ciscoes	39	39	39	42	40	40	42	39	41	40	40	40	43	40	45	46
	Mussels	47	48	53	51	50	52	54	51	54	54	53	55	53	53	58	60
	Naturalized open habitat species	48	53	60	56	57	51	54	59	57	59	63	65	59	60	61	66
	Oak savannah species	44	56	54	54	52	44	50	57	50	54	56	57	51	57	57	60
	Riparian species	48	50	53	54	56	48	51	59	52	57	59	60	55	57	56	62
	Riverine species	46	48	52	52	51	57	50	53	52	55	52	54	53	51	54	58
	Sandy species	50	56	58	57	60	50	55	64	56	61	63	65	59	62	59	65
	Snakes and lizards	51	54	57	57	58	62	54	62	56	63	59	61	57	59	58	63
	Turtles	39	45	48	48	48	57	44	52	45	56	52	55	49	51	50	58
	Wetland species	46	50	53	54	56	50	50	57	52	57	60	61	57	55	58	63
	Working landscapes species	61	61	68	64	62	61	62	66	65	65	65	67	64	65	68	69
# groups secured to ≥60%		1	1	3	1	2	2	1	4	1	5	6	10	1	5	5	12

Table 3 Species groups that could be secure with ≥60% probability of persistence over 27 years under the Baseline scenario and under each optimal set of management strategies. Total costs have been discounted to present values at a rate of 3% and annualized to derive an average cost per year.

Species groups	Number of species in group	Baseline scenario	Optimal strategies						
			S5	S2	S14	S5 + S14	S7 + S14	S11	S15
Turtles	8								
Riverine species	19								
Ciscoes	2								
Mussels	10								✓
Oak savannah species	2								✓
Riparian species	3							✓	✓
Alvar species	8							✓	✓
Wetland species	18							✓	✓
Sandy species	7						✓	✓	✓
Bats	4								
Mixed forest species	6				✓	✓	✓	✓	✓
Forest species	19				✓	✓	✓	✓	✓
Artificial structure-dependent species	3			✓	✓	✓	✓	✓	✓
Naturalized open habitat species	12			✓	✓	✓	✓	✓	✓
Snakes and lizards	9		✓			✓	✓	✓	✓
Working landscapes species	3	✓	✓	✓	✓	✓	✓	✓	✓
Number of species groups secured:		1	2	3	5	6	7	10	12
Annualized cost (million CAD):		0.0	4.8	5.5	10.2	15.0	22.0	97.1	113.4

Table 4 Potential carbon co-benefits, in megatonnes (Mt) of carbon (C) or carbon dioxide emissions equivalent (CO_2e), of actions in the protecting habitat (S4) and restoration and regeneration (S7) strategies in the PTM with direct and quantifiable carbon benefits.

Strategy	Action	Total area (km^2)	Average carbon density (kg/m^2)	Area of avoided land conversion (km^2)	Avoided C release (Mt)	Avoided CO_2e release (Mt)	Restorable C (Mt)	Restorable CO_2e (Mt)
S4	Protect 10% of priority areas	6392.53	27.82	109.83	3.06	11.2	-	-
S7	Restore 1% of shorelines	47.55	28.01	-	-	-	1.33	4.88
	Restore 50 km^2 of wetland and 25 km^2 of areas connecting wetlands	75	33.86	-	-	-	2.54	9.31
	Restore 1200 km^2 of forest transition areas	1200	27.82	-	-	-	33.65	123.38
Total					3.06	11.2	40.58	148.77

FIGURES

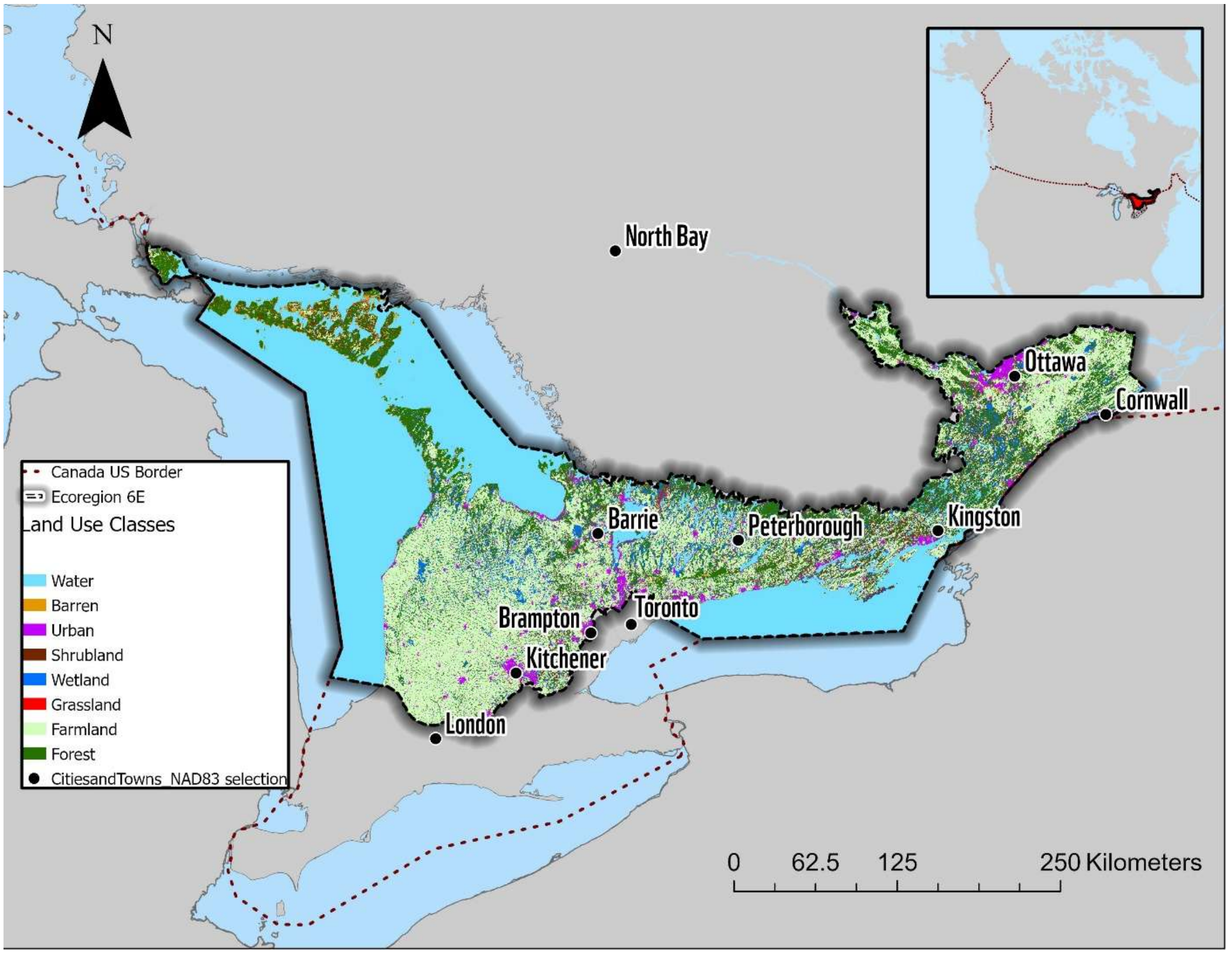

Figure 1 The Lake Simcoe-Rideau ecoregion (Ontario Provincial Ecoregion 6E) of southern Ontario, Canada. Data layers: Ecoregion 6E – Ontario GeoHub, Ontario Ministry of Natural Resources and Forestry. *EcoRegion* [Data set]. 2023. Land Information Ontario; https://geohub.lio.gov.on.ca/datasets/lio::ecoregion/about. Land Use Classes – Agriculture and Agri-Food Canada. *Annual Space-Based Crop Inventory for Canada, 2020* [Data set]. 2020. Agroclimate, Geomatics and Earth Observation Division, Science and Technology Branch; https://open.canada.ca/data/en/dataset/32546f7b-55c2-481e-b300-83fc16054b95.

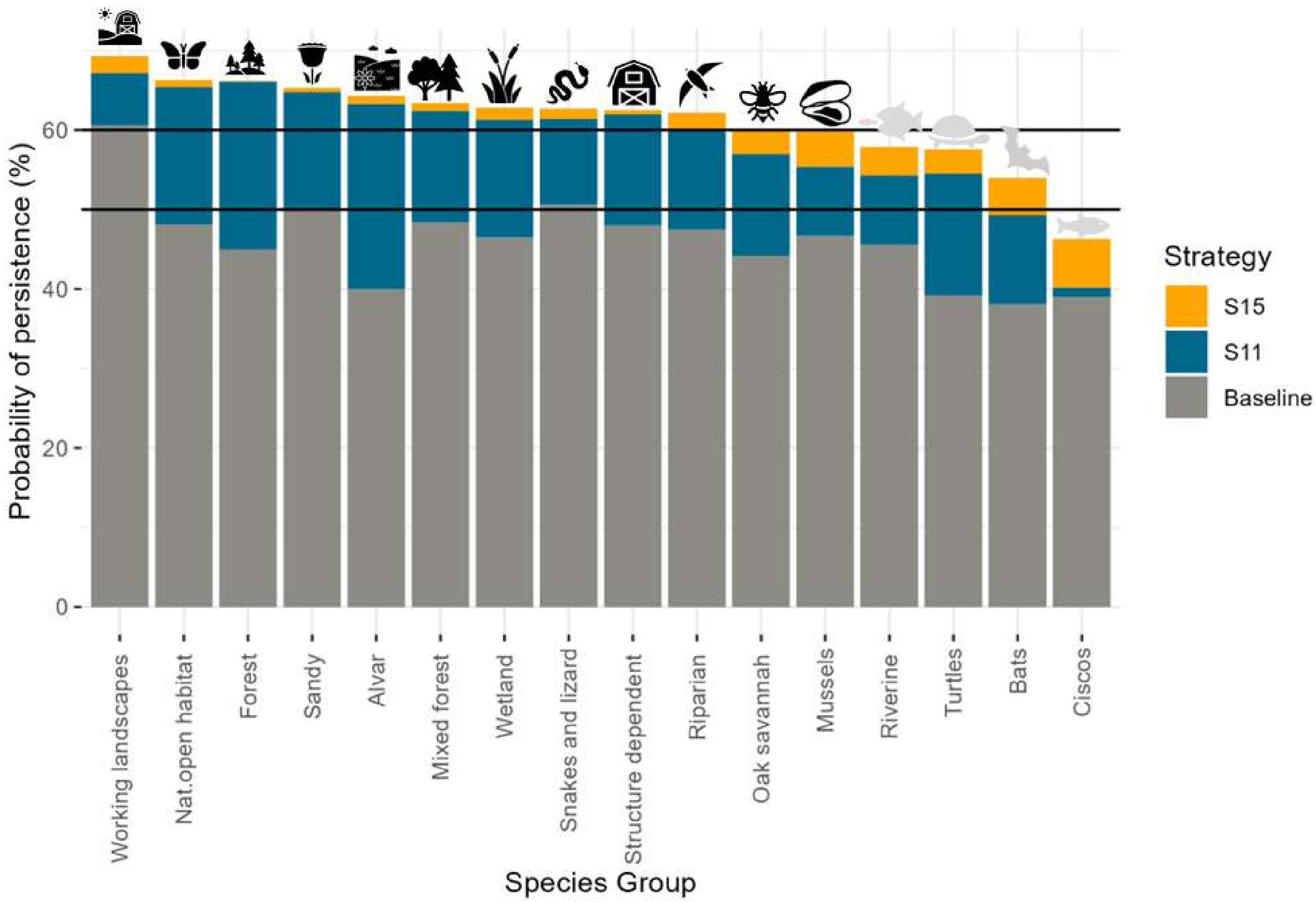

Figure 2 Expected probability of persistence of species groups in the Lake Simcoe-Rideau ecoregion over 27 years under the Baseline scenario (business-as-usual) and with implementation of either strategy S11 (combination of S2, S4, and S7) or S15 (combination of all strategies, S1 to S8).

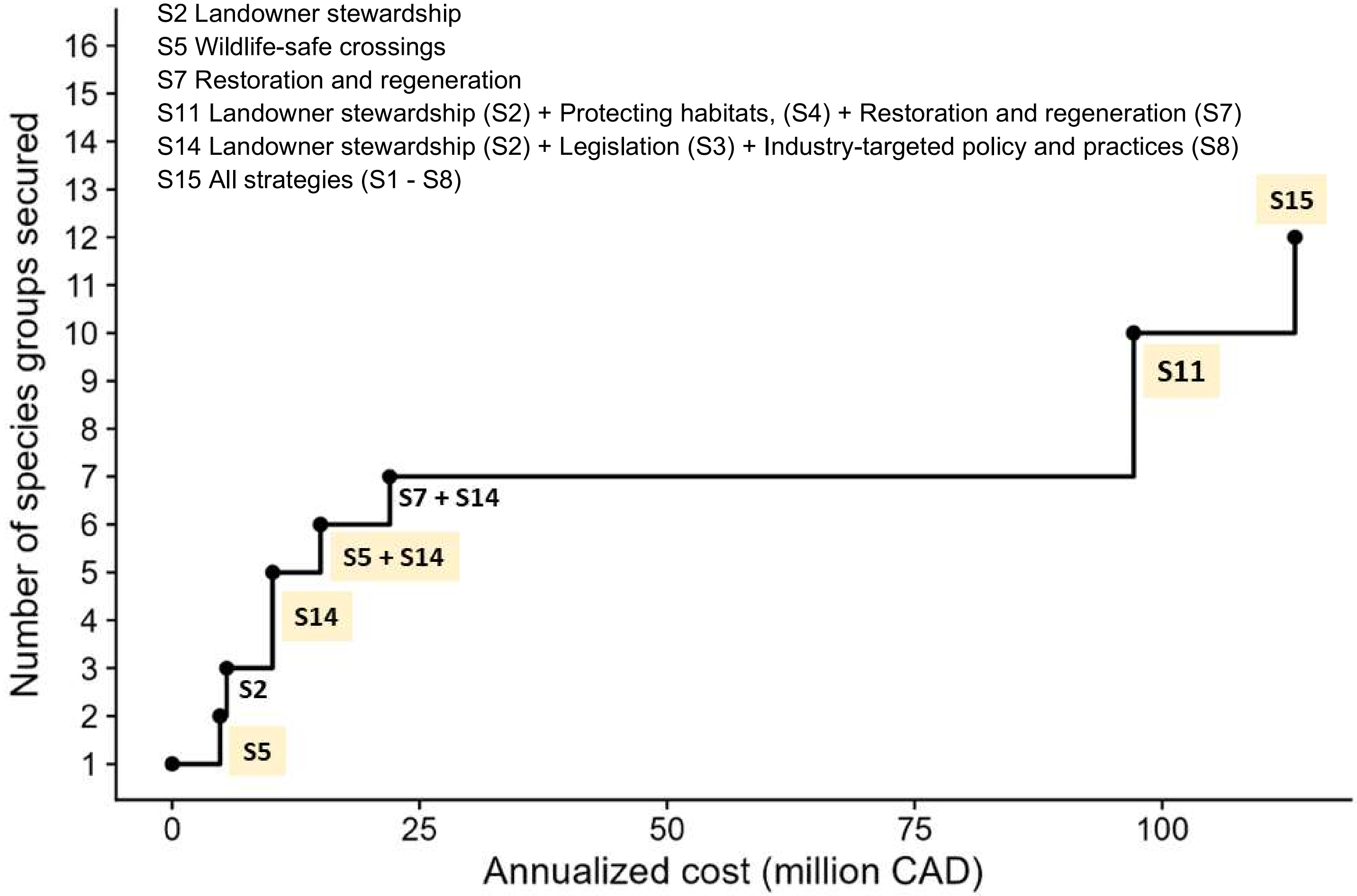

Figure 3 Pareto front indicating the number of species groups that could be secured to at least a 60% probability of persistence by different Pareto optimal solutions (represented by the black dots along the line). Highlighted solutions indicate strategies that were also optimal when maximizing the number of species groups that would experience ≥15% benefit. Annualized costs are based on the total costs discounted by a rate of 3%.

SUPPORTING INFORMATION

Appendix A Data Tables

Table A-1 *Species of conservation concern in the Lake Simcoe-Rideau ecoregion, grouped into 16 species groups based on similarity in responses to threats and management actions.*

COMMON NAME	SCIENTIFIC NAME	POPULATION	TAXON	COSEWIC[1] ASSESSMENT	SARA[2] STATUS	ONTARIO ESA[3] STATUS
Alvar/rock barren/shield habitat species						
Common Nighthawk	*Chordeiles minor*		Birds	Special Concern	Threatened	Special concern
Eastern Whip-poor-will	*Antrostomus vociferus*		Birds	Threatened	Threatened	Threatened
Loggerhead Shrike Eastern ssp.	*Lanius ludovicianus ssp.*		Birds	Endangered	Endangered	Endangered
Dwarf Lake Iris	*Iris lacustris*		Vascular Plants	Special Concern	Special Concern	Special concern
Gattinger's Agalinis	*Agalinis gattingeri*		Vascular Plants	Endangered	Endangered	Endangered
Houghton's Goldenrod	*Solidago houghtonii*		Vascular Plants	Special Concern	Special Concern	Threatened
Juniper Sedge	*Carex juniperorum*		Vascular Plants	Endangered	Endangered	Endangered
Lakeside Daisy	*Tetraneuris herbacea*		Vascular Plants	Special Concern	Threatened	Threatened
Artificial/man-made structure-dependent species						
Barn Owl	*Tyto alba*	Eastern	Birds	Endangered	Endangered	Endangered
Barn Swallow	*Hirundo rustica*		Birds	Special Concern	Threatened	Threatened
Chimney Swift	*Chaetura pelagica*		Birds	Threatened	Threatened	Threatened
Bats						
Eastern Small-footed Myotis	*Myotis leibii*		Mammals	Not at Risk	No Status	Endangered
Little Brown Myotis	*Myotis lucifugus*		Mammals	Endangered	Endangered	Endangered
Northern Myotis	*Myotis septentrionalis*		Mammals	Endangered	Endangered	Endangered
Tri-colored Bat	*Perimyotis subflavus*		Mammals	Endangered	Endangered	Endangered

COMMON NAME	SCIENTIFIC NAME	POPULATION	TAXON	COSEWIC[1] ASSESSMENT	SARA[2] STATUS	ONTARIO ESA[3] STATUS
Forest species						
Jefferson Salamander	*Ambystoma jeffersonianum*		Amphibians	Endangered	Endangered	Endangered
Unisexual Ambystoma	*Ambystoma laterale - (2) jeffersonianum*	Jefferson Salamander dependent	Amphibians	Endangered	Endangered	Endangered
West Virginia White	*Pieris virginiensis*		Arthropods	Not at Risk	Special Concern	Special concern
Acadian Flycatcher	*Empidonax virescens*		Birds	Endangered	Endangered	Endangered
Canada Warbler	*Cardellina canadensis*		Birds	Special Concern	Threatened	Special concern
Cerulean Warbler	*Setophaga cerulea*		Birds	Endangered	Endangered	Threatened
Golden-winged Warbler	*Vermivora chrysoptera*		Birds	Threatened	Threatened	Special concern
Kirtland's Warbler	*Setophaga kirtlandii*		Birds	Endangered	Endangered	Endangered
Olive-sided Flycatcher	*Contopus cooperi*		Birds	Special Concern	Threatened	Special concern
Wood Thrush	*Hylocichla mustelina*		Birds	Threatened	Threatened	Special concern
Pale-bellied Frost Lichen	*Physconia subpallida*		Lichens	Endangered	Endangered	Endangered
Gray Fox	*Urocyon cinereoargenteus*		Mammals	Threatened	Threatened	Threatened
American Ginseng	*Panax quinquefolius*		Vascular Plants	Endangered	Endangered	Endangered
Blunt-lobed Woodsia	*Woodsia obtusa*		Vascular Plants	Threatened	Threatened	Endangered
Broad Beech Fern	*Phegopteris hexagonoptera*		Vascular Plants	Special Concern	No Status	Special concern
Butternut	*Juglans cinerea*		Vascular Plants	Endangered	Endangered	Endangered
Goldenseal	*Hydrastis canadensis*		Vascular Plants	Special Concern	Threatened	Special concern
Green dragon	*Arisaema dracontium*		Vascular Plants	Special Concern	No Status	Special concern
Hart's-tongue Fern	*Asplenium scolopendrium*		Vascular Plants	Special Concern	Special Concern	Special concern
Lake species						
Shortjaw Cisco	*Coregonus zenithicus*		Fishes	Threatened	Threatened	Threatened
Shortnose Cisco	*Coregonus reighardi*		Fishes	Endangered	Endangered	Endangered
Mixed forest species						
Eastern Wood-pewee	*Contopus virens*		Birds	Special Concern	Special Concern	Special concern
Red-headed Woodpecker	*Melanerpes erythrocephalus*		Birds	Endangered	Endangered	Endangered
Black Bear	*Ursus americanus*		Mammals	Not at Risk	No Status	No Status
Eastern/Algonquin Wolf	*Canis sp. cf. lycaon*		Mammals	Threatened	Special Concern	Threatened
Four-leaved Milkweed	*Asclepias quadrifolia*		Vascular Plants	Endangered	No Status	Endangered
Spotted Wintergreen	*Chimaphila maculata*		Vascular Plants	Threatened	Threatened	Threatened

COMMON NAME	SCIENTIFIC NAME	POPULATION	TAXON	COSEWIC[1] ASSESSMENT	SARA[2] STATUS	ONTARIO ESA[3] STATUS
Molluscs						
Eastern Pondmussel	*Sagittunio nasutus*		Molluscs	Special Concern	Special Concern	Special concern
Hickorynut	*Obovaria olivaria*		Molluscs	Endangered	Endangered	Endangered
Kidneyshell	*Ptychobranchus fasciolaris*		Molluscs	Endangered	Endangered	Endangered
Mapleleaf	*Quadrula quadrula*	Great Lakes–Upper St. Lawrence	Molluscs	Special Concern	Special Concern	Special concern
Northern Riffleshell	*Epioblasma torulosa rangiana*		Molluscs	Endangered	Endangered	Endangered
Rainbow Mollusc	*Villosa iris*		Molluscs	Special Concern	Special Concern	Special concern
Rayed Bean	*Paetulunio fabalis*		Molluscs	Endangered	Endangered	Endangered
Round Pigtoe	*Pleurobema sintoxia*		Molluscs	Endangered	Endangered	Endangered
Snuffbox	*Epioblasma triquetra*		Molluscs	Endangered	Endangered	Endangered
Wavy-rayed Lampmussel	*Lampsilis fasciola*		Molluscs	Special Concern	Special Concern	Threatened
Naturalized open habitat (tall-grass prairie; open meadow) species						
American Bumble Bee	*Bombus pensylvanicus*		Arthropods	Special Concern	No Status	No Status
Gypsy Cuckoo Bumble Bee	*Bombus bohemicus*		Arthropods	Endangered	Endangered	Endangered
Monarch	*Danaus plexippus*		Arthropods	Endangered	Special Concern	Special concern
Red-tailed Leafhopper	*Aflexia rubranura*	Great Lakes Plains	Arthropods	Special Concern	Special Concern	Special concern
Yellow-banded Bumble Bee	*Bombus terricola*		Arthropods	Special Concern	Special Concern	Special concern
Grasshopper Sparrow, *pratensis* ssp.	*Ammodramus savannarum pratensis*		Birds	Special Concern	Special Concern	Special concern
Henslow's Sparrow	*Ammodramus henslowii*		Birds	Endangered	Endangered	Endangered
Short-eared Owl	*Asio flammeus*		Birds	Threatened	Special Concern	Special concern
Yellow-breasted Chat *virens* ssp.	*Icteria virens virens*		Birds	Endangered	Endangered	Endangered
American Badger *jacksoni* ssp.	*Taxidea taxus jacksoni*		Mammals	Endangered	Endangered	Endangered
Forked Three-awned Grass	*Aristida basiramea*		Vascular Plants	Endangered	Endangered	Endangered
Hairy Valerian	*Valeriana edulis ssp. ciliata*		Vascular Plants	Endangered	No Status	Threatened
Oak savannah species						
Mottled Duskywing	*Erynnis martialis*	Great Lakes Plains	Arthropods	Endangered	No Status	Endangered
Rusty-patched Bumble Bee	*Bombus affinis*		Arthropods	Endangered	Endangered	Endangered

COMMON NAME	SCIENTIFIC NAME	POPULATION	TAXON	COSEWIC[1] ASSESSMENT	SARA[2] STATUS	ONTARIO ESA[3] STATUS
Riparian species						
Macropis Cuckoo Bee	*Epeoloides pilosulus*		Arthropods	Endangered	Endangered	No Status
Bank Swallow	*Riparia riparia*		Birds	Threatened	Threatened	Threatened
Provancher's Fleabane	*Erigeron philadelphicus var. provancheri*		Vascular Plants	Special Concern	No Status	No Status
Riverine species						
Hungerford's Crawling Water Beetle	*Brychius hungerfordi*		Arthropods	Endangered	Endangered	Endangered
Rapids Clubtail	*Phanogomphus quadricolor*		Arthropods	Endangered	Endangered	Endangered
American Eel	*Anguilla rostrata*		Fishes	Threatened	No Status	Endangered
Black Redhorse	*Moxostoma duquesnei*		Fishes	Threatened	Threatened	Threatened
Bridle Shiner	*Notropis bifrenatus*		Fishes	Special Concern	Special Concern	Special concern
Brook Trout	*Salvelinus fontinalis*		Fishes	Not yet assessed	No Status	No Status
Channel Darter	*Percina copelandi*	Lake Ontario	Fishes	Endangered	Endangered	Special concern
Cutlip Minnow	*Exoglossum maxillingua*		Fishes	Special Concern	Special Concern	Threatened
Eastern Sand Darter	*Ammocrypta pellucida*	Ontario	Fishes	Threatened	Threatened	Endangered
Grass Pickerel	*Esox americanus vermiculatus*		Fishes	Special Concern	Special Concern	Special concern
Lake Sturgeon	*Acipenser fulvescens*	Great Lakes-Upper St. Lawrence	Fishes	Threatened	No Status	Endangered
Northern Brook Lamprey	*Ichthyomyzon fossor*	Great Lakes-Upper St. Lawrence	Fishes	Special Concern	Special Concern	Special concern
Northern Sunfish	*Lepomis peltastes*	Great Lakes-Upper St. Lawrence	Fishes	Special Concern	Special Concern	Special concern
Pugnose Shiner	*Notropis anogenus*		Fishes	Threatened	Threatened	Threatened
Redside Dace	*Clinostomus elongatus*		Fishes	Endangered	Endangered	Endangered
River Redhorse	*Moxostoma carinatum*		Fishes	Special Concern	Special Concern	Special concern
Silver Lamprey	*Ichthyomyzon unicuspis*	Great Lakes-Upper St. Lawrence	Fishes	Special Concern	Special Concern	Special concern
Silver Shiner	*Notropis photogenis*		Fishes	Threatened	Threatened	Threatened
Ogden's Pondweed	*Potamogeton ogdenii*		Vascular Plants	Endangered	Endangered	Endangered

COMMON NAME	SCIENTIFIC NAME	POPULATION	TAXON	COSEWIC[1] ASSESSMENT	SARA[2] STATUS	ONTARIO ESA[3] STATUS
Sandy habitat species						
Piping Plover	*Charadrius melodus circumcinctus*		Birds	Endangered	Endangered	Endangered
Deerberry	*Vaccinium stamineum*		Vascular Plants	Threatened	Threatened	Threatened
Dwarf Hackberry	*Celtis tenuifolia*		Vascular Plants	Threatened	Threatened	Threatened
Gillman's Goldenrod	*Solidago gillmanii*		Vascular Plants	Endangered	No Status	Endangered
Hill's Thistle	*Cirsium hillii*		Vascular Plants	Threatened	Threatened	Threatened
Lowland Toothcup	*Rotala ramosior*	Great Lakes Plains	Vascular Plants	Threatened	Threatened	Endangered
Pitcher's Thistle	*Cirsium pitcheri*		Vascular Plants	Special Concern	Special Concern	Threatened
Snakes and Lizards						
Butler's Gartersnake	*Thamnophis butleri*		Reptiles	Endangered	Endangered	Endangered
Common Five-lined Skink	*Plestiodon fasciatus*	Great Lakes/St. Lawrence	Reptiles	Special Concern	Special Concern	No Status
Eastern Foxsnake	*Pantherophis vulpinus*	Great Lakes/St. Lawrence	Reptiles	Threatened	Endangered	Threatened
Eastern Hognose Snake	*Heterodon platirhinos*		Reptiles	Threatened	Threatened	Threatened
Eastern Milksnake	*Lampropeltis triangulum*		Reptiles	Special Concern	Special Concern	No Status
Eastern Ribbonsnake	*Thamnophis sauritus*	Great Lakes population	Reptiles	Special Concern	Special Concern	Special concern
Gray Ratsnake	*Pantherophis spiloides*	Great Lakes/St. Lawrence	Reptiles	Threatened	Threatened	No Status
Massasauga	*Sistrurus catenatus*	Great Lakes/St. Lawrence	Reptiles	Threatened	Threatened	Threatened
Queensnake	*Regina septemvittata*		Reptiles	Endangered	Endangered	Endangered
Turtles						
Blanding's Turtle	*Emydoidea blandingii*	Great Lakes/St. Lawrence	Reptiles	Endangered	Endangered	Threatened
Eastern Musk Turtle	*Sternotherus odoratus*		Reptiles	Special Concern	Special Concern	Special concern
Midland Painted Turtle	*Chrysemys picta marginata*		Reptiles	Special Concern	Special Concern	No Status
Northern Map Turtle	*Graptemys geographica*		Reptiles	Special Concern	Special Concern	Special concern
Snapping Turtle	*Chelydra serpentina*		Reptiles	Special Concern	Special Concern	Special concern
Spiny Softshell	*Apalone spinifera*		Reptiles	Endangered	Endangered	Endangered
Spotted Turtle	*Clemmys guttata*		Reptiles	Endangered	Endangered	Endangered
Wood Turtle	*Glyptemys insculpta*		Reptiles	Threatened	Threatened	Endangered

COMMON NAME	SCIENTIFIC NAME	POPULATION	TAXON	COSEWIC[1] ASSESSMENT	SARA[2] STATUS	ONTARIO ESA[3] STATUS
Wetland species						
Western Chorus Frog	*Pseudacris triseriata*	Great Lakes/St. Lawrence-Canadian Shield	Amphibians	Threatened	Threatened	No Status
Bogbean Buckmoth	*Hemileuca sp.*		Arthropods	Endangered	Endangered	Endangered
Hine's Emerald	*Somatochlora hineana*		Arthropods	Endangered	Endangered	Endangered
Black Tern	*Chlidonias niger*		Birds	Not at Risk	No Status	Special concern
King Rail	*Rallus elegans*		Birds	Endangered	Endangered	Endangered
Least Bittern	*Ixobrychus exilis*		Birds	Threatened	Threatened	Threatened
Louisiana Waterthrush	*Parkesia motacilla*		Birds	Threatened	Threatened	Threatened
Prothonotary Warbler	*Protonotaria citrea*		Birds	Endangered	Endangered	Endangered
Rusty Blackbird	*Euphagus carolinus*		Birds	Special Concern	Special Concern	Special concern
Yellow Rail	*Coturnicops noveboracensis*		Birds	Special Concern	Special Concern	Special concern
Spotted Gar	*Lepisosteus oculatus*		Fishes	Endangered	Endangered	Endangered
American Water-willow	*Justicia americana*		Vascular Plants	Threatened	Threatened	Threatened
Black Ash	*Fraxinus nigra*		Vascular Plants	Threatened	No Status	Endangered
Eastern Prairie Fringed-orchid	*Platanthera leucophaea*		Vascular Plants	Endangered	Endangered	Endangered
Hill's Pondweed	*Potamogeton hillii*		Vascular Plants	Special Concern	Special Concern	Special concern
Small White Lady's-slipper	*Cypripedium candidum*		Vascular Plants	Threatened	Threatened	Endangered
Swamp Rose-mallow	*Hibiscus moscheutos*		Vascular Plants	Special Concern	Special Concern	Special concern
Tuberous Indian-plantain	*Arnoglossum plantagineum*		Vascular Plants	Special Concern	Special Concern	Special concern
Working landscape (Agriculture) species						
Bobolink	*Dolichonyx oryzivorus*		Birds	Threatened	Threatened	Threatened
Eastern Meadowlark	*Sturnella magna*		Birds	Threatened	Threatened	Threatened
Upland Sandpiper	*Bartramia longicauda*		Birds	Not at Risk	No Status	No Status

1 COSEWIC: Committee on the Status of Endangered Wildlife in Canada
2 SARA: Species at Risk Act
3 ESA: Endangered Species Act

Table A-2 *List of actions included in individual management strategies.*

		MANAGEMENT STRATEGIES AND ACTIONS
S1		*Wildlife Management*
	a	Research and provide education on ways to reduce human-wildlife coexistence to minimize wolf/bear decline.
	b	Coordinate a deer management program in partnership with local communities and First Nations in target areas to protect plant species/forest understory.
	c	Develop and implement a strategy to address illegal collection of herpetiles and fish.
	d	Education and outreach on managing turtle by-catch through recreational fishing.
	e	Partner with existing nurseries in the region to propagate endangered plant species and host plants for endangered insects.
	f	Create and maintain a captive rearing program for rusty-patched bumble bee.
S2		*Landowner stewardship*
	a	Review existing landowner BMPs and create new ones based on gaps, incorporating TEK where appropriate.
	b	Build relationships with landowners and landowner associations through engagement and stewardship activities.
	c	Provide funding for education and incentives for landowner action.
	d	Upgrade wastewater treatment plant infrastructure on rural properties.
S3		*Legislation and policy*
	a	Develop a SARA and Ontario ESA support fund.
	b	Improved land-use planning to ensure biodiversity recovery at the municipal level, including plans for naturalization.
	c	Advocate for stricter policy and regulation on neonics.
	d	Modify the Ontario Endangered Species Act (similar to alvar and tall grass prairie designations for MB Act) to incorporate ecosystem approaches, and advocate for substantive changes to better protect SAR.
	e	Address over-allocation of water resources through reviewing and improving legislation and policies regarding water consumption/removal (>10,000L) and licensing/permitting.
	f	Review and advocate for a strengthened Migratory Birds Act.
S4		*Protecting habitat*
	a	Protect 10% of habitat within the study region through a variety of protected and conserved area mechanisms including conservation easements and land acquisitions.
	b	Create, tighten/update and implement permits for recreational use of sandy and alvar habitats at the municipal and provincial level.
	c	Plan and alter trail networks to reduce impacts on sensitive areas (i.e., selection of trail sites, frequency, number, area) and sensitive times (breeding and nesting).
	d	Create, tighten/update and implement regulation for shoreline development of sandy and alvar habitats at the municipal and provincial level.
	e	Review and update wetland inventory to assess spatial distribution, quantity and size through research and use this information to guide policy changes to protect wetlands including re-invoking/strengthening Ontario Wetland Conservation Strategy.
S5		*Wildlife-safe crossing*
	a	Fix perched culverts to facilitate more seamless animal crossing (i.e., address hanging culverts for aquatic species).
	b	Identify key areas for replacing or installing wildlife-safe fences as well as installing ecopassages on roads, railways, and pathways.
	c	Address issues with dams.
	d	Addressing turbine mortality from large hydro dams for migratory fish species (focus on American eel) via an advocacy/awareness/lobbying campaign.

		MANAGEMENT STRATEGIES AND ACTIONS
S6		*Invasive species and disease management*
	a	Additional resourcing to support butternut canker research, recovery and BMPs, including the establishment of citizen science program to become a butternut assessor.
	b	Additional resourcing to support research on the distribution of bats, and mechanisms on the spread of WNS, as well as communication/outreach plan to prevent the spread of WNS and disturbance to bats.
	c	Additional staff capacity throughout the entire region to remove invasive species.
	d	Clean equipment to prevent invasive species through installation of clean equipment stations and enforcement officers.
	e	Mussel specific: Collaborate with the baitfish industry to reduce the impacts of commercial baitfishing on host species
	f	Conduct a review to understand what additional actions are required to address invasive species prevention and education. Where gaps are to be addressed, amplify and encourage more education components to make them more effective.
	g	Additional resourcing for invasive zebra and quagga mussel control to help restore Diporeia and Mysis, which are the most important prey supply for ciscoes in lakes.
S7		*Restoration and regeneration*
	a	Install nest boxes and provide education on artificial nesting structures for bats, birds, turtles and snakes.
	b	Restore and maintain 50km^2 (total) of both inland and coastal sand dunes.
	c	Naturalize and restore a total of 92.3km (1% of total shoreline in area) of riparian corridors and buffers and shorelines along water courses, with a specific focus on creating hibernacula for snakes.
	d	Restore 40km^2 grassland habitat.
	e	Restore 50km^2 of wetlands and 25km^2 for connectivity between existing wetlands, with a special focus on creating hibernacula for snakes.
	f	Expand and create seed nurseries for habitat restoration, specifically create a new nursery in eastern Ontario that specializes in Ecoregion 6 native plants.
	g	Improve urban habitat complexity and connectivity by planting pollinator gardens, shrubs and trees to provide suitable habitat throughout modified areas and improved connectivity and corridors for wildlife movement.
	h	Restore 1200km^2 of forest.
S8		*Industry-targeted policy and practices*
	a	Outreach and relationship building with industry (forestry, mining, quarrying, energy), stakeholders (CAs, ENGOs), and rightsholders by providing educational and communication materials around current BMPs.
	b	Enhance native planting through education and increasing capacity by providing incentives for nurseries to carry more native plant stock.
	c	Provide incentives to promote better conservation of forests.
	d	Create standards for effective stormwater ponds management and maintenance including creation and execution of BMPs.
	e	Apply and incentivize low-impact development to manage stormwater run-off in 10 priority areas.
	f	Review current dam BMPs and append standardized practices that will consider environmental priorities such as maintaining natural flow from dams that cannot be removed.
	g	Update current BMPS and promote best practices and collaborate with industry leaders to address impact of water quality specifically for mussels.
	h	Reduce window strikes for birds by educating and enforcing current BMPs for new builds in urban areas including amplifying FLAP guidelines.

Appendix B PTM Detailed methods and Additional Results

Study region

The Lake Simcoe-Rideau ecoregion (Fig 1) is part of the Mixedwood Plains Ecozone and covers about 6.4% of the province of Ontario. The unique physiographic features of this region, such as the underlying bedrock, soils, and topography alongside the mild and moist climate, contribute to the high levels of net primary productivity (Liu et al. 2002) and result in high levels of biodiversity, including many species that are restricted to this region. These physiographic features also give rise to unique habitats such as alvars, which are limestone bedrock communities with sparse vegetation that typically consist of shrubs, native herbaceous vegetation, and very few trees (Crins et al. 2009). The ecoregion also encompasses more than 80% of Ontario's Greenbelt, an area designated by the provincial government in 2005 to protect the existing agricultural land base and the natural heritage and hydrological systems, and to mitigate and build resilience to climate change (Ministry of Municipal Affairs 2017).

The Lake Simcoe-Rideau ecoregion is characterized by a large human footprint (Hirsh-Pearson et al. 2022). Currently, 57% of its land area consists of working landscapes primarily dedicated to agricultural and grazing activities, while 30% is forest cover (Crins et al. 2009). The region is also politically complex: natural resources and the environment are managed by a network of watershed-based conservation authorities, multiple levels of government, environmental non-profit organizations, landowners and Indigenous rightsholders (Drescher et al. 2017; Olive and Penton 2018; Ray et al. 2021).

Scope and objective

Experts agreed to define the extent of the study area using the boundaries of Ontario provincial ecoregion 6E—the Lake Simcoe-Rideau ecoregion (Fig 1). Experts also agreed on a time horizon of 27 years to coincide with the timelines for achieving the global biodiversity goals for 2050 under the GBF (Convention on Biological Diversity 2022). This 27-year time horizon falls within the range of time horizons used in PTMs for other regions (Carwardine et al. 2019; Camaclang et al. 2021; Kehoe et al. 2021) and represents a compromise between the short management and policy cycles of 2 - 5 years, and the much longer timeframes needed to measure ecological responses and species recovery.

PTM identifies which actions will minimize the cost and maximize the benefits to the biodiversity features of interest in the region. To determine these biodiversity features, experts were asked to review the full list of species in the ecoregion that are classified as Endangered, Threatened, or of Special Concern under the federal Species at Risk Act (SARA) or the Ontario Endangered Species Act (ESA), and by the Committee on the Status of Endangered Wildlife in Canada or the Committee on the Status of Species at Risk in Ontario. Following a facilitated discussion, experts identified a total of 133 species that were of conservation concern in the region (Appendix A Table A-1). This list included three species—the Black Bear, Upland Sandpiper, and Brook Trout—that are not currently considered to be at risk but have been observed by experts to have undergone recent declines or have significant social or cultural importance. In addition, not all species on the list had been confirmed to be currently extant in the region, but were included for their historic presence in the region (e.g., Rusty-patched Bumble Bee), or in anticipation of future northward range shifts due to climate change (e.g., Goldenseal).

Management actions and strategies

Experts worked together in small working groups to identify key threats to the species of conservation concern and develop a list of actions that they believed would address threats and improve the probability of persistence of those species. Experts were asked to include only actions that are not already occurring or expected to occur and continue over the 27-year time horizon.

Experts identified a total of 48 actions, which were organized into eight broad management strategies (Appendix A Table A-2), with the criteria that each strategy could be implemented independently of any other strategy and included actions that directly benefit species, noting that research and monitoring activities do not benefit species directly unless they inform other conservation actions. Experts also identified six combinations of two or more individual strategies that may have synergistic effects when implemented together (S9-S14); together with a final combination of all individual strategies (S15), this results in a total of 7 combined strategies to consider for the analysis.

Cost and Feasibility

Experts worked in small groups to further define actions that would address the key threats to the species groups and estimate the annual costs, in 2022 Canadian dollars, of planning and implementing the proposed actions over the 27-year period (inclusive of labour, equipment, materials, capital assets, and other operational costs such as overheads, travel, or honoraria). Cost estimates were informed by experts' personal experience and publicly available information on costs for similar actions, such as annual reports from non-profit organizations and government documents. In addition to the experts participating in the PTM process, we also consulted 12 other individuals to obtain feedback on the cost estimates for several actions. These individuals are from conservation authorities and non-profit organizations with knowledge and experience in implementing similar actions in the region.

Following best practices in economic analyses, we calculated the present value (PV) of the total costs of each action using the recommended social discount rate of 3% (Treasury Board of Canada Secretariat 2022). We calculated the total cost of each management strategy as the sum of the present value costs of all the actions in that strategy, while the total cost of a combined strategy was the sum of the present value costs of the individual strategies in the combination. To facilitate comparisons and communication of the results, we also converted the total present value costs of each strategy into annualized values. The annualized cost represents the average cost per year of a strategy, such that the sum over the time period in present value terms equals the total present value cost of that strategy (US Environmental Protection Agency 2016).

For each action, expert groups also provided an estimate of the probability that the action will be implemented (i.e., probability of uptake) and the probability that the action will be successful if it is implemented (i.e., probability of success). These two estimates were multiplied together to obtain an estimate for the feasibility of the action. We calculated the overall feasibility of a strategy by finding the average of the feasibility of all the actions within that strategy, while the overall feasibility of each combined strategy was determined as the average of the feasibility of all the individual strategies that make up that combination.

Baseline scenario

The benefit of each management strategy was assessed relative to a baseline or counterfactual scenario—that is, what the future would be if the strategy is not implemented. For this PTM assessment, ongoing biodiversity protections and conservation actions are considered "business-as-usual" and form part of the baseline scenario. This included current legislative protection and recovery actions for species at risk under SARA, the Ontario ESA and other provincial and federal legislation as of 2022 that protect wildlife and their habitat. It also includes local and regional stewardship, restoration, and wildlife management initiatives that are expected to continue to 2050, such as ongoing habitat restoration and tree planting programs, existing beneficial management practices (BMP) for agricultural activities, water restoration action plans, and captive rearing and reintroduction programs for turtles and the Mottled Duskywing (*Erynnis martialis*). Conservation initiatives with funding already secured and that are expected to take place over the next several years were also considered part of the baseline scenario, including: the federal government's 2 Billion Trees program, which aims to plant 2 billion trees across the country (Government of Canada 2023); the commitment to protect 30% and restore 30% of Canada's lands and waters by 2030; and recent increases in provincial funding for the Greenlands Conservation Partnership and the conservation land tax incentive program to promote private land stewardship and greater protection for ecologically important natural areas.

The baseline scenario could also be influenced by potential threats and pressures to biodiversity over the next 27 years. Experts highlighted that population growth and impacts from additional housing alongside recent and anticipated provincial policy changes that lead to reduced environmental and biodiversity protections will continue to put species at risk of extinction. Impacts of climate change—extreme weather events, in particular—as well as new introductions of invasive species and overall reduced ecosystem resilience will likely worsen over the coming decades. At the same time, the rising costs of implementing conservation actions, along with the limited supply and increasing demand for conservation tools and resources—such as native seeds and soil— were predicted to pose major challenges to the success of conservation and species recovery over the next 27 years.

Benefits

PTM uses a modified Delphi structured elicitation protocol to obtain expert estimates of the conservation benefits of management strategies (Carwardine et al. 2012; Hemming et al. 2018). We defined the benefit of each management strategy as the difference between the probability of functional persistence in the region in 2050 with the strategy and the probability under the baseline scenario (that is, without the strategy). We defined functional persistence as having viable, self-sustaining populations that continue to perform their ecological function (Chadès et al. 2015; Firn et al. 2015; Camaclang et al. 2021), where a probability of 0 equates to a zero chance of persistence and 1 equates to a 100% chance of persistence.

To facilitate the elicitation process, experts were asked to group species based on potential similarity of responses to threats and management actions, such that species within a group will have similar probabilities of persistence under the baseline scenario and the different management strategies. This resulted in a total of 16 groups that ranged in size from two to 19 species (Appendix A Table A-1). Experts were then asked to provide their individual estimates of the probability of persistence of each species group under the baseline scenario and under each management strategy or combination strategy, assuming that all actions in a given strategy will be implemented successfully. For each value, experts were asked to provide what they believe is the most likely estimate, as well as the estimate under the most pessimistic scenario (i.e., lowest plausible estimate) and the most optimistic scenario (i.e., highest plausible estimate).

After the initial round of estimates, experts were given the opportunity to review summaries of all anonymized expert estimates, along with any additional comments or rationale provided. Experts were then invited to revise their own estimates, if desired, based on this new information. This approach maintains the independence of responses while avoiding many of the pitfalls of unstructured group elicitation methods, such as 'groupthink' (Martin et al. 2012).

Cost-effectiveness Analysis

We used the finalized estimates of the probability of persistence to calculate the benefit (B_{ij}) of a given management strategy i for each species group j. To do this, we first calculated the difference between the probability of persistence of the species group j under the strategy i (p_{ijk}) and the probability of persistence under the baseline scenario (p_{ojk}), as estimated by expert k. We then averaged the values over the number of experts that provided an estimate for that species group and management strategy (K_{ij}). That is,

$$B_{ij} = \frac{\sum_{k=1}^{K_{ij}} \left(p_{ijk} - p_{0jk}\right)}{K_{ij}}.$$

We used the estimates of the benefit under the most likely scenario to evaluate the cost-effectiveness of management strategies and perform the complementarity analysis. We calculated the total benefit of a given strategy (B_i) by first weighting each B_{ij} according to the number of species in group j (w_j), and summing across all species groups. That is,

$$B_i = \sum_{j=1}^{G} w_j \, B_{ij},$$

where G is the total number of species groups.

We then calculated the expected benefit of a management strategy i by multiplying the total benefit (B_i) by the estimated feasibility of the strategy (F_i). We then divided this value by the estimated cost of the strategy (C_i) to calculate a cost-effectiveness (CE) score, as follows:

$$CE_i = \frac{B_i F_i}{C_i} * a,$$

where $a = 10^6$, which is used as a scaling constant to ensure that the benefits and costs are in the same or similar order of magnitude. Strategies with high *CE* scores have greater expected benefits relative to the cost, and therefore are more cost-effective.

Complementarity analysis

To assess complementarity among management strategies, we assumed that species groups that achieve a probability of persistence equal to or greater than a particular threshold value will be 'secure'. We calculated the expected probability of persistence of each group j under strategy i (p_{ij}) as follows:

$$p_{ij} = \frac{\sum_{k=1}^{K_{0j}} p_{ojk}}{K_{0j}} + B_{ij} F_i,$$

where p_{ojk} is the probability of persistence of species group j under the baseline scenario as estimated by expert k, and K_{oj} is the number of experts who provided estimates of the probability of persistence of group j under the baseline scenario.

We set the threshold probability of persistence to 60% based on the range of values for the expected probability of persistence under the proposed management strategies and the preference of the experts to aim for higher probabilities of persistence. We then identified optimal solutions—sets of complementary management strategies that will secure the greatest number of species groups while minimizing the cost—by solving the following integer linear programming problem (Chadès et al. 2015) for a range of budgets:

$$\max \sum_{i=1}^{S} \sum_{j=1}^{G} T_{ij} x_{ij} ,$$

subject to the following constraints:

$$\sum_{i=1}^{S} x_{ij} \leq 1,$$

$$x_{ij} \leq y_i, \text{ and}$$

$$\sum_{i=1}^{S} C_i y_i \leq C_{max},$$

where $T_{ij} = 1$ and $x_{ij} = 1$ if group j is considered 'secure' under strategy i, and 0 otherwise; S is the total number of strategies and G is the total number of species groups; y_i is a decision variable that indicates whether strategy i is selected (1) or not (0); C_i is the total cost of implementing strategy i; and C_{max} is the total budget available. The first constraint ensures that a maximum of one strategy is counted towards group j, while the second constraint ensures that the contribution of strategy i to group j is zero when strategy i is not selected (i.e., when $y_i = 0$). The final constraint ensures that the total cost of all selected strategies do not exceed the given budget.

As with many multi-objective optimization problems, there is not always a single feasible solution that achieves both objectives of maximizing benefit and minimizing the costs at the same time (Ruzika and Wiecek 2005). The solutions identified are therefore Pareto optimal solutions, representing trade-offs wherein greater benefits can only be achieved by increasing costs (Ruzika and Wiecek 2005; Chadès et al. 2015).

When the budget is fixed, the solution to implement is typically determined by the budget constraint. However, if the budget is flexible or is yet to be secured, a choice must be made on which of the solutions should be adopted. To help inform this choice, we performed the complementarity analysis using the expected benefits estimate (i.e., $B_{ij} \times F_i$) to examine the set of Pareto optimal solutions that could maximize the number of species groups that would gain an expected benefit of ≥15% probability of persistence above baseline estimates. Our aim was to determine which strategies could maximize both the number of species groups secured with at least 60% probability of persistence and the number of groups that could gain at least 15% probability of persistence above the baseline for the least cost.

We found all but two of the Pareto optimal solutions that could maximize the number of species groups secured with ≥60% (S2 and S7 + S14; Fig 3) could also result in the most species groups receiving ≥15% expected benefit for the least cost (Fig B-1). In addition to the species groups that could be secured to ≥60% probability of persistence, strategy S5 (wildlife safe crossings) could also provide >15% expected benefit for turtles, while combination strategy S14 could also result in >15% benefit for alvar species. Finally, combination strategies S11 (i.e., landowner stewardship (S2), protecting habitat (S4) and restoration and regeneration (S7) strategies combined) and S15 (i.e., all strategies combined) could provide ≥15% benefit for six and eleven species groups, respectively; these species groups include the bats and turtles (Table B-1), which were not expected to be secure with at least 60% probability of persistence under those strategies.

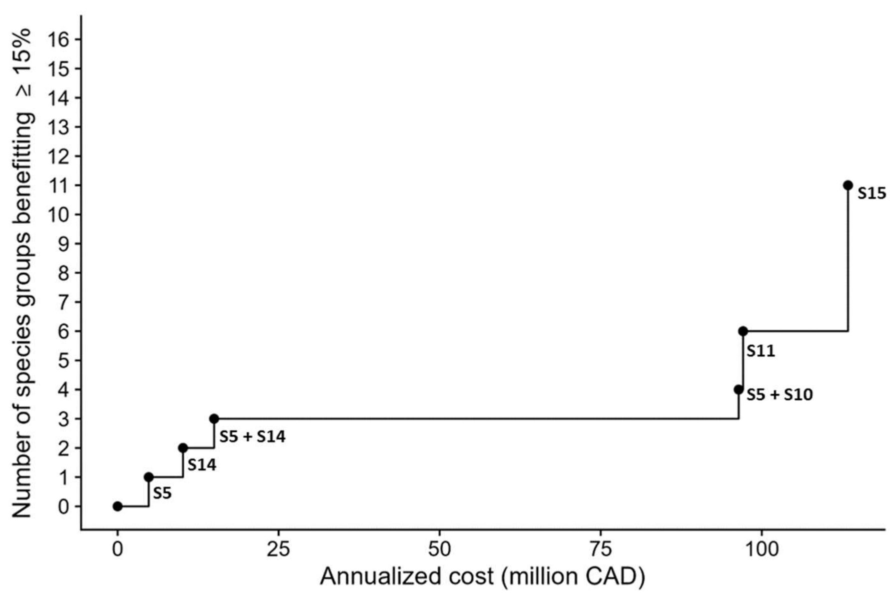

Figure B-4 *Pareto front indicating the number of species groups that could achieve an increase of at least 15% in probability of persistence under the different Pareto optimal solutions (represented by the black dots along the line). Annualized costs represent the average cost per year over 27 years.*

Table B-1 *Species groups with ≥15% expected benefit (improvement in probability of persistence over 27 years compared to the Baseline scenario) under different Pareto optimal strategies. Total costs have been discounted to present values at a rate of 3% and annualized to derive an average cost per year.*

Species groups	Number of species in group	Optimal strategies					
		S5	S14	S5 + S14	S5+10	S11	S15
Turtles	8	✓		✓	✓	✓	✓
Riverine species	19						
Ciscoes	2						
Mussels	10						
Oak savannah species	2						✓
Riparian species	3						✓
Alvar species	8		✓	✓	✓	✓	✓
Wetland species	18					✓	✓
Sandy species	7					✓	✓
Bats	4						✓
Mixed forest species	6						✓
Forest species	19		✓	✓	✓	✓	✓
Artificial structure- dependent species	3						✓
Naturalized open habitat species	12				✓	✓	✓
Snakes and lizards	9						
Working landscapes species	3						
Number of species groups secured:		1	2	3	4	6	11
Annualized cost (million CAD):		4.8	10.2	15.0	96.4	97.1	113.4

Uncertainty Analysis

Expected benefit estimates

To examine the effect of uncertainty in the estimates of the probability of persistence on the set of Pareto optimal solutions, we also performed the complementarity analysis using expert estimates for the most optimistic (highest) and most pessimistic (lowest) scenarios, and compared the set of Pareto optimal solutions identified under the different scenarios. We also assessed how well the optimal solutions identified under the most likely scenario (henceforth, 'most likely' solutions; Fig 3) performed under the most optimistic and pessimistic scenarios. That is, we assessed the number of species groups that could be secured by the 'most likely' solutions when considering the probability of persistence under the most optimistic and most pessimistic scenarios.

Under the most optimistic scenario, most species groups could be secured with ≥60% probability of persistence. Therefore, we also determined which strategies could secure the most species groups to a higher threshold of 70% probability of persistence for the least cost. In contrast, under the most pessimistic scenario, no species groups were predicted to have at least 60% probability of persistence under any of the management strategies. Therefore, for this scenario, we also identified Pareto optimal solutions for a lower threshold of ≥50% probability of persistence.

We found that, out of the set of 'most likely' solutions (Fig 3), strategy S11 was also identified as an optimal solution under both the most optimistic and pessimistic scenarios (Figs B-2 and B-3), thus making S11 a potentially robust choice in the face of uncertainty in expected benefit estimates. We also found that the majority of the 'most likely' solutions were also identified as optimal under the most optimistic scenario (henceforth, 'most optimistic' solutions) when considering a 70% probability of persistence threshold (Fig B-2). Only two of the 'most likely' solutions—S5 and the combination of S5 and S14—were not part of the 'most optimistic' solutions set for this threshold, as they had higher costs compared to other strategy combinations (i.e., S3 or S13, respectively) that yield the same benefit, in terms of the number of species groups secured (Fig B-2).

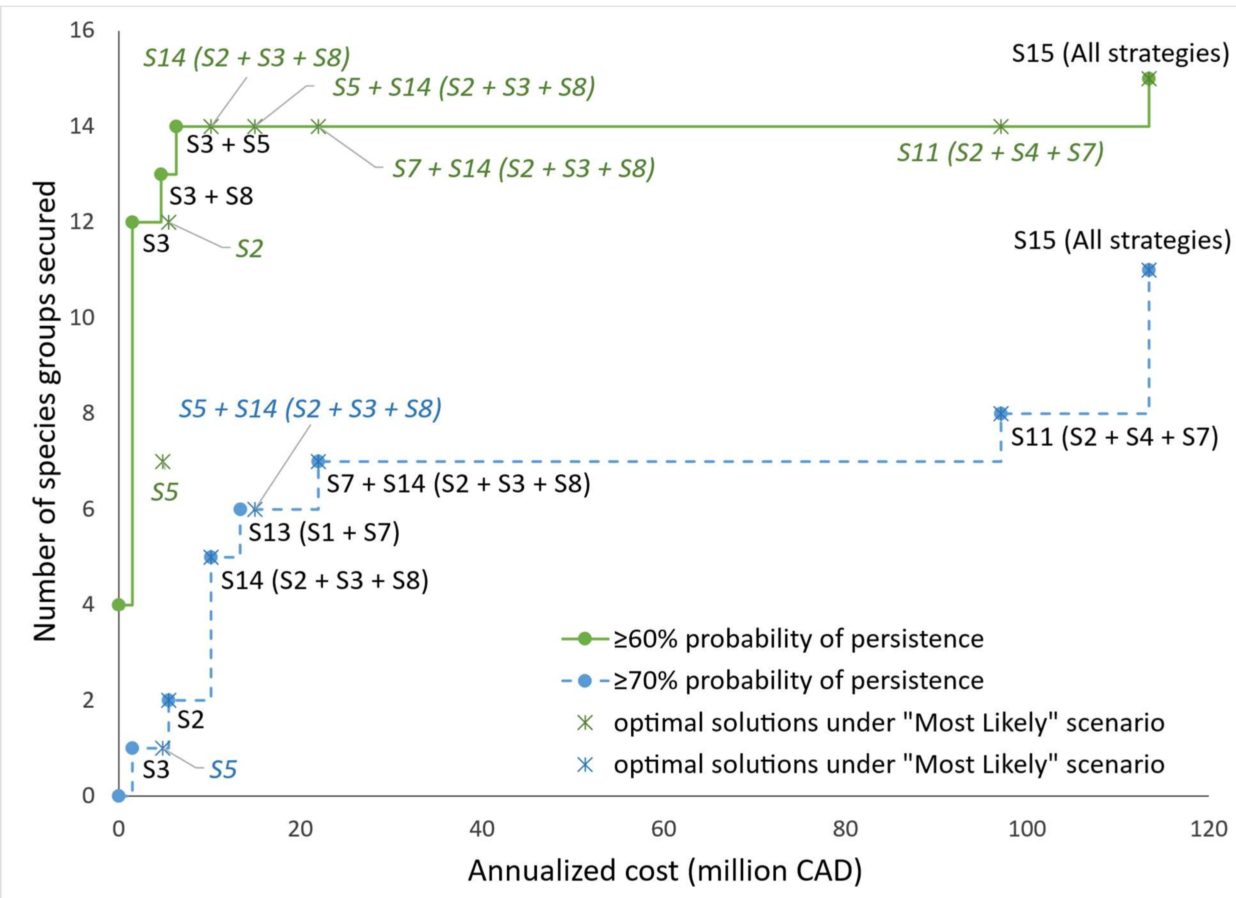

Figure B-2 *Pareto fronts showing the performance of the optimal solutions under the most optimistic scenario (represented by the filled circles along the lines) against the two objectives of minimizing cost and maximizing the number of species groups secured to a given probability of persistence threshold. Results are shown for two persistence thresholds: 60% (solid green line) and 70% (dashed blue line). Total costs have been discounted to present values using a discount rate of 3% then annualized to derive an average cost per year. Asterisks (*✳*) indicate strategy sets that were identified as optimal under the most likely scenario based on a 60% probability of persistence threshold.*

When considering the lower threshold of 60% probability of persistence, the set of 'most optimistic' solutions differed from the 'most likely' solutions, with only strategy S15 identified as optimal in both scenarios (Fig B-2). However, apart from strategy S5, the set of 'most likely' solutions still performed reasonably well under the most optimistic scenario, in that they could secure the same number of species groups as the 'most optimistic' solutions, but at higher costs (Fig B-2). Similarly, apart from strategy S11, the 'most likely' solutions were not identified as optimal under the most pessimistic scenario, but most performed reasonably well in terms of the number of species groups secured to at least 50% probability of persistence (Fig B-3).

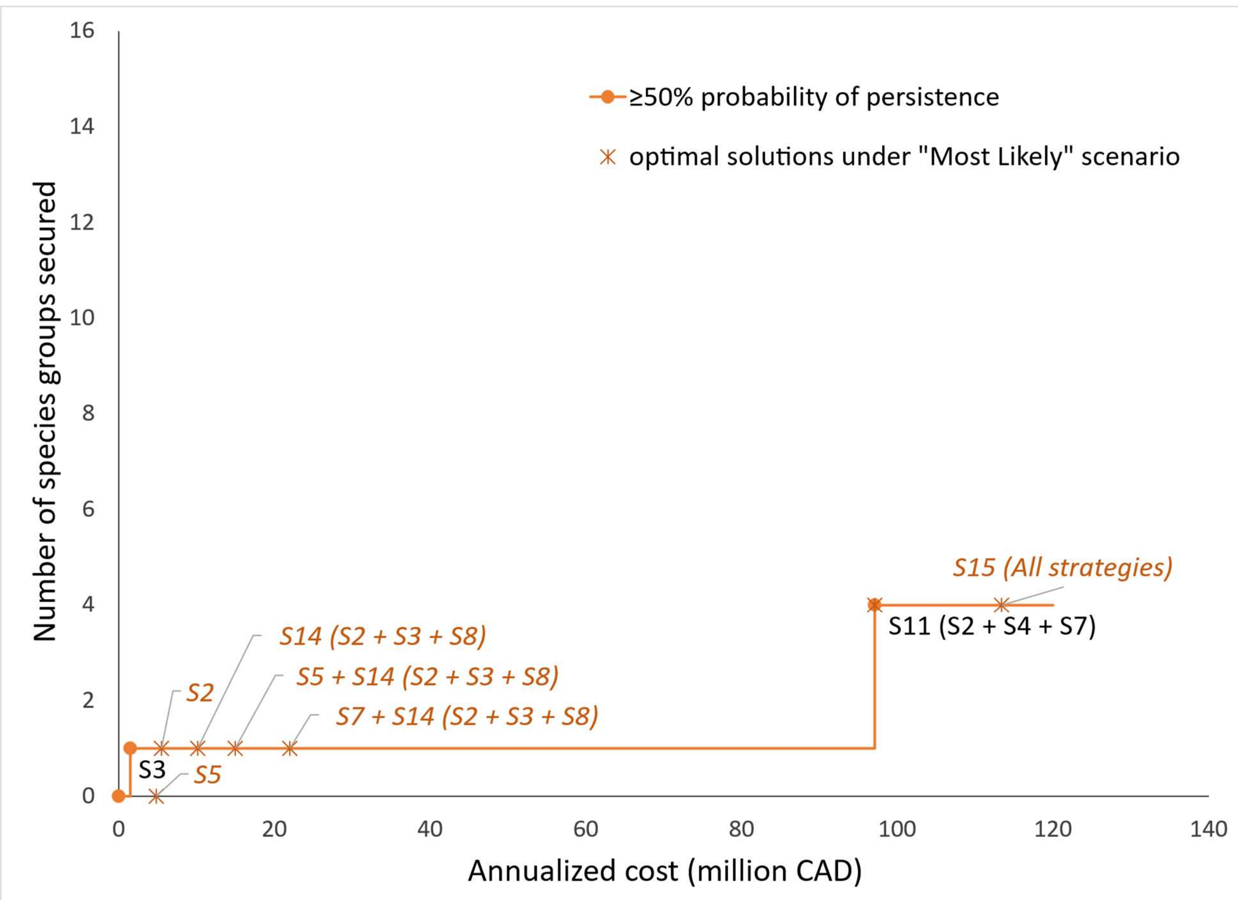

Figure B-3 *Pareto fronts showing the performance of the optimal solutions (represented by the filled circles along the lines) under the most pessimistic scenario, against the two objectives of minimizing cost and maximizing the number of species groups secured to at least 50% probability of persistence threshold. Total costs have been discounted to present values using a discount rate of 3% then annualized to derive an average cost per year. Asterisks (*) indicate strategy sets that were identified as optimal under the most likely scenario based on a 60% probability of persistence threshold.*

Discount rates

To examine the effect of different discount rates on the optimal solutions, we also performed the analysis with 0% and 7% discount rates applied to the costs to reflect, respectively, no discounting and the rate for private investment recommended by the Treasury Board of Canada. We found that the optimal solutions identified were identical to those found when using a 3% discount rate, but with different cost values reflecting the discount rates (Fig B-4). This suggests that the choice of discount rate did not have much effect on the optimal solutions.

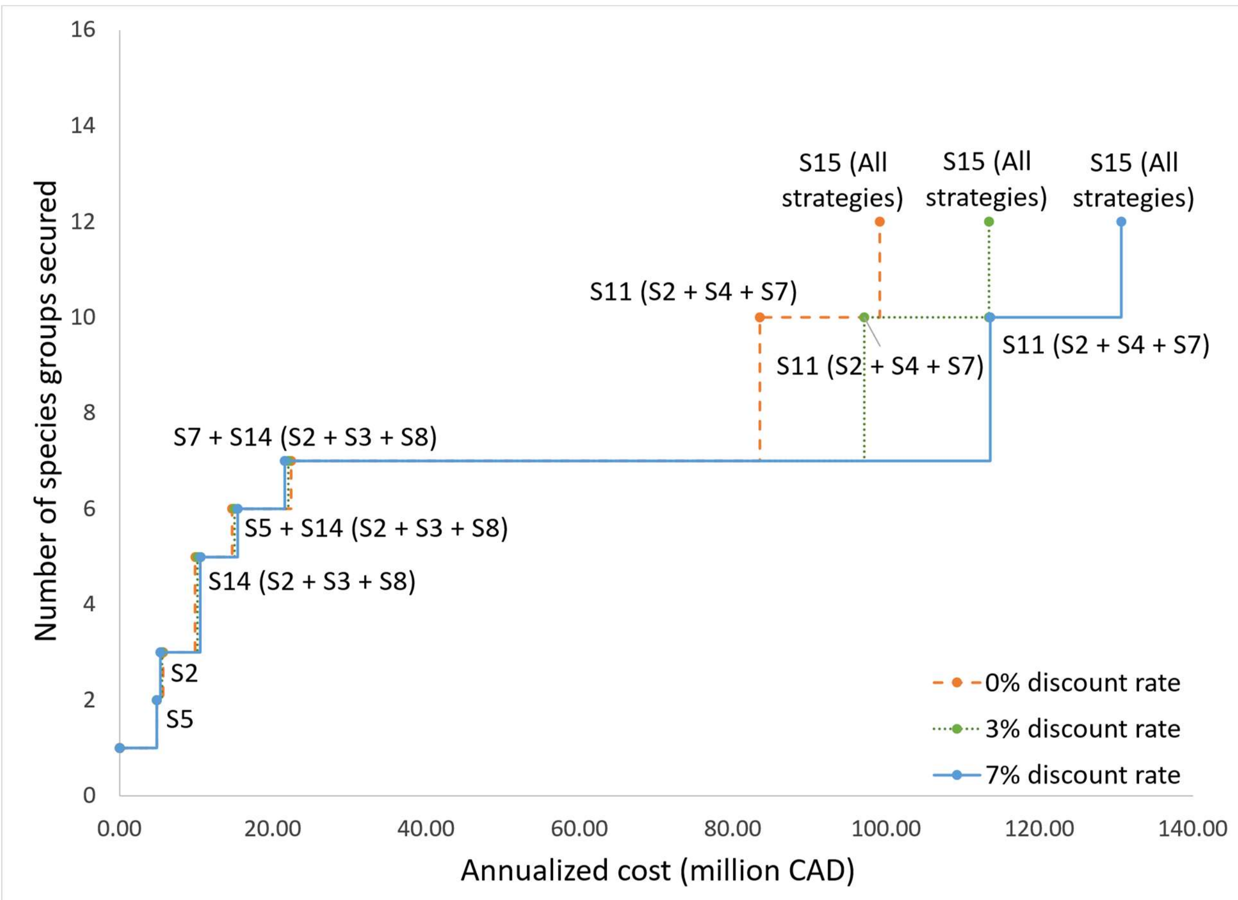

Figure B-4 *Pareto front indicating the number of species groups that could be secured to ≥60% probability of persistence under the most likely scenario by implementing the Pareto optimal solutions (represented by the black dots along the line) with different cost discounting rates.*

Accounting for the number of species per species group

When finding the optimal combinations of complementary management strategies that will maximize the total number of species groups secured for the least cost, we assigned equal value to all species groups. However, due to differences in the number of species included in each group (Appendix A, Table A-1), two strategies that secure the same number of groups may, in fact, secure different numbers of species. To account for the variation in the number of species in the species groups, we weighted the benefit of each species group by the number of species in the group, as follows:

$$\max \sum_{i=1}^{S} \sum_{j=1}^{G} w_j T_{ij} x_i,$$

subject to:

$$\sum_{i=1}^{S} x_{ij} \leq 1,$$

$$x_{ij} \leq y_i, \text{ and}$$

$$\sum_{i=1}^{S} C_i y_i \leq C_{max},$$

where w_j is the number of species in species group j, $T_{ij} = 1$ and $x_{ij} = 1$ if group j is considered 'secure' under strategy i, and 0 otherwise; S is the total number of strategies and G is the total number of species groups; y_i is a decision variable that indicates whether strategy i is selected (1) or not (0); C_i is the total cost of implementing strategy i; and C_{max} is the total budget available.

The set of Pareto optimal strategies that could maximize the number of species groups secured (Fig 3) were also identified as optimal when we accounted for the number of species in each species groups. In addition, two new Pareto optimal solutions were identified: 1) the combination of strategies S2 and S7, which could secure a total of 53 species in six species groups for a total of $318 million ($17.3 million per year) over 27 years, and 2) the combination of strategies S5 and S10 (which itself is a combination of strategies S4 and S7), which could secure 74 species in seven species groups for around $1.77 billion (or $96.4 million per year) over 27 years.

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Appendix C Carbon co-benefits of management strategies

Nature is a powerful tool for removing atmospheric carbon. Specifically, nature-based climate solutions (NbCS)—such as protecting intact ecosystems and restoring degraded habitats—can support climate mitigation and resiliency as well as biodiversity (Seddon et al., 2021), particularly when spatial prioritization exercises optimize for co-benefits. This analysis estimates the potential carbon benefits of biodiversity conservation actions identified in the Priority Threat Management (PTM) assessment for the Lake Simcoe-Rideau ecoregion, which identified actions that would maximize the number of species groups secured for the least cost.

Methods and Results

We assessed the biodiversity conservation actions identified in the PTM to evaluate their potential carbon benefits, in terms of avoided emissions (e.g., through habitat protection) and removals (e.g., through habitat restoration). The selection of actions for assessment relied on four components: (1) direct carbon co-benefits (e.g., physical restoration of habitat rather than broad policy changes), (2) quantification of the conservation action (i.e., an area-based estimate for the amount and type of land restored or protected), (3) reasonable quantifiable estimate of avoided emissions or removals, excluding actions with high uncertainty surrounding potential carbon benefits, and (4) availability of openly accessible geospatial data. Based on these criteria, the scope of the carbon benefits analysis was narrowed to four actions:

- protecting 10% of the ecoregion focusing on ecologically significant areas (S4, action a);
- naturalizing and restoring 1% of the shoreline area (S7, action c);
- restoring 50 km^2 of wetland and 25 km^2 of areas connecting wetlands (S7, action e); and
- restoring 1200 km^2 of area in forest transition zones (S7, action h).

We note that the carbon benefits presented here represent best estimates according to the information available, and do not fully account for incomplete data, all components of additionality (e.g., to estimate avoided land use change, we used rates of land use change rather than identifying zoning plans for development), future degradation of ecosystems, and continued carbon sequestration by ecosystems. Furthermore, all carbon estimates have uncertainties associated with limited field sampling and discrepancies between models (Sothe et al., 2022). Thus, the carbon benefit estimates provided primarily serve to guide management actions at broad scales.

Strategy S4 Protecting Habitat

To estimate the carbon co-benefits of habitat protection, we determined the potential avoided emissions of protecting priority areas using a national dataset of carbon stocks (Sothe et al., 2022), which estimates the total carbon stored in biomass and soils to a depth of 1 m. We assumed that habitat protection will prevent degradation or conversion, and that the existing carbon stock will be retained. To account for additionality, we excluded existing protected areas listed in the Canadian Protected and Conserved Areas Database (CPCAD; Environment and Climate Change Canada, 2023) from the analysis. We recognize that a limitation of our analysis, however, is that there may be some areas zoned for protection that are not currently included within CPCAD. In the absence of openly accessible data on zoning for developments, we estimated the probability of land use conversion using data on land cover change between 1992-2020 (European Space Agency, 2021) and used this to calculate the potential amount of avoided land conversion based on the assumption that transition rates between land use states will remain constant through time despite potential changes in development pressure or conservation awareness (Iacono et al., 2015). The estimated carbon benefits from this analysis represent presently stored carbon and does not consider additional carbon sequestered over time.

Action S4a: Protect 10% of habitat within the study region through a variety of protected and conserved area mechanisms including conservation easements and land acquisitions.

We identified potential sites to prioritize for habitat protection within the Lake Simcoe-Rideau ecoregion based on the following key areas identified by experts as part of the PTM process:

- areas with high climate change sensitivities;
- forest interior and mature forest;
- grassland patches greater than 50 ha;
- wetlands;
- Important Bird Areas (IBAs), Key Biodiversity Areas (KBAs);
- corridors to enhance habitat connectivity for large mammals and other species;
- Natural Heritage Systems (NHS)—areas and wildlife corridors in Ontario which support ecological connectivity and have significant ecological value, defined in the Greenbelt Plan, Oak Ridges Moraine Conservation Plan, Niagara Escarpment Plan, and the Growth Plan for the Greater Golden Horseshoe (Ontario Ministry of Natural Resources and Forestry, 2018);
- areas with bat caves, hibernacula, and known maternity roosting sites;
- alvar habitats; and the
- Algonquin to Adirondacks (A2A) region—the last intact north-south forest corridor in eastern North America, located on the eastern side of the ecoregion (Algonquin to Adirondacks Collaborative, 2014).

We mapped the locations of these priority areas using publicly available datasets (Table C-1) in ArcGIS Pro v.3.2. To determine forest interior areas, all forest type pixels (coniferous, broadleaf, mixed-wood, undifferentiated) within the ecoregion were extracted from the 30 m resolution Agriculture and Agri-Food Canada Annual Crop Inventory land cover dataset (Agriculture and Agri-Food Canada, 2021). Areas within 100 m of the forest edge were removed to obtain the interior or core habitat. Grassland pixels within the ecoregion were also extracted from the same dataset, keeping contiguous patches with an area greater than 50 ha (500 m^2).

Table C-1. *Datasets representing ecologically significant areas prioritized for protection.*

Dataset	Source	Specifications
Land cover	Annual Crop Inventory (Agriculture and Agri-Food Canada, 2021)	Raster 30-m resolution
Important Bird Areas (IBAs)	Important Bird Areas of Canada Database (Bird Studies Canada, 2015)	Vector, polygon
Key Biodiversity Areas (KBAs)	Key Biodiversity Areas (Key Biodiversity Areas Canada, 2022)	Vector, polygon
Natural Heritage System Areas	Natural Heritage System Areas (Ontario Ministry of Natural Resources and Forestry, 2018)	Vector, polygon
Bat and snake, alvar habitats	Provincially Tracked Species (1 km grid) (Natural Heritage Information Centre, 2023)	Vector, polygon
Algonquin to Adirondacks (A2A) region	2014 Regional Connectivity Mapping Data Set (Algonquin to Adirondacks Collaborative, 2014)	Vector, polygon
Ontario wetlands	Wetlands (Ontario Ministry of Natural Resources and Forestry, 2023)	Vector, polygon
Protected areas	Canadian Protected and Conserved Areas Database (CPCAD) (Environment and Climate Change Canada, 2023)	Vector, polygon

Ecologically significant areas such as Important Bird Areas (IBAs), Key Biodiversity Areas (KBAs), Natural Heritage Systems (NHS) and the Algonquin to Adirondacks (A2A) region were clipped to the ecoregion. The Provincially Tracked Species 1-km grid dataset (Natural Heritage Information Centre, 2023) was filtered for all areas containing bat caves, snake habitats, and alvar habitats. Lastly, the Ontario Wetlands database (Ontario Ministry of Natural Resources and Forestry, 2023) was filtered for all wetlands assessed based on perceived ecosystem and human utility values.

All map layers were merged and converted to a binary raster, with a value of 1 for the priority areas and 0 for all other areas. As the aim of the action is to protect additional habitat within the ecoregion, we excluded any existing protected areas within the CPCAD dataset by assigning these areas a value of 0. To calculate the mean carbon storage and potential avoided emissions, we randomly selected an equivalent of 10% of the ecoregion (6392.5 km^2) from the set of priority areas using the `pandas` package in python v3.9. We then determined the total carbon storage within the sampled area using a national dataset of terrestrial carbon stocks (Sothe et al., 2022) with the `rasterstats` package. We performed this procedure 10 times, and estimates from each iteration were averaged. The average carbon stock value was divided by the total area of 6392.5 km^2 to find the mean carbon density within potential protected areas. We also estimated the maximum and minimum carbon density in potential protected areas by preferentially selecting areas with the highest and lowest carbon stock, respectively, from the set of priority areas.

To forecast the amount of avoided carbon emissions, we assumed that conservation actions taken to protect habitat will prevent future land conversion and thus retain all carbon currently present in protected areas. We calculated a 28-year natural to human-dominated land use conversion probability of 1.72% by computing a Markov chain transition matrix with the European Space Agency (ESA) CCI Land Cover Time Series v. 2.1.1 (1992-2020) (European Space Agency, 2021). This was done using the `giddy` package for spatiotemporal data analysis (Kang et al., 2024). We used this conversion probability to forecast the amount of avoided land conversion—that is, the area that would have been converted over approximately 30 years in the absence of the habitat protection action. We did this by multiplying the total area that would be protected (6392.5 km², or 10% of the ecoregion) by the natural-to-human conversion probability of 1.72%. We then determined the avoided carbon emission by multiplying the avoided land conversion value by the mean carbon density of potential protected areas, and converted carbon to CO_2 emissions equivalent (CO_2e) using a unit conversion factor of 3.67 (United States Environmental Protection Agency, 2023).

Protecting 6392.5 km² (equivalent to 10% of the Lake Simcoe-Rideau ecoregion) of habitat within the identified priority areas could result in the protection of between 141.8 - 254.1 megatonnes (Mt) of stored carbon (Table C-2). When sites for protection were randomly selected, the average amount of stored carbon within 6392.5 km² of priority areas was 177.8 Mt, resulting in an average density of 27.8 km/m² (Table C-2). Based on the conversion factor of 3.67, this would be equivalent to around 652 Mt in CO_2 emissions (CO_2e).

Using the estimated natural-to-human land use change probability of 1.72%, the protection of 6392.5 km² could potentially result in avoided conversion of 109.83 km² of habitat. Based on the average carbon density of 27.8 kg/m², this would result in the avoided release of 3.06 Mt of carbon, or 11.2 Mt CO_2e (Table C-2).

Table C-2 *Potential carbon benefits of protecting 6392.53 km² (~10% of Lake Simcoe-Rideau ecoregion) of priority areas in the ecoregion. Potential storage indicates the amount of carbon (and carbon dioxide emission equivalents, CO_2e) currently stored in potential protected areas, while avoided release indicates the amount that would have been released due to conversion in the absence of habitat protection.*

		Potential storage		**Carbon density**	**Avoided release**	
	Iteration	**Carbon (Mt)**	**CO_2e (Mt)**	**(kg/m²)**	**Carbon (Mt)**	**CO_2e (Mt)**
Randomly selected	1	177.83	652.03			
	2	177.89	652.26			
	3	177.78	651.85			
	4	177.81	651.97			
	5	177.81	651.95			
	6	177.82	651.99			
	7	177.87	652.19			
	8	177.88	652.22			
	9	177.85	652.11			
	10	177.85	652.13			
	Average	**177.84**	**652.07**	**27.82**	**3.06**	**11.20**
With highest C	-	254.10	931.71	39.75	4.37	16.01
With lowest C	-	141.82	520.00	22.18	2.44	8.93

Strategy S7 Restoration and regeneration

We used net restorable carbon—that is, the change in carbon storage following the restoration of a converted land to its natural state—as a measure of the carbon benefit of restoration and regeneration actions. For each action, we first identified potential restoration areas based on the criteria provided by experts in the detailed action descriptions. From these, we identified priority sites using the Restoration Opportunities Optimization Tool (ROOT; Beatty et al., 2018). ROOT conducts multiple iterations of an optimization procedure; for each iteration, it identifies an optimal set of sites (i.e., pixels) of a given target size (area) that could maximize total restorable carbon and biodiversity if restored to their natural state. For these analyses, we set ROOT to run ten iterations to account for computational feasibility, assigning equal weights to restorable carbon and biodiversity. We considered sites selected as part of the optimal solution in five out of the ten iterations as priorities for restoration.

We used 250 m resolution raster datasets on the net restorable carbon and the biodiversity benefit of restoration action as inputs into ROOT. We derived estimates of net restorable carbon for each restoration action using raster data from Currie et al. (2023) that represented the change in carbon storage resulting from restoration, summed across the different natural land cover classes that converted lands within a given pixel could be restored to. As the restoration actions in the PTM primarily focus on restoration to a specific land cover class (i.e., shoreline, wetland, or forest), we multiplied the values from Currie et al. (2023) by the proportion of each pixel area that would be restored by a given restoration action, and used this modified raster dataset in ROOT to identify priority restoration zones for that action. For estimates of the potential biodiversity benefit of restoration actions, we used the restoration component of the Species Threat Abatement and Restoration ($STAR_R$) score (Mair et al., 2021) calculated by Currie et al. (2023) for species with ranges in Canada. We modified this dataset to reflect species priorities in the PTM assessment by assigning higher weights to species identified as the targets of the restoration action (w=3) and to other species of conservation concern assessed in the PTM (w=2) in the calculation of the $STAR_R$ score.

From the set of ROOT-generated priority sites, we randomly selected the equivalent of the target restoration area using the `pandas` package in python v3.9. Due to size of each pixel, the total area of sampled sites differed slightly from the target restoration area. We generated ten random samples and calculated the net restorable carbon for each sample using the `rasterstats` package. We used the average value across the ten samples to estimate the mean carbon density (kg/m^2) across priority zones, then multiplied the target restoration area by the mean carbon density to estimate the mean net restorable carbon for the restoration action. We also estimated the minimum and maximum net restorable carbon for each action by selecting the equivalent of the target restoration area from ROOT-generated priority sites with the lowest and highest net restorable carbon values, respectively, and calculating the total across these areas. We converted all restorable carbon values to CO_2 equivalent emissions using a unit conversion factor of 3.67 (United States Environmental Protection Agency, 2023). As in Currie et al. (2023), the net restorable carbon values represent the potential net stored carbon for sites once restored to their natural state, and does not account for the length of time needed to reach that state.

Action S7c: Naturalize and restore a total of 92.3 km (1% of total shoreline in area) of riparian corridors and buffers and shorelines along water courses, with a specific focus on creating hibernacula for snakes.

We clipped shoreline data from the Atlas of Canada National Frameworks (Natural Resources Canada, 2014) to the study area. To represent restorable shoreline habitat, we segmented the shorelines by 1 km portions and applied a 250 m buffer on either side, resulting in 500 m^2 restoration zones and a total area of approximately 4755 km^2. We used ROOT to select optimal restoration zones, assigning higher weights to snake species (w = 3) included in the list of species of conservation concern (Appendix A Table A-1) in the calculation of the $STAR_R$ score. ROOT was run with an approximate target area of 1% of the total shoreline in the ecoregion to identify priority shoreline restoration zones. From these priority zones, approximately 47.5 km^2 of restorable area (equivalent to 1% of shoreline restoration zones for the ecoregion) was randomly selected ten times to derive an estimate of the average net restorable carbon and carbon density.

The amount of restorable carbon within 1% of shorelines in the ecoregion, selected from the set of ROOT-generated priority zones, ranged from 1.2 - 1.4 Mt C (Table C-3). The mean net restorable carbon was 1.33 Mt (4.88 Mt CO_2e), based on a mean density of 28.01 kg/m^2 (Table C-3).

Table C-3. *Total restorable carbon (C) and carbon dioxide emissions equivalents (CO_2e) of restoring 1% of shorelines in the Lake Simcoe-Rideau ecoregion. Target area restorable carbon and CO_2e values were calculated based on the target of 47.55 km^2 for restoration and the mean carbon density of 28.01 kg/m^2.*

		Sampled area			Carbon	Target area	
	Iteration	**Size (km^2)**	**Restorable Carbon (Mt)**	**Restorable CO_2e (Mt)**	**density (kg/m^2)**	**Restorable carbon (Mt)**	**Restorable CO_2e (Mt)**
Randomly selected	1	47.50	1.34	4.91			
	2	47.49	1.37	5.02			
	3	47.20	1.32	4.85			
	4	47.32	1.34	4.90			
	5	47.29	1.28	4.68			
	6	47.48	1.31	4.81			
	7	47.36	1.33	4.87			
	8	47.27	1.34	4.92			
	9	47.44	1.33	4.87			
	10	47.32	1.31	4.82			
	Average	**47.37**	**1.33**	**4.86**	**28.01**	**1.33**	**4.88**
With highest C		47.63	1.40	5.14	29.40	1.40	5.13
With lowest C		47.41	1.22	4.46	25.64	1.22	4.47

Action S7e: Restore 50 km^2 of wetlands and 25 km^2 for connectivity between existing wetlands, with a special focus on creating hibernacula for snakes.

We extracted wetlands from the 30-m resolution Annual Crop Inventory land cover dataset (Agriculture and Agri-Food Canada, 2021) for the study area. To obtain potential connectivity corridors between existing wetlands, we applied a buffer of 500 m (Petranka & Holbrook, 2006; Rannap et al., 2009); this buffer size helped ensure that the core habitats of semiaquatic species surrounding wetland edges were included in the corridor (Semlitsch & Bodie, 2003). The buffered wetland was divided using a 10 km^2 hexbin grid to obtain potential restoration zones. To identify priority zones for restoration, we used ROOT to select approximately 50 km^2 of restorable wetland and 25 km^2 of areas connecting wetlands within the 500 m buffer. Both terrestrial and aquatic species of conservation concern considered in the PTM (Appendix A Table A-1) were included in the optimization, and snake species were assigned a higher weight (w = 3) in the calculation of the $STAR_R$ score to reflect their priority for habitat restoration. Within these priority zones, net restorable carbon was calculated for ten random samples and the average value used to estimate the mean carbon density.

The total net restorable carbon in 50 km^2 of wetlands and 25 km^2 of areas connecting wetlands within priority restoration zones ranged from 2.4 - 2.6 Mt C (Table C-4). On average, the total net restorable carbon, based on the mean carbon densities for wetlands and connecting areas, was 2.54 Mt (9.31 Mt CO_2e) (Table C-4).

Action S7h: Restore 1200 km^2 of forest.

Experts identified the transition zones between core forests and altered habitats, with a focus on afforestation in the Algonquin to Adirondacks (A2A) Region, as key areas for forest restoration. To determine transition zones between core forest and altered habitats, we extracted all forest type pixels (coniferous, broadleaf, mixed-wood, undifferentiated) within the ecoregion from the 30-m resolution Annual Crop Inventory land cover dataset (Agriculture and Agri-Food Canada, 2021). Areas up to 150 m outside of the forest boundary were considered part of the forest transition zone with potential for restoration, as edge habitats occur 100 - 200 m from transitional boundaries (Didham & Ewers, 2012; Didham & Lawton, 1999). Furthermore, the presence of source trees within small distances (~100 m) may facilitate seed recruitment and the success of forest restoration (Zahawi et al., 2021). As the restoration action focuses on afforestation in the A2A region, we excluded existing forested areas from the set of key areas for restoration. The remaining area was divided using a 10 km^2 hexbin grid to obtain potential restoration zones. We used ROOT to identify optimal restoration zones with a target area of 1200 km^2. Only terrestrial species were included in calculating the $STAR_R$ metric, with species of conservation concern (Appendix A Table A-1) assigned a higher weighting (w = 2). From the set of ROOT-generated priority restoration zones, approximately 1200 km^2 of restorable area was randomly selected ten times to estimate the average net restorable carbon and carbon density.

The total amount of restorable carbon in 1200 km^2 of priority forest restoration zones ranged from 33.2 - 33.5 Mt C (Table C-5). On average, the net restorable carbon was 33.7 Mt (123.4 Mt CO_2e) based on the estimated mean carbon density of 27.82 kg/m^2 (Table C-5).

Table C-4. *Total restorable carbon (C) and carbon dioxide emissions equivalents (CO_2e) of restoring 50 km² of wetlands and 25 km² of areas connecting wetlands in the Lake Simcoe-Rideau ecoregion. Restorable carbon and CO_2e values for the target area were calculated based on the restoration target of 50 km² for wetlands and 25 km² for connecting areas, and the corresponding average carbon density estimated from ten random samples of the approximate target size.*

	Iteration	Sampled area: Size (km²)	Sampled area: Restorable Carbon (Mt)	Sampled area: Restorable CO_2e (Mt)	Carbon density (kg/m²)	Target area: Restorable Carbon (Mt)	Target area: Restorable CO_2e (Mt)
50 km² of wetland areas							
Randomly selected	1	48.81	1.59	5.84			
	2	49.96	1.75	6.41			
	3	49.58	1.63	5.96			
	4	49.94	1.69	6.20			
	5	49.91	1.73	6.33			
	6	49.94	1.73	6.33			
	7	49.36	1.62	5.93			
	8	49.95	1.72	6.30			
	9	49.92	1.69	6.19			
	10	48.35	1.59	5.83			
	Average	49.57	1.67	6.13	33.73	1.69	6.18
With highest C		50.03	1.75	6.41	34.93	1.75	6.40
With lowest C		49.81	1.59	5.85	32.02	1.60	5.87
25 km² of connecting areas							
Randomly selected	1	24.94	0.87	3.18			
	2	24.95	0.87	3.18			
	3	24.99	0.87	3.18			
	4	24.81	0.82	3.02			
	5	24.81	0.82	3.02			
	6	24.93	0.87	3.18			
	7	24.97	0.87	3.18			
	8	24.67	0.81	2.98			
	9	24.85	0.85	3.10			
	10	24.86	0.85	3.10			
	Average	24.88	0.85	3.11	34.12	0.85	3.13
With highest C		25.02	0.87	3.18	34.69	0.87	3.18
With lowest C		23.76	0.76	2.77	31.78	0.79	2.91
Total (wetland and connecting areas)							
Average						2.54	9.31
Highest C storage (max)						2.61	9.58
Lowest C storage (min)						2.40	8.78

Table C-5. *Total restorable carbon (C) and carbon dioxide emissions equivalents (CO_2e) of restoring 1200 km² of forest in the Lake Simcoe-Rideau ecoregion. Target area restorable carbon and CO_2e values were calculated based on the forest restoration target of 1200 km² and the average carbon density of 28.04 kg/m².*

		Sampled area			Carbon	Target area	
	Iteration	Size (km²)	Restorable Carbon (Mt)	Restorable CO_2e (Mt)	density (kg/m²)	Restorable Carbon (Mt)	Restorable CO_2e (Mt)
Randomly selected	1	1195.34	33.38	122.39			
	2	1199.23	33.64	123.33			
	3	1199.27	33.54	122.98			
	4	1197.24	33.62	123.26			
	5	1199.52	33.64	123.36			
	6	1198.25	33.64	123.35			
	7	1198.31	33.64	123.34			
	8	1199.73	33.64	123.36			
	9	1199.02	33.65	123.37			
	10	1195.72	33.59	123.15			
	Average	1198.16	33.60	123.19	28.04	33.65	123.38
With highest C		1200.13	33.51	122.88	27.92	33.51	122.86
With lowest C		1199.74	33.18	121.65	27.65	33.18	121.68

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