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Conservation in heavily urbanized biodiverse regions requires urgent management action and attention to governance

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Abstract

Throughout history, humans have settled in areas of high biodiversity. Today these areas are home to our biggest urban centers with biodiversity at increasing risk from escalating cumulative threats. Identifying the management strategies to conserve species within such regions, and ensuring effective governance to oversee their implementation, presents enormous challenges. Using a novel Priority Threat Management (PTM) approach that calculates the cost-effectiveness of conservation action and co-governance, we discover that the 102 species at risk of local extinction within Canada's most diverse, heavily urbanized coastal region, the Fraser River estuary, require urgent investment in management strategies costing an estimated CAD$381 M over 25 years. Our study also suggests that co-governance underpins conservation success in urban areas, by increasing the feasibility of management strategies. This study underscores that biodiversity conservation in heavily urbanized areas is not a lost cause but does require strategic planning, attention to governance, and large-scale investment.

KEYWORDS

conservation planning, cost-effectiveness, decision science, estuary, expert elicitation, governance, priority threat management, threatened species

1 | INTRODUCTION

For the first time in human history, over half of the world's population lives in urban areas, with over 5 billion people expected to inhabit such regions by 2030 (Seto, Güneralp, & Hutyra, 2012). Human populations tend to concentrate in areas of high biological diversity (Luck, 2007) and our expanding footprint now threatens vital remaining habitat, bringing biodiversity to the brink of extinction and heralding the sixth mass extinction (Ceballos et al., 2015). Although the vast majority of conservation interventions for protecting biodiversity have ignored urban areas where our human footprint is often most acute (Kennedy, Oakleaf, Theobald, Baruch-Mordo, & Kiesecker, 2019; Miller & Hobbs, 2002), managing these areas for conservation benefits is critical if we are to avert significant global biodiversity loss and ecosystem collapse (Seto et al., 2012). Yet implementing conservation interventions in these regions poses unique challenges, given conflicting demands of human resource use and wildlife, highly contested remaining habitat, and the high costs associated with conservation action in regions of high human pressure.

While often overlooked, governance—the structures that determine who makes decisions, how they are made, and to what effect and where—is a key factor influencing the feasibility of conservation management (Lockwood, Davidson, Hockings, Haward, & Kriwoken, 2012; Stoll-Kleemann et al., 2006), particularly in regions of high competing interests. Surprisingly, little is known about whether the conservation benefits of building and supporting environmental governance outweigh the costs (Wätzold & Schwerdtner, 2005), especially since effective governance is likely to determine the success or failure of conservation interventions. Within heavily urbanized systems, there is an urgent need to discover and prioritize the management strategies and governance systems that will give biodiversity the highest chance of survival.

The challenge of modern conservation in urban settings is exemplified in coastal regions. Most of the world's mega-cities are located in coastal areas, with 70% built on estuaries (Demographia, 2018). As a result, estuaries, which are among the most productive and dynamic environments in the world, are also most at risk due to the complex nature of multiple threats and competing interests (Lotze et al., 2006). In such highly-modified regions, systematic tools are urgently needed to identify the most effective ways to conserve remaining biodiversity.

Priority Threat Management (PTM) is a quantitative decision support framework used to assess the cost-effectiveness and complementarity of alternative management strategies for recovering biodiversity within a region (Carwardine et al., 2019). By harnessing scientific and expert-derived information, PTM prioritizes management strategies to conserve the most species for the least cost (Carwardine et al., 2019; Martin et al., 2018). PTM has been applied in rural areas to identify strategies that will ensure the persistence of species and ecosystems in Australia (Carwardine et al., 2012; Chadés et al., 2015; Firn et al., 2015; Firn et al., 2015; Ponce Reyes et al., 2019) and more recently in Canada (Martin et al., 2018; Walsh et al., 2020).

Here, we use PTM to quantify the benefits of conservation action and assess the cost-effectiveness of improved governance in a biologically diverse, urbanized and heavily contested region, the Fraser River estuary (Figure 1, Appendix S1), which is home to Canada's third largest metropolitan area, the Greater Vancouver area. The Fraser River estuary historically supported the largest wild salmon runs in the world (Fraser, Starr, & Fedorenko, 1982), providing key resources to people and

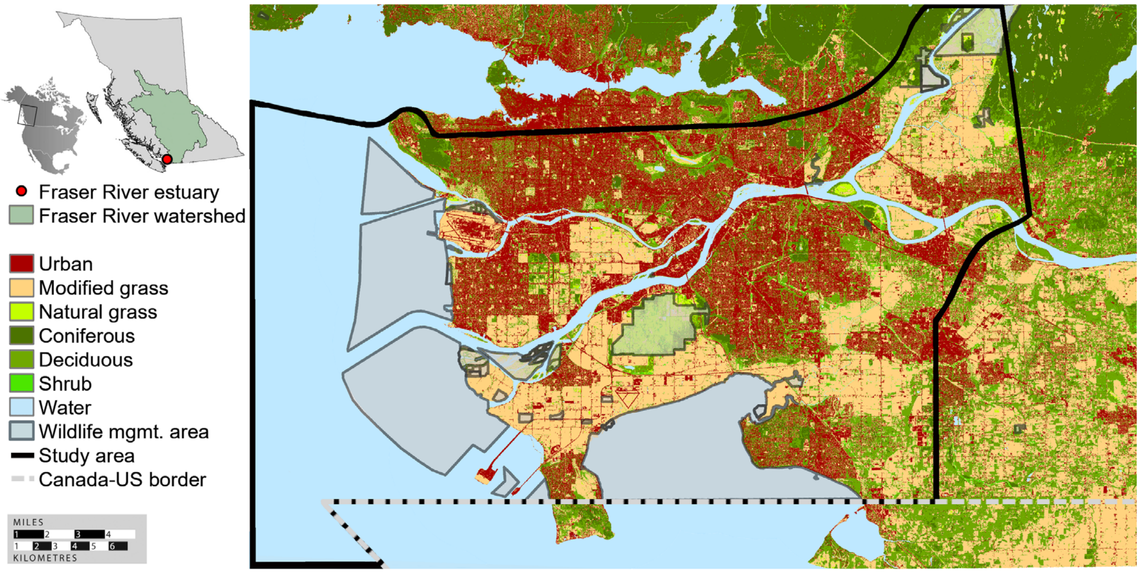

FIGURE 1 Study Area of Fraser River estuary (Vancouver, Canada) covering a terrestrial area of 1,072 km^2 and all surrounding marine areas including the estuary's plume (variable in area and not shown on map). The Fraser River is the fourth largest river within Canada and drains ~1/3 of British Columbia. Land Cover (5-m resolution) calculated using Lidar and Multispectral Scanner imagery (Vancouver Fraser Port Authority, Metro Vancouver Land Cover Classification, 2014). "Modified grass" is predominantly farmland under the Agricultural Land Reserve mandate, with the exception of Vancouver International Airport. "Wildlife mgmt. area" indicates the 2018 location of provincially-designated Wildlife Management Areas and other lands managed for conservation purposes (available at https://catalogue.data.gov.bc.ca/dataset/conservation-lands)

numerous species including the endangered southern resident killer whale, of which less than 75 individuals remain today. This region is crucial to people too: Coast Salish First Nation communities (Indigenous Peoples) have lived in the estuary since time immemorial (Lepofsky et al., 2009) and it is now home to over half of British Columbia's expanding population. With less than 30% of its habitat intact (Groulx, Mosher, Luternauer, & Bilderback, 2004), the Fraser River estuary faces multiple cumulative threats including, pollution, widespread dredging and diking, resource exploitation, agricultural intensification, urban sprawl, climate change, and numerous large-scale future industrial developments (Boundary Bay Conservation Committee, 2016; Calbick, McAllister, Marshall, & Litke, 2004; Groulx et al., 2004). At present, there is no single overarching conservation management plan for species of conservation concern and no governance structure to bring together the more than 64 First Nation, municipal, provincial, and federal governments that oversee the Fraser River estuary's valuable resources. Through the application of PTM, the goals of this study are to identify the most cost-effective strategies to conserve the species of conservation concern in our study region. In doing so, we aim to provide a blueprint for conservation action that investigates the importance of improved governance within this heavily urbanized biodiverse region.

2 | METHOD

2.1 | Data collection

Conservation research is often focused on identifying threats to species rather than identifying the most cost-effective management strategies needed to reduce these threats. We contributed to bridging this gap by applying the PTM framework which includes a structured expert elicitation framework, an often untapped data source to estimate the response of wildlife populations to management interventions (Carwardine et al., 2019; Hemming, Burgman, Hanea, McBride, & Wintle, 2017; Martin et al., 2012; McBride, Fidler, & Burgman, 2012). This is the first application of PTM in an urbanized region with cumulative threats to multiple species spanning both terrestrial and aquatic environments. Due to the serious nature of the large-scale threats facing our study region, alongside prioritizing the most cost-effective management strategies for this imperiled region, we advance PTM to include an assessment of halting major industrial development and an evaluation of the cost-effectiveness of co-governance.

Each stage of our approach was co-developed with local members of First Nations, federal, provincial, and municipal governments, industry consultants, academics, NGOs, and those working toward designing and implementing improved governance in the region. In total, 65 experts were consulted primarily through a series of three workshops: (a) a 1-day workshop to discuss project goals; (b) a 1-day workshop with 12 experts in estuarine governance, in which we facilitated a group discussion to outline a co-governance strategy for the region; (c) a 3-day expert elicitation workshop with 24 ecological experts, during which the species and strategies (benefits, feasibility, and costs) were defined (Carwardine et al., 2019). This collaborative process follows 10 key steps (Carwardine et al., 2019) detailed below.

First, we conducted an in-depth review of the species of conservation concern and the potential management actions to conserve them; this included relevant peer-reviewed scientific literature and federal, provincial, and local species reports (Data set S1). After a facilitated group discussion with our ecological experts, additional species deemed to be of high economic or cultural importance were added to our species list (see Appendix S2 for full inclusion criteria). After reaching a group consensus, 102 species were included in our final assessment.

Second, by reviewing individual species reports and other available data we summarized the threats to our species of concern and grouped the species for analysis according to two criteria: their common threats and the conservation benefits of carrying out management strategies to abate these threats (Appendix S2, Data set S1). This resulted in 13 major species groups that were assumed to benefit from management strategies (Appendix S3) to a similar extent. Species groups ranged in size from 1 to 24 individual species (Table S1).

Third, we defined our performance measure, in this case, species persistence at a self-sustaining minimal viable population size within the study area in 25 years. This timeframe was chosen as it encompasses multiple generation times for most species considered in the analysis and is still within the timeframe of experience of the experts. For species that have a longer life-span than our time period (e.g., sturgeon and southern resident killer whales) we deemed a population to persist if its growth rate was estimated to be positive in 25 years.

Fourth, we defined a baseline scenario of “No additional action” where business as usual development, urban sprawl, agricultural intensification, and climate change are left to continue without any additional management. No large-scale conservation projects were deemed to have ongoing consistent funding over 25 years and therefore were not included in our baseline scenario; however, a minimum duty of care as required under the federal *Species at Risk Act* was assumed.

Fifth, we developed one overarching co-governance strategy (Appendix S4) to assess whether co-governance is a cost-effective intervention and if so to what degree. To develop our co-governance strategy, we conducted an online survey (13 invited respondents who had in-depth experience with estuarine co-governance) to review previous management of the study region by the Fraser River Estuary Management Program (FREMP, disbanded in 2013). The results of this survey found that while the majority of respondents agreed that FREMP was moderately effective in achieving its vision of a living working river, no respondents deemed it to be “very effective,” this was due to a lack of long term funding, appropriate inclusion of partners (including First Nations) and prioritization of industry and development (Appendix S4). Following the survey, we held a 1-day workshop with 12 of our 13 survey respondents. We facilitated a group discussion to outline a high-level co-governance strategy for the region. This resulted in an outline for a co-governance model that we coined the Fraser River Estuary Act (Appendix S4). The key attributes of this co-governance act were: shared decision-making authority between First Nations, Federal and Provincial government, enabling legislation to ensure consistent funding, clear vision, data sharing, and communication and outreach (Appendix S4).

Sixth, we developed 10 direct management strategies with associated sub-actions. These were fleshed out as part of our expert elicitation workshop and spanned terrestrial to marine habitat management within and adjacent to the Fraser River estuary. A strategy was included if it was deemed to feasibly reduce the impact of one or more threats, with the constraint that benefits to species' persistence must be quantifiable (Carwardine et al., 2012), for example, a strategy that *only* contains monitoring or further research was not included. Our 10 direct management strategies were all centered around abating the multiple threats to this highly modified region. However, the threats facing our study region continue to escalate. From growing urban centers and habitat loss, to increased transport corridors and pipelines, these pressures pose significant challenges to already imperiled biodiversity. Since avoiding these threats may be more effective than abating the negative impacts once they have occurred (Holl & Aide, 2011), we examined an additional strategy of Halting Future Major Industrial Developments within the study area. Due to uncertainties in the costs and feasibility of Halting Future Major Industrial Developments, this strategy was evaluated only in terms of its potential benefit to species persistence probabilities.

Seventh, we developed detailed actions for each of our 10 direct management strategies (total of 64 actions) that would need to be implemented to fulfill the strategy goals, which were aimed at abating the major threats to our species of concern (Appendix S3). Each strategy was assessed as if it were carried out independently of any other strategy (e.g., what is the benefit of Aquatic Disease Control compared with a baseline scenario where no other additional strategies are implemented?). However, this ignores potential synergies between strategies. After a group discussion and consensus on which strategies may have a synergistic nature, four combinations of strategies were also evaluated (Appendix S3). This brought the total number of management strategies for evaluation to 14.

Eighth, for all but the Halting Future Major Industrial Developments strategy, detailed costs of each strategies' actions, including labor, equipment, and outreach costs, were estimated in line with cost reporting standards (Carwardine et al., 2019; Iacona et al., 2018). Experts worked in teams and used relevant literature to estimate the monetary cost of every action within a strategy. Labor inputs were converted to dollar values using estimated pay rates for the position and the percentage of the position dedicated to each strategy, and costs per hectare converted to total costs for each management unit by multiplying by the treatment area, overhead and materials costs were calculated separately to avoid issues related to the economy of scale (Carwardine et al., 2012, 2019). Any unknown costs were followed up post-workshop with additional practitioners and consultants with appropriate field experience (Data set S2 for full costings information).

The cost estimates of all underlying actions were summed to give the total estimated cost per management strategy. The cost of strategies varied depending on the duration of an action and spatial scale. To compare costs among strategies, we calculated the present value for each action, where future costs were discounted to present day values and summed to give the total cost of the strategy within the 25-year time horizon. We used a 4% discount rate which is consistent with Canadian public goods investments (Boardman, Moore, & Vining, 2008). Due to particularly high uncertainties in final costs for two strategies a cost range was given (Green Infrastructure and Fisheries Regulation). In these cases, the midpoint between minimum and maximum cost was used and the range was analyzed as part of the uncertainty analysis.

To estimate the cost of co-governance, we outlined the Fraser River Estuary Act, a form of governance that would coordinate policy across orders of government and mandate long term funding and public communications (Appendix S4). For comparison, British Columbia's recently enacted *Water Sustainability Act* which aims to ensure a sustainable supply of fresh, clean water, required an initial estimated \$25 M in funding and an ongoing annual cost of ~\$2 M. Taking these costs and using our 4% discount rate over 25 years resulted in a total estimated cost of co-governance of ~\$55 M.

Ninth, our 24 ecological experts worked in teams to produce a single estimate of feasibility for each action making up a strategy. These estimates consisted of a combination of uptake (will the action be implemented?) and success (will implementation achieve its goal?). The final feasibility for each action was calculated as the product of the likelihood of uptake and success (Carwardine et al., 2019). Strategy feasibilities were then discussed as a group and adjusted to utilize the wisdom of the group and ensure a general consensus. In order to investigate the impact of co-governance on our strategies, estimates on the difference in the feasibility of each of our strategies with and without co-governance were provided by each expert independently (Ponce Reyes et al., 2019). The average increase in feasibility of strategies with co-governance (across experts) was then calculated.

Tenth, the conservation benefits to species groups of each management strategy were estimated using a structured expert elicitation technique (Hemming et al., 2017; Martin, Burgman, et al., 2012). While this technique is particularly useful when empirical data is absent or incomplete, it is not without its own limitations. Experts are prone to many forms of bias and uncertainty, can be overconfident, and can provide inaccurate estimates (Martin, Burgman, et al., 2012; O'Hagan et al., 2006; Soll & Klayman, 2004). We attempted to minimize these uncertainties by using a structured elicitation technique which can reduce bias and tap into the "wisdom of the group" that has been found to provide more accurate estimates than those of individuals (Hemming, Walshe, Hanea, Fidler, & Burgman, 2018).

The first step in this structured technique is to clearly define the parameters being estimated. The estimated benefit of a management strategy was defined as the difference in the probability of persistence from baseline to the implementation of that strategy 25 years from now. Our species groups were assembled by common threats. The baseline scenario assumed business as usual with no additional management beyond minimum duty of care as required by law. Management strategies were expected to have a similar benefit to the species within a group. Therefore, benefits estimates here represent the average benefit to all species contained within a group. We used a four-point elicitation procedure (Hemming et al., 2017; Martin, Burgman, et al., 2012), which comprises a most likely (best guess), upper (optimistic) and lower (pessimistic) estimates, and an assessment of the confidence that the true value lies within these bounds (a minimum confidence of 60% was acceptable). Probability of persistence estimates were provided by each expert for the baseline scenario and for the implementation of management strategies. Experts only provided estimates for those species groups and strategies that they had professional experience with. The minimum number of estimates for any one species group and strategy combination was 5, which is within an acceptable range by which a group judgement outperforms that of an individual (Hemming et al., 2018) (average number of experts per estimate = 11, Table S2). In order to directly compare benefits estimates across experts, each estimate was standardized to the same level of confidence, in this case 80%, using the following formulae (Hemming et al., 2017):

$$\text{Lower standardized interval}: B-((B-L)*(S/C)) \quad (1)$$

$$\text{Upper standardized interval}: B+((U-B)*(S/C)) \quad (2)$$

Where B is the best guess, L is the lower estimate, U is the upper estimate, S is the standardized level of confidence, and C is the level of confidence given by the experts.

A combined group assessment standardized to 80% confidence levels was provided to the experts and individual experts had the opportunity to independently update their estimates of the benefits of strategies if they saw fit.

2.2 | Calculating the expected benefit of strategy implementation

The total expected benefit of a strategy is calculated as the sum across all species groups of the difference in the probability of persistence with and without the implementation of the strategy (Carwardine et al., 2019) where the benefits estimates provided by multiple experts are averaged first:

$$B_i = \sum_{j=1}^{N} \frac{\sum_{k=1}^{M_j} \left(P_{ijk} - P_{0jk}\right)}{M_j} \quad (3)$$

Where, P_{ijk} is the estimate from expert k of the probability persistence for species group j if strategy i is implemented; P_{0jk} is the probability of persistence of species group j under a baseline scenario (the strategy is not implemented), estimated by the same expert k; N is the number of species groups; and M_j is the number of experts who provided estimates for species group j (Carwardine et al., 2019).

Management strategies were prioritized in two distinct ways: first, strategies were ranked independently according to their cost-effectiveness, and second, by identifying complementary sets of strategies that optimize the number of species groups crossing probability of persistence thresholds for a given budget.

2.3 | Calculating strategy cost-effectiveness

Using the first method, the strategy that provides the highest benefit-to-cost ratio is ranked highest. The cost-effectiveness of each strategy i (CE_i) is given by the total benefit of the strategy (B_i) multiplied by the feasibility of the strategy (F_i), divided by its total cost (C_i):

$$CE_i = \frac{B_i F_i}{C_i} \quad (4)$$

2.4 | Identifying complementary sets of strategies

The highest-ranking strategies in terms of cost-effectiveness may be redundant if they focus on the same species groups and fail to conserve others. Furthermore, a strategy with a high cost-effectiveness rank does not indicate whether it will conserve a high number of species groups at a given threshold of persistence. To identify optimal sets of strategies in terms of the number of species groups reaching threshold probabilities of persistence, we undertook a second prioritization using a complementarity analysis (Chadés et al., 2015). In this analysis, solutions are a trade-off between maximizing the number of species groups reaching a threshold of persistence probability while minimizing the cost, and thus requires a multi-objective optimization (Chadés et al., 2015). First, we calculate the probability of persistence for each species group given the implementation of each strategy, calculated as:

$$M_{ij} = B_{0j} + B_{ij} F_i \quad (5)$$

Where B_{0j} is the baseline probability of persistence for species group j, B_{ij} is the improved probability of persistence for species group j if strategy i is implemented (averaged across experts), and F_i is the feasibility of strategy j.

We then define the thresholds of probability of persistence, in this case, 50, 60, 70, and 80%. Each threshold of persistence is analyzed separately—as each provides a unique solution (i.e., set of strategies). The strategies that allow any species groups to reach a given persistence threshold compared with baseline are selected. Then, the strategies with the lowest cost per number of species reaching the persistence threshold are selected and ordered from least to most expensive. Then, the optimal sets of strategies are chosen that maximize the number species reaching a given probability of persistence threshold at incremental budgets. The results for a given budget may be a single strategy or a combination of strategies, for example, two strategies may conserve more species than a single strategy and will be selected if their total cost is lower than the cost of the single strategy. Furthermore, the number of species in each species group is considered in the selection of strategies. For example, a strategy that conserves one large species group will be chosen over a strategy of the same cost that conserves multiple species groups but fewer overall species.

2.5 | Uncertainty analyses

Various forms of uncertainty are inherent in the PTM methodology. We address uncertainty in two key parameters in our analysis: the benefits of implementing management strategies and the cost of management strategies.

First, we report on the differences in the benefits estimated by individual experts to gain an understanding on whether experts' estimates were largely in agreement. This was carried out before these estimates were averaged to arrive at the final group estimate used in subsequent analysis. Second, we compare the cost-effectiveness and selection of complementary sets of strategies for optimistic (upper bound), best guess (most likely), and pessimistic estimates (lower bound). This step allows us to check how robust our results are to experts' benefits estimates under the best and worst case scenarios. Third, two strategies had particularly high uncertainties related to their costs since data was not available in order to assess the level of action needed. A minimum and maximum estimated cost for these two management strategies was estimated by experts and we compared the cost-effectiveness and selection of complementary sets of strategies under maximum and minimum costs.

3 | RESULTS

We discover that under a business as usual scenario, two-thirds of species within the Fraser River estuary are predicted to have less than a 50% probability of persistence over the next 25 years ($n = 67$ of total 102 species; 8 of 13 species groups, Figure 2, Table 1). Importantly, all management strategies are necessary to ensure that all species have a better than even chance of persisting in this landscape over the next 25 years, at an estimated total cost of \$326 M CAD. The implementation of co-governance resulted in considerable monetary savings at the 50% persistence threshold and the conservation of additional species at the 60% persistence threshold (Figure 4). However, even under full management with co-governance, 4 of 13 species groups are not predicted to

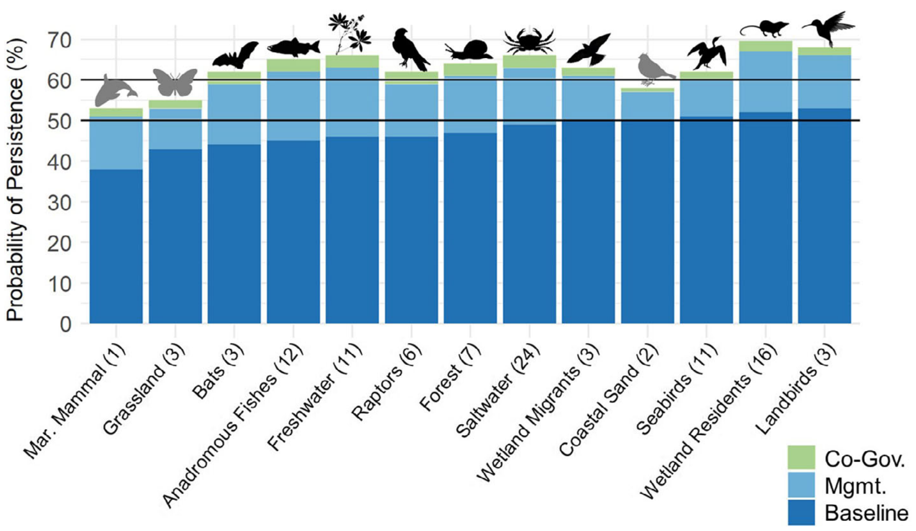

FIGURE 2 Probability of persistence for each of 13 species groups under increasing levels of investment over 25 years. Baseline (dark blue) represents species persistence probabilities under no additional management; management (Mgmt. - light blue) represents implementing all management strategies; co-governance (Co-Gov - green) represents the implementation of an overarching co-governance strategy. Under full management and co-governance, 10 of 13 species groups (96 of 102 species; black species silhouettes) reach a 60% probability of persistence. Species groups are ordered from lowest to highest probability of persistence under baseline scenario

TABLE 1 Probability of persistence for each species group and strategy within the study area under a "best guess" most likely scenario with the implementation of co-governance—calculated by: (benefit × feasibility) + baseline (Equation (5))

Strategy	B	S1	S2	S3	S4	S5	S6	S7	S8	S9	S 10	S 11	S 12	S 13	S 14
Cost (M $)	0	100	32	62	3	3	61	15	2	2	45	134	123	108	326
Species group															
Seabirds	51	51	51	51	51	53	58	54	51	52	54	53	57	58	62
Raptors	46	59	53	47	47	48	46	51	48	46	48	58	52	48	62*
Landbirds	53	63	61*	56	61	57	54	60*	57	53	57	66	63	58	68
Anadromous fishes	45	50*	50*	57	51	50*	60*	55	45	52	61*	53	63*	64	66
Bats	44	57	52	48	44	48	44	52	49	44	50*	57	58	47	62*
Marine mammal	38	39	40	42	38	43	47	43	38	40	45	41	51*	51*	53
Coastal sand	50	55	51	52	54	52	50	52	52	50	50	57	52	51	58
Grassland	43	52	49	44	45	45	43	47	46	43	43	51*	46	44	55
Forest	47	63	53	48	49	51	47	49	49	47	47	60	49	48	63
Freshwater	46	55	53	56	55	50	50	54	48	47	59	58	65	59	66
Saltwater	49	55	51	54	58	53	54	54	50	51	60*	57	63	63	66
Wetland residents	52	62	58	60*	60*	56	54	60*	55	53	63	65	67	61	69
Wetland migrants	50	57	54	56	57	52	50	55	52	50	59	60	63	57	63

Note: Numbers with asterisks indicate the threshold is only passed with the inclusion of co-governance. Strategy key: B = Baseline; S1 = Public Land Management; S2 = Private Land Management; S3 = Green Infrastructure; S4 = Problematic Species Management; S5 = Transportation Regulation; S6 = Fisheries Regulation; S7 = Pollution Control; S8 = Population Augmentation; S9 = Aquatic Disease Control; S10 = Aquatic Habitat Restoration; S11 = combination of S1, S2, and S8; S12 = S3 + S7 + S10; S13 = S6 + S9 + S10; S14 = All Strategies.

reach a 60% persistence threshold (6 of 102 species, Figure 2). No species groups are estimated to exceed the 70% persistence threshold (under any management strategy tested within our most likely "best guess" scenario, see Figure S2 for persistence probabilities under best and worst case scenarios).

3.1 | Aquatic habitat restoration and halting development are the most beneficial strategies

In terms of the total estimated benefits to species persistence, Halting Future Major Industrial Development rivals Aquatic Habitat Restoration as the most beneficial direct management strategy (Figures 3, S1, and S2). Crucially, if major industrial developments continue in the region, the persistence of many iconic species such as the southern resident killer whale, Anadromous Fishes, including salmon and sturgeon, and Saltwater Species, including the migratory western sandpiper, are likely to be jeopardized (Appendix S3). Due to high uncertainties in the feasibility and cost of Halting Future Major Industrial Development, this strategy was only assessed in terms of the direct benefits to species persistence probabilities. The notable benefit of prevention rather than cure should not be overlooked as an important strategy in conserving species in our study region.

3.2 | Cost-effective, complementary strategies

To assess which combinations of strategies were predicted to conserve the most species per dollar spent under different budgets, we examined the complementarity of different management strategies (Chadés et al., 2015). Encouragingly, by undertaking only two of the most cost-effective strategies together, Transport Regulation and Pollution Control (Table 2), the majority of species ($n = 98$ of 102; 11 species groups), are predicted to reach a better than even chance of persistence at a total cost of only \$19 M over 25 years (Figure 4). Importantly however, the remaining four species which do not reach this threshold are the iconic southern resident killer whale, monarch butterfly, western bumblebee and barn swallow (Table 1, Appendix S5). Conserving these four species at this threshold requires costly management strategies and additional investment (Figures 2 and 4, Table 1).

Achieving a higher probability in species persistence is more difficult and requires greater investment. For example, the implementation of Problematic Species

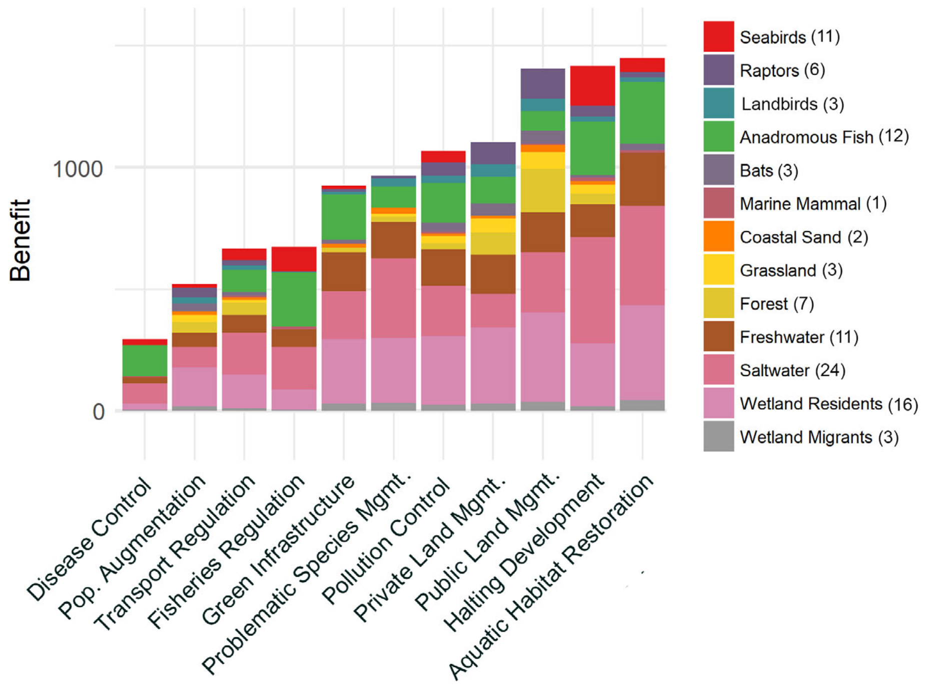

FIGURE 3 Estimated benefit of management strategies by species group and strategy in terms of improvement in species group probability of persistence from baseline. Each species group is weighted by the number of species it contains. Halting Future Major Industrial Development is abbreviated to Halting Development. All strategies are described in full in Appendix S3. Numbers in brackets represent the number of species in each group

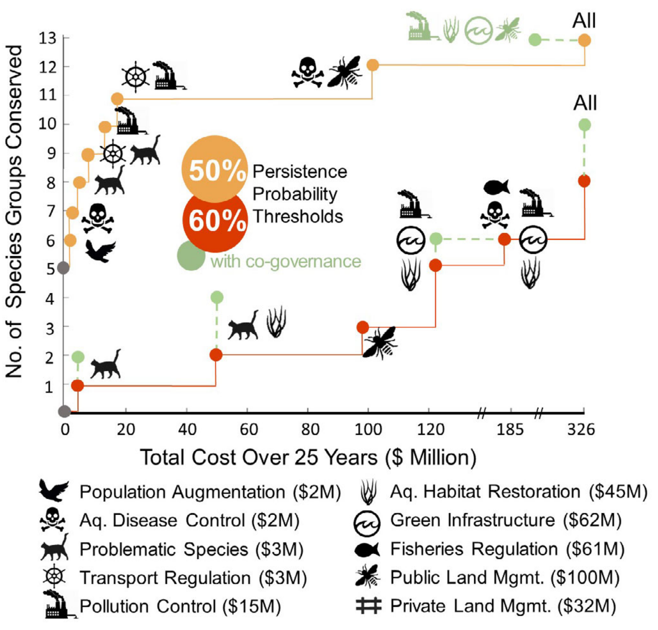

FIGURE 4 The estimated number of species groups reaching 50% (orange) and 60% (red) persistence probabilities within the study area for different levels of investment in complementary sets of management strategies over 25 years. Baseline scenario shown in grey. Strategies improved their capacity to conserve species when co-governance was implemented either by increasing the number of species groups reaching a specified persistence threshold or reducing the cost of achieving an equivalent ecological outcome (in green). For example, with co-governance only four strategies are needed to conserve all species groups at a 50% probability of persistence (saving up to $104 M in conservation spending). Co-governance was estimated to cost ~$55 M over 25 years (not shown in graph)

Management secures eight species groups ($n = 82$) at the 50% threshold, but only one species group is secured at the 60% threshold (Landbirds, $n = 3$, Figure 4, Table 1). Likewise, a total investment of ~$100 million conserves 12 species groups at the 50% threshold, but only three at the 60% threshold (Figure 4). In order to give species groups the best chance of persistence in our study region, all management strategies are needed at a total estimated cost of $326 M.

3.3 | The importance of co-governance

Employing a co-governance structure, in which First Nations and other governments work together to oversee and coordinate the implementation of conservation management (Appendix S4), is estimated to increase the feasibility of all management strategies, and thus boosts their cost-effectiveness and species persistence probabilities (Table 2, Figures S3 and S4). Due to an increase in feasibility, all strategies are estimated to benefit from co-governance, but to slightly different degrees. Complex strategies spanning many municipalities and encompassing a diverse array of actions are estimated to benefit the most from co-governance. For example, Aquatic Restoration is estimated to increase its feasibility by 15%, Public Land Management and Green Infrastructure both increase by 13%, and Pollution Control (in aquatic and terrestrial habitats) increases by 12%. On the other hand, Aquatic Disease Control and Fisheries regulation benefit the least, with a 4 and 5% increase in

TABLE 2 Management strategies ranked in order of their cost-effectiveness (CE) rank considering a strategy's total benefit to species groups of conservation concern, CE score (Equation (4)), feasibility (%), increase in feasibility as a result of co-governance shown in brackets, and total 25-year CAD$ cost (in millions)

CE rank	CE score (10^4)	Strategy	Benefit	Feasibility	Cost (M)
1	177	Problematic species Mgmt. (PSM)	859	64 (+7)	3
2	94	Transport regulation (TR)	611	53 (+11)	3
3	78	Population augmentation (PA)	448	36 (+9)	2
4	74	Aquatic disease control (AD)	285	57 (+4)	2
5	33	Pollution control (PC)	957	54 (+12)	15
6	15	Aquatic restoration (AR)	1,318	51 (+15)	45
7	11	Private land Mgmt. (PrLM)	971	37 (+11)	32
8	8	Combination of AD and AR and FR	1,503	59 (+8)	108
9	8	Combination of PC and AR and GI	1850	54 (+13)	123
10	8	Green infrastructure (GI)	827	57 (+13)	62
11[a]	7	Fisheries regulation (FR)	647	69 (+5)	61
12[a]	7	Public land Mgmt. (PuLM)	1,238	53 (+13)	100
13	6	Combination of PA and PrLM and PuLM	1809	42 (+11)	134
14	4	All strategies	2,681	53 (+10)	326

[a]The cost-effectiveness (CE) rank of strategies was the same with and without co-governance except for the 11th and 12th ranked strategies, which switch rank position under the implementation of co-governance.

feasibility, respectively, perhaps because these strategies are less likely to require coordination from a large array of different stakeholders. On average, the feasibility of strategies increases by 10% when co-governance is implemented (Table 2, Appendix S4, S6).

Due to the increase in feasibility of management under co-governance, strategies could achieve a higher probability of persistence for species groups (Equation (5)). For example, at the 50% probability of persistence threshold, when co-governance is implemented, only two-thirds of the management resources would be required to achieve the same conservation impact (Figure 4). To conserve all species groups at a 50% threshold without co-governance, all strategies are required at a total estimated cost of $326 M. Whereas, when including co-governance, only four management strategies (Public Land Management, Green Infrastructure, Pollution Control, and Aquatic Habitat Restoration) are needed to ensure all species have a better than even chance of persisting, costing an estimated $223 M and saving $104 M (Figure 4). Therefore, at the 50% threshold, as a result of the cost-savings of needing fewer conservation strategies when co-governance is implemented, up to $104 M could be spent on the development and support of co-governance before it becomes equally cost-effective to instead implement all management actions (Figure 4).

Co-governance was assessed in the form of a Fraser River Estuary Act and is estimated to cost approximately $55 M in total (see Methods). The potential savings that could thus be made with co-governance are over double its likely cost. Adding $55 M to the cost of all 10 management strategies brings the total estimated cost of conservation to $381 M over 25 years ($15 M per year) or $6 per person per year in the greater Vancouver region (based on population in 2019).

At the 60% persistence threshold, co-governance is estimated to increase the number of species conserved. For example, the combination of Problematic Species Management and Aquatic Habitat Restoration is estimated to conserve two species groups without co-governance (Landbirds, $n = 3$; Wetland Residents, $n = 16$) and four species groups with co-governance (Landbirds, $n = 3$; Wetland Residents, $n = 16$; Anadromous Fishes, $n = 12$; Saltwater Species, $n = 24$, Figure 4)—more than doubling the estimated number of species conserved at a 60% probability of persistence (from 19 to 55 species).

The inclusion of co-governance, in conjunction with all 10 direct management strategies, allows for two additional species groups (Raptors, $n = 6$; and Bats, $n = 3$) to reach the 60% persistence threshold (Table 1, Figure 2), bringing the total number of species reaching this threshold to 96 of 102. However, even when implementing all management strategies in conjunction with co-governance, three species groups (Marine Mammals, $n = 1$; Grassland Species, $n = 3$; and Coastal Sand Ecosystem Species,

$n = 2$) still are not estimated to reach a 60% threshold of persistence, underscoring the challenge of species conservation in highly urbanized contested landscapes.

3.4 | Uncertainty of results

We find uncertainty in our results related to differences in individual experts estimates (Figure S5) and differences between optimistic (upper bound) and pessimistic (lower bound) estimates (Figure S6, Data set S3, and Appendix S6 for full discussion). Despite this, the cost-effectiveness ranking of strategies is estimated to be relatively robust to uncertainty. The top eight most cost-effective strategies remain the same under optimistic (upper), pessimistic (lower) and most likely best guess scenarios and independent of whether or not co-governance is implemented (Table 2, Table S3). However, there was considerable differences in the selection of complementary strategies under best and worst case scenarios (Figure S6). A cost range was given for two strategies: Green Infrastructure ($60–62 M) and Fisheries Regulation ($42–80 M). The only change in results was a drop in the cost-effectiveness of Fisheries Regulation when using its highest cost (from 11th to 13th most cost-effective strategy, Table S3). The cost range had no impact on the selection of complementary strategies.

4 | DISCUSSION

4.1 | Reason for cautious optimism

We show that with strategic planning and the correct tools, conservation action in imperiled urban regions is likely to curtail biodiversity loss. In our case, co-governance was estimated to be a key component of ensuring that species have the highest possible chance of survival and that funds are spent in the most cost-effective manner. Our approach can help decision-makers determine the most cost-effective management strategies and assess whether an overarching co-governance structure will provide value for money—something that is often assumed to be useful, but has not previously been quantified with respect to its cost-effectiveness. Given the overall relatively low probabilities of persistence for species in our study region, we recommend adhering to the precautionary principle and urgently implementing all management strategies in conjunction with halting major future developments and co-governance.

4.2 | The benefits of co-governance

Good governance is widely accepted as beneficial to conservation (Biermann et al., 2012; Green et al., 2016; Lockwood et al., 2012; Stoll-Kleemann et al., 2006). However, the ways in which governance can influence conservation effectiveness have primarily been assessed for protected area management and in prioritizing investment between countries—where countries with lower levels of governance are deemed as higher risk and therefore less worthy of investment (Eklund, Arponen, Visconti, & Cabeza, 2011; Miller, Agrawal, & Roberts, 2013; Waldron et al., 2013). Surprisingly, no study has assessed the cost-effectiveness of governance itself, even though it is likely that supporting successful governance structures could provide a deeper leverage point for effective conservation.

Our results suggest that co-governance is a cost-effective strategy that could improve the feasibility of all our management strategies, and because of this, it was the only way in which key species groups (Raptors and Bats) are estimated to reach a 60% threshold of probability of persistence. Many questions remain as to what kind of co-governance structure is best for our particular study region, that is, legislated versus nonlegislated, elected versus nonelected board, how to address legal pluralism (Canadian and Indigenous law), considerations related to implementing the United Nations Declaration on the Rights of Indigenous Peoples, intergovernmental cooperation via delegated authority or strategic agreements, complementary amendments to existing Canadian federal and provincial laws, and secretariat composition and function. Here we only assessed one conceptual co-governance framework (Appendix S4). Further research on the feasibility of different forms of co-governance, how co-governance can maximize the feasibility of direct management strategies, and an uncertainty analysis on the estimated impact of co-governance would likely be of benefit to policy makers.

A central tenet of any co-governance structure in this region is that First Nations must be a full partner. Reinstating Indigenous resource governance and conservation policy has been shown to deliver biodiversity, economic, and cultural benefits (Ens, Scott, Rangers, Moritz, & Pirzl, 2016). For example, Indigenous guardian programs can provide a three-fold return on investment in terms of social, economic, cultural, and environmental value (Social Ventures Australia, 2016). To achieve successful conservation outcomes in the Fraser River Estuary, it is crucial that First Nations play a leadership role in designing and implementing co-governance, as well as carrying out management actions, and having support in developing necessary capacity.

In our case, even the limited form of co-governance described was expected to bring a wealth of co-benefits in addition to conservation outcomes. These benefits include: better cohesion between partners, stricter adhesion to regulations, long-term collaboration on projects, the security of ongoing funding, participatory decision making, a better balance between healthy ecosystems and development opportunities, savings in time and resources, better access to information (such as spatial data), and more public engagement. Our technique is the first to explicitly quantify the cost-effectiveness of co-governance in terms of species conservation and provides a blueprint for future work in imperiled regions.

4.3 | The value of investing in nature

While the overall cost of conservation management is estimated to be ~$381 M over 25 years ($15 M annually or $6 per person per year in greater Vancouver), it is worth considering the potential financial return-on-investment of many of our strategies. For example, in 1998, the average estimated value from commercial, recreational, and Aboriginal fisheries in the Fraser River basin was $300 M *annually* (Marshall, 1998), more than 20 times the estimated annual cost of our entire strategy portfolio ($15 M annually). Recent reports for sockeye salmon, just one species of conservation concern in our study area, value commercial and recreational revenue of this fishery at between $9 and 25 M annually (Fisheries and Oceans Canada, 2012; Fisheries and Oceans Canada and British Columbia Minister of Agriculture, 2011). Whale tourism revenue (including, but not limited to, the southern resident killer whale) amounts to $26 M annually in the Salish Sea (Raincoast Conservation Foundation, 2016). Other aspects that are not currently costed include: the cultural value of many species for Indigenous communities, the likely cost-effectiveness of green infrastructure (Kousky, Olmstead, Walls, & Macauley, 2013), and the number of jobs and tourism revenue created through conservation management and eco-tourism. Together, the $15 M estimated annual cost of improving the persistence of species of conservation concern is likely to be more than offset by the substantial economic benefits generated.

4.4 | Difficult threats to tackle

Unlike results from Priority Threat Management assessments conducted in less contested landscapes (Carwardine et al., 2012; Chadés et al., 2015), no species groups were estimated to reach a >70% probability of persistence within the Fraser River estuary under our most likely scenario, even if all management strategies and co-governance were implemented. We posit five likely reasons why.

First, many of the species in our region are migratory and therefore threats and large-scale regime shifts affecting productivity outside the bounds of our study area can have a detrimental effect on their estimated probability of persistence within the Fraser River estuary.

Second, some of the most difficult conservation challenges arise in regions with multiple competing uses. It is therefore possible that reaching higher persistence probabilities is unlikely given current threats and management options. Additionally, no strategies explicitly addressed increased human population densities and associated urbanization. Multiple large-scale industrial threats also face our study region, including (but not limited to): the Trans Mountain pipeline, a new container terminal in an ecologically sensitive area, an expanded coal and shipping terminal, and a new bridge that would allow for more shipping traffic into the estuary (for full list of threats see Boundary Bay Conservation Committee, 2016). The gravity of these multiple future threats is underscored when considering that the benefits from Halting Future Major Industrial Development are estimated to be greater than nine out of 10 management strategies.

Third, the impacts of climate change are also expected to be particularly severe in the study region, where temperature increases are affecting fish migration success, reproduction, and survival (Martins, Hinch, Cooke, & Patterson, 2012), ocean acidification can affect calcifying organisms, and sea level rise can drastically alter coastal habitats (Robins et al., 2016). While climate change was considered by experts as part of the baseline scenario, it was not assessed in more detail due to current regional data limitations.

Fourth, it is possible that our management strategies need to be adjusted and improved in order to reach higher probabilities of persistence. Alongside our core group of 24 ecological experts that provided benefit estimates, when developing our strategies, we gained insights from a total of 65 experts in the region and are confident that with current knowledge we have covered the main strategies needed. However, our strategies were designed with feasibility in mind and it is possible that more ambitious plans are needed to reach higher conservation outcomes.

Fifth, our results are subject to numerous sources of uncertainties in our experts' estimates. The considerable range in benefits estimated by individual experts (Figure S5) reflects the diversity of views in our expert group and shows the inherent uncertainty in expert elicitations and the importance of not relying on estimates from a single individual expert (Hemming et al., 2018). In-depth experimental or observational data could have reduced uncertainty and aided decision makers on the design and likely impact of our management strategies but is not currently available. The uncertainties and limitations inherent in expert estimates are compounded by the complex nature of heavily modified regions that are facing multiple escalating threats. For example, it is difficult for experts to predict the future benefit to species of implementing our strategies while also accounting for the many uncertain variables related to data gaps, the effect of cumulative threats, and an increasing human footprint in the region. In addition to this, while it was logistically necessary to group species by their common threats, this added another layer of uncertainty in experts' estimates, since not all species will benefit to the same degree as a result of the implementation of a conservation strategy. Furthermore, this analysis does not fully address the inherent uncertainties related to the true cost of management strategies. Due to the high economic value of the study region (where costs are prone to external market shifts, changes in policy regimes, and inflation) and the uncertainty in general of the costs of conservation in riverine systems (Bernhardt et al., 2005), all costs should be treated as estimates only. Finally, while methodologies exist to address uncertainty in both cost and benefit estimates, our current approach does not address uncertainties in estimates of feasibility.

Despite these challenges, timely action based on the information at hand is likely more effective than waiting for more information while species continue to decline (Martin et al., 2012). Therefore, we argue that these uncertainties are outweighed by the urgent need for action. Our results indicate that *all* management strategies are needed in order to give species the best chance of survival in this region. Despite the uncertainty inherent in our results, because we are not recommending choosing between strategies, we reduce the risk of making "the wrong" decision in terms of what strategy to implement. Moreover, all of our management strategies provide environmental, cultural, and economic co-benefits. Importantly, our flexible approach can be updated, adapted, and improved as more species-specific information on threats and effective actions to abate these threats becomes available. This approach can also be updated in light of external shifts in markets or policy.

5 | CONCLUSIONS

Conservation action plans that explicitly consider the value of co-governance along with the benefits, costs, and feasibility of action are urgently required for highly contested regions. The attributes of the Fraser River estuary converge to form an important case study for the prioritization of management strategies and co-governance in heavily urbanized biodiverse socio-ecological systems. Our expert elicited assessment shows that conservation is possible in highly contested regions and the return on investment likely offsets the cost of management—but that co-governance is key to increase the cost-effectiveness of management and ultimately the probability of species persistence. In a world of rapid urban sprawl and ongoing biodiversity loss, our approach provides a methodology to identify the most cost-effective strategies to conserve biodiversity in areas of high ecological, cultural, and economic importance. We have the tools to effectively curtail biodiversity loss, but we must employ them while there is still time to act (Martin, Nally, et al., 2012).

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CONFLICT OF INTEREST

There are no competing interests.

AUTHOR CONTRIBUTIONS

Laura J. Kehoe and Tara G. Martin were responsible for research design and data collection. Laura J. Kehoe was responsible for data analysis and figure preparation. Laura J. Kehoe, Julia K. Baum, and Tara G. Martin were responsible for manuscript writing and preparation. Jessie Lund was responsible for species threat database. All authors provided input on management strategy design and manuscript writing and have read and have approved the final version of this manuscript.

DATA AVAILABILITY STATEMENT

All relevant data available in the supplementary information.

ETHICS STATEMENT

We complied with all relevant ethical regulations: informed consent was obtained from all participants and this study was approved by the Human Research Ethics Board of the University of Victoria (Approval Number BC16-454).

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of this article.

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