






## RESEARCH ARTICLE

# Decision analysis rooted in Indigenous and Western scientific knowledge identifies cost-effective strategies for managing hyperabundant deer to restore keystone places

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Natural Sciences and Engineering Research Council of Canada, Vanier Canada Graduate Scholarships; Liber Ero Chair in Conservation; UBC, Faculty of Forestry, Graduate Program Internal Awards, Indigenous and Community Engagement Research Fund; UBC Indigenous Strategic Initiatives Fund; Natural Sciences and Engineering Research Council of Canada, Grant/Award Number: RGPIN-2019-04535

**Handling Editor:** Chelsey Gerala Armstrong

**Abstract**

1. The hyperabundance of herbivores—a result of altered human relationality with the land and the extirpation of predators—is leading to large-scale degradation of keystone ecosystems across the globe. Designing and implementing socially acceptable and cost-effective strategies that meaningfully reduce herbivore populations while allowing for the recovery of ecological function and cultural relationality is an inherently complex issue. As a result, decision paralysis is common, leading to delayed or avoided action and continued ecosystem loss and degradation.
2. Using a structured decision-making process that incorporated expert elicitation, population modelling and cost-effectiveness analyses while honouring multiple knowledge systems, we identified five discrete and four portfolio strategies for managing hyperabundant black-tailed deer (*Odocoileus hemionus columbianus*) in the Southern Gulf Islands of British Columbia, Canada, with consideration to benefit, feasibility and cost objectives.
3. Hunting led by local Indigenous Nations was ranked the most cost-effective strategy when benefits considered well-being of peoples and place holistically, and accounted for both Indigenous and Western science worldviews. When only

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Western perspectives were included, increased licensed hunting by local communities and hiring professional deer reduction specialists were ranked the most cost-effective. However, while increased licensed hunting had a >50% likelihood of project uptake and success (i.e. feasibility), the strategy had <50% likelihood of achieving any benefit objective. In comparison, Indigenous-led hunting, professional deer reduction specialists, and all portfolio strategies had >50% likelihood of meeting at least one benefit objective, although only Indigenous-led hunting also had >50% likelihood of achieving feasibility objectives.

4. *Synthesis and applications.* We provide a roadmap for decision-makers across the globe to robustly and transparently assess the problem of herbivore hyperabundance and inform solutions within their context. Within the Salish Sea, our work highlights the need to support hunting, and in particular, Indigenous-led hunting, as cost-effective strategies to promote revitalization of well-being of peoples and place.

#### KEYWORDS

black-tailed deer, expert elicitation, hyperabundant herbivores, Indigenous knowledge, structured decision-making, trophic cascades, well-being

## 1 | INTRODUCTION

The increased abundance of herbivores due to the alteration of human–nature relationships and extirpation of predators is leading to large-scale degradation of ecosystems across the globe (Bliege Bird & Nimmo, 2018; Cuerrier et al., 2015; Ripple et al., 2014). Without these top-down regulating forces, ungulates (hoofed mammals, for example deer, wild boar, elk, moose) have become hyperabundant—the persistent, human-driven elevation of population densities across multiple years (Moore et al., 2023). Hyperabundant herbivores drastically alter understory vegetative cover and composition, and without timely intervention, can result in local species decline and extinction in the short term (i.e. trophic cascade) and ecosystem collapse in the long term (Estes et al., 2011; Xu et al., 2023).

In North America, managing hyperabundant black-tailed deer (*Odocoileus hemionus*) and white-tailed deer (*Odocoileus virginianus*) (i.e. population control) has been a widely recognized conservation issue for the past few decades due to declines in regulation (Côté et al., 2004; McShea, 2012). Several hyperabundant wildlife management programmes have been developed and implemented with varying levels of success across the continent (Simard et al., 2013; Warren, 2011).

One location where the impacts of hyperabundant deer and potential management strategies are of significant concern is in the Southern Gulf and San Juan Islands of the Salish Sea, off the coast of British Columbia (BC), Canada and Washington, United States (Arcese et al., 2014; Beckett et al., 2022; Gonzales & Arcese, 2008; Martin et al., 2011). This island archipelago has been stewarded (i.e. long-term duty of care) by local Indigenous communities for thousands of years and contains diverse keystone ecosystems

of immense ecological and cultural significance (Charlie, 2021; Claxton & Price, 2019; Cuerrier et al., 2015; Turner & Hebda, 2012). Colonization in the early 1800s dispossessed many Indigenous Peoples from their lands and practices, and predators such as wolves (*Canis lupus*) and cougars (*Puma concolor*) were purposefully locally extirpated from these islands as settlers viewed them as a threat (Klees Van Bommel et al., 2020; Murphy & Black, 2015). Concomitantly, the logging of mature forests into early seral stands, as well as the conversion to highly nutrient- and water-rich agriculture and residential gardens, has provided forage subsidies that contribute to inflated deer populations (Fisher et al., 2024; Long et al., 2024). The combination of altered population regulation and landscape conversion—along with declines in hunting by settler communities and compounding capitalistic and colonial stressors (i.e. housing development, restrictive hunting regulations, discriminatory enforcement, public sentiments; Claxton & Price, 2019; Dick et al., 2022; WSÁNEĆ Leadership Council, 2022)—has resulted in large-scale overbrowsing from native black-tailed deer (>10 deer/km<sup>2</sup>) and introduced herbivores (i.e. European fallow deer (*Dama dama*), goats and sheep (*Ovis* spp.), Canada goose (*Branta canadensis*)) (Arcese et al., 2014).

Discussions about hyperabundant deer management are now underway with decision-making bodies in the Salish Sea (Parks Canada, 2019; Parks Canada Agency Government of Canada, 2023). However, implementing management actions for hyperabundant wildlife in a timely and effective manner is challenging, as decision paralysis delays action (i.e. prolonged indecision from choice overload and/or fear of choosing incorrectly) (DeFries & Nagendra, 2017). There are a range of approaches to consider when reducing the impact of hyperabundant wildlife, and the diverse and often conflicting perspectives behind these options stoke decision-makers'

fears of public backlash and socio-political controversy (Gamborg et al., 2020; Martin et al., 2020). Structured decision-making (SDM) offers a transparent, repeatable and defensible method to tackle this complex problem by identifying and prioritizing a diverse range of management strategies that are (1) ecologically and culturally beneficial, (2) socially acceptable and (3) cost efficient (Hemming et al., 2022).

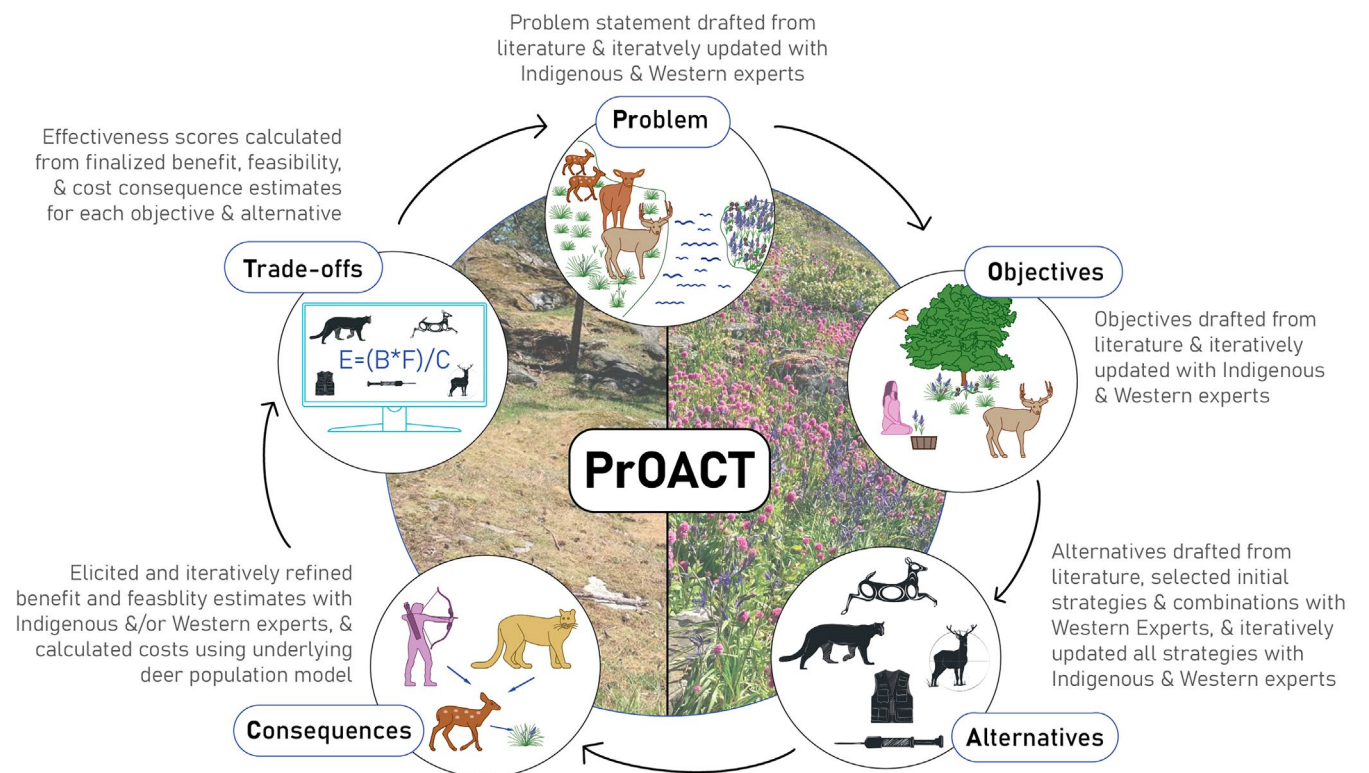
Therefore, we—a group of Indigenous and Western scientists, land stewards and knowledge holders in the region—applied a structured decision-making process to identify effective solutions to address deer hyperabundance in the Salish Sea of British Columbia. Authorship includes two Western science graduate students who served as the decision analysts and facilitators, as well as the six Indigenous hunters, Elders and knowledge holders from local Coast Salish Nations (Quw'utsun (Cowichan), Spune'luxutth (Penelakut), W SÁNEĆ (Saanich)) and 11 Western government scientists and academics (from Parks Canada and various regional academic institutions) who participated in the decision analysis process. Regionally, this work led to the development and assessment of nine management strategies to reduce deer density to a level that would allow for recovery of keystone ecosystems. Globally, we present a process for systematically designing solutions for hyperabundant wildlife that balance ecological, societal, cultural and financial needs while honouring knowledge and value systems.

## 2 | MATERIALS AND METHODS

We present our process for combining structured decision-making, expert elicitation, population modelling and cost-effectiveness approaches to identify effective herbivore management strategies that are rooted in place-based context and that honour multiple knowledge systems. We share the application of this approach within the context of the Southern Gulf Islands of the Salish Sea.

### 2.1 | Structured decision-making

We conducted a structured decision analysis to identify and estimate the success of different hyperabundant deer management strategies in the Southern Gulf Islands (Gregory et al., 2012; Hemming et al., 2022; Figure 1). We relied on a diverse and inclusive group of experts knowledgeable on the ecology, hunting and management of deer, all of whom were involved throughout the decision analysis as equitable co-authors, sharing their knowledge in a relational manner based in continuous ethical consent (Tuhawai Smith, 2021; Behavioural Research Ethics Board approval H19-01635). We recruited two groups—from existing relationships, stakeholder analysis (Bryson, 2004) and snowball recommendations (Cohen & Arieli, 2011)—the first composed of Indigenous hunters, Elders and knowledge holders from local Coast



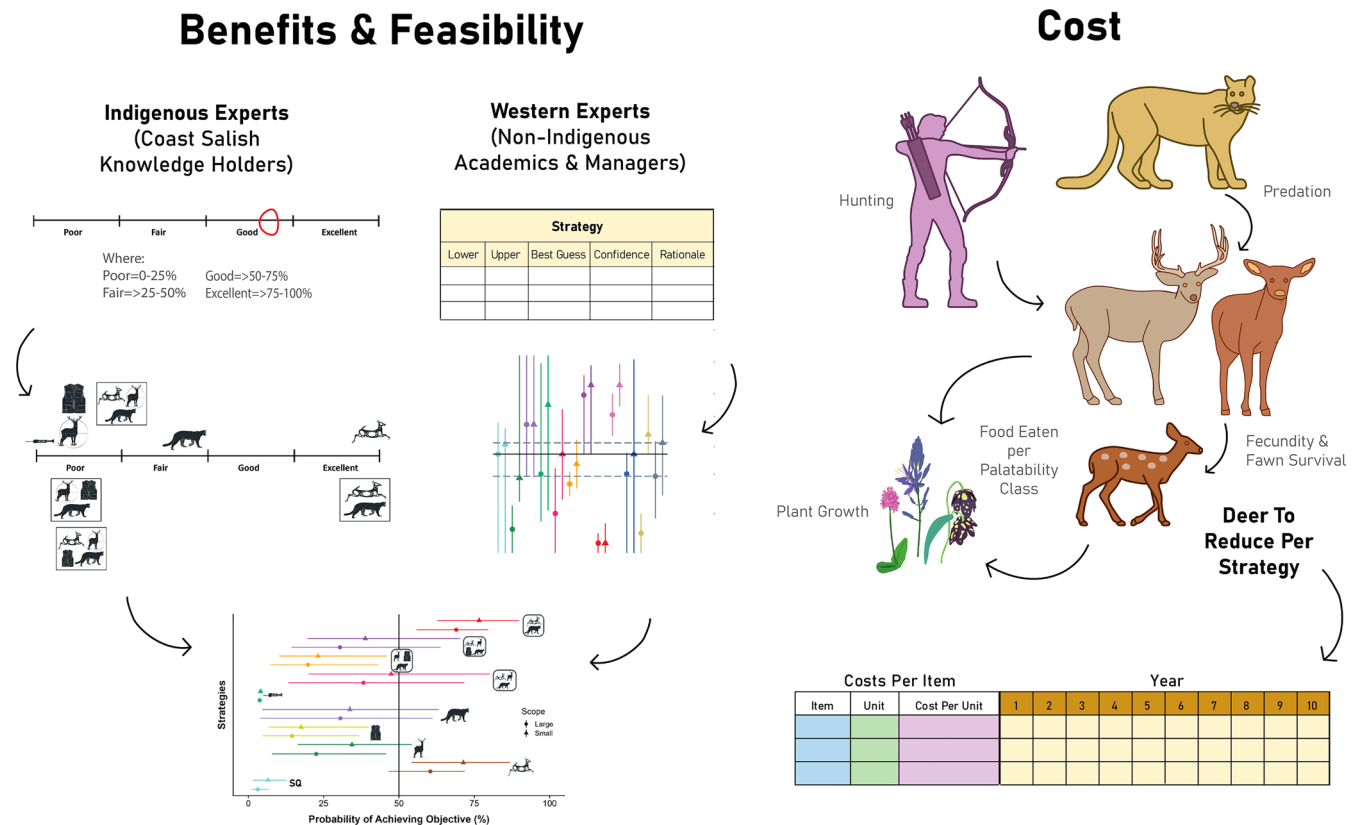
**FIGURE 1** Structured decision-making method illustrating the iterative steps of SDM (ProACT): Defining the Problem, eliciting Objectives, selecting Alternatives, estimating Consequences and calculating Trade-offs. Each step highlights the approach used in our analysis and the contribution of Indigenous experts and Western experts throughout the decision analysis process. Photos are browsed (left) and intact (right) oak meadows in the Salish Sea, highlighting the intensity of ecosystem alterations and the need for decision analyses.

Salish Nations (Indigenous experts), and the second composed of non-Indigenous academics and government managers (Western experts), for a total of 17 experts (Supporting Information). The groups had separate meetings due to logistics and differences in availability, but also to create culturally safe and trauma-informed spaces for the Indigenous experts—safe places of healing that empower Indigenous members to share their perspectives and stories (Tujague & Ryan, 2021). Working synchronously but separately through the steps of structured decision-making (SDM) (i.e. ProACT; Hemming et al., 2022), the groups defined the decision problem, succinct objectives and alternative management strategies to meet those objectives. The experts then estimated the likely outcome of those actions meeting the objectives ('consequences')—or measurable outcomes relating to the benefit, feasibility and cost of undertaking different actions—before evaluating trade-offs between outcomes through a cost-effectiveness analysis (Hemming et al., 2018; Martin, Burgman, et al., 2012). These steps were performed iteratively throughout the decision analysis—refining and adjusting the elements of ProACT over a four-year period (September 2020 to July 2024) in response to discussion and knowledge sharing within and between groups performed by facilitators (Supporting Information).

## 2.2 | Structured expert elicitation

Structured expert elicitation was used to estimate the consequences of undertaking proposed strategies on the expert-defined benefit and feasibility objectives, tailored to each group's needs (Figure 2; Martin, Burgman, et al., 2012). Literature-derived drafts of the problem, objectives and potential management strategies were discussed and iteratively adapted throughout the analysis, predominantly within groups (intra-group) during numerous in-person or online meetings, but as possible between groups (inter-group) through knowledge sharing performed by facilitators (Supporting Information). For the elicitation of consequence values, the IDEA (Investigate, Discuss, Estimate, Aggregate) structured elicitation protocol was used, as it elicits more accurate and well-calibrated expert judgements by minimizing groupthink (Hemming et al., 2018).

For the Investigate step, intra-group experts discussed the questions being asked before providing their initial best-guess, worst-case and best-case estimates of consequences, in which Indigenous experts scored strategies visually and Western experts performed a 4-point elicitation of best-guess estimates and confidence intervals (Supporting Information). For the Discuss and Estimate steps,



**FIGURE 2** Methods for obtaining estimates for cost-effectiveness analyses. Benefits and feasibility (left) were elicited from Indigenous experts and Western experts, with Indigenous experts' elicitation centred on visual assessments and oral storytelling and Western experts' on spreadsheet elicitation and written rationales. Costs (right) were calculated based on modelled estimates of annual deer removal, computed by modifying relationships between plant growth, food consumption, deer reproduction, predation and hunting based on regional- and strategy-specific variables.

consequence values from all individuals were anonymously presented back to each group, providing intra-group experts an opportunity to discuss estimates, clear up misunderstandings and review inter-group values, before adjusting individual estimates. For the Aggregate step, standardized consequence estimates were averaged by and/or across groups (Supporting Information) and were updated and visually shared with all experts throughout the process. Multiple iterations of the Discuss, Estimate and Aggregate steps were performed over the four-year period (~15 meetings in total) until all experts finalized their estimates. R Studio (version 4.3.3) was used for all quantitative analyses (R Core Team, 2024).

In addition to eliciting quantitative values, we recorded qualitative data from all experts, using semi-structured interview approaches (Brinkmann, 2014). Participants were asked a range of pre-established questions, discussions were given the flexibility to develop as needed, and written transcripts or comments were recorded (Supporting Information). All available written materials were then processed in NVivo 14 (Lumivero, 2023), and, to highlight critical information about the decision analysis, interview and commentary texts were informally coded around objective- and strategy-specific primary codes, utilizing a deductive qualitative analytical approach based in a SDM (i.e. PROACT) rooted theoretical framework (Ezzy, 2013).

## 2.3 | Cost estimation using deer population modelling

Costs were calculated for each strategy based on the total estimated number of deer to be removed to recover ecological integrity—defined as falling below the 8 deer/km<sup>2</sup> regional threshold recommended by Arcese et al. (2014). Annual values for each strategy were estimated using a deer demographic population model, combining ecological models of logistic growth, predator–prey relationality, fecundity and mortality, and using regionally derived data (Figure 2). Models accounted for decreasing search efficiency and strategy effectiveness due to effects of density on capture efficiency (Irvine & Thorley, 2024). Sensitivity analyses were calculated around each strategy model, altering just one input variable to best- or worst-case scenario estimates to calculate a range of values per strategy to be input into costing. Unit costs were derived from a combination of project budgets, interviews with managers, published and grey literature and online equipment costs, and the net present-day value (NPV) of each strategy's budget was computed in Canadian dollars across the project time. More in-depth information detailing the design of these models and their underlying assumptions, variables and references, as well as on costs and discounted NPV calculations, is presented in Supporting Information.

## 2.4 | Cost-effectiveness analyses

We used a cost-effectiveness approach to examine trade-offs between strategies, which scores the overall ability of a strategy

to achieve its expected benefit (benefit × feasibility) relative to its financial cost, using the equation (Joseph et al., 2009):

$$\text{Cost – Effectiveness} = \frac{\text{Benefit}_{ij} \times \text{Feasibility}_{ij}}{\text{Cost}_j} \times 100$$

where benefit and feasibility were estimated by experts for each individual objective (*i*) and alternative strategy (*j*), cost was NPV for each strategy (*j*), and values were multiplied by 100 for ease of comparison.

All strategy estimates were evaluated in terms of additionality, or compared to 'what would have happened in the absence of the proposed strategy', defined as the status quo and developed from literature and expert discussion (Hemming et al., 2022). The sensitivity of cost-effectiveness estimates to uncertainty was evaluated using the experts best- and worst-case scenarios and comparing these to the outputs using the experts' best guess.

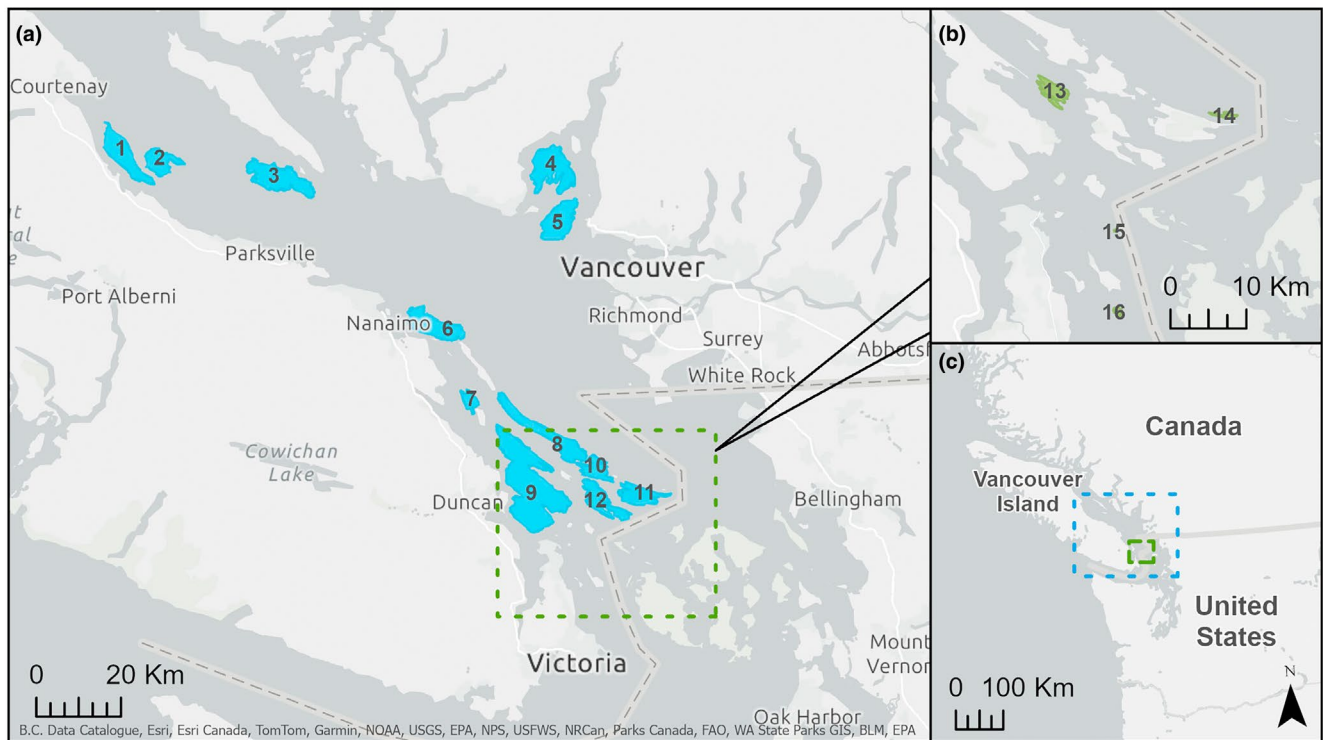
## 3 | RESULTS

Working through the decision analysis steps iteratively with all experts, we evaluated the cost-effectiveness of nine different deer management strategies (five discrete and four portfolio) on the basis of six different objectives (three benefits, two feasibilities, one cost) for different island contexts within the Southern Gulf Islands.

### 3.1 | Problem definition

The decision problem was defined as identifying the optimal management strategies to recover browsing-sensitive and culturally significant native plant species' recruitment, persistence and function in the Salish Sea by managing hyperabundant black-tailed deer in a way that was societally and culturally acceptable, cost-effective and ecologically sound.

The spatial extent of this problem was defined as the Southern Gulf Islands of the Canadian Salish Sea (Figure 3). These islands vary in size, human population, habitat complexity and land ownership, all of which impact the ability to effectively carry out deer management. Therefore, the spatial scope was considered in both 'small' and 'large' island contexts. All small islands considered in our assessment are part of the federally protected Gulf Islands National Park Reserve (GINPR, managed by Parks Canada) and were considered 'small' due to their size and lack of permanent residents. The majority of 'large' islands are part of the Islands Trust local governing body, are home to permanent human populations and are ~30× larger than small islands. Impact focused on camas (*Camassia* spp.) and Garry oak (*Quercus garryana*) meadows—endangered keystone places that are ecologically and culturally important ecosystems in the Salish Sea that were stewarded by Coast Salish Nations for thousands of years as Indigenous food systems (Charlie, 2021; Turner & Hebda, 2012). Analysis focused on native black-tailed deer—a keystone species serving a vital ecological role and a significant source of food and



**FIGURE 3** Large (a) and small (b) islands part of the decision analysis in the Salish Sea (c). Name and size (km<sup>2</sup>) of all numbered islands: 1. Denman Island (52), 2. Hornby Island (30), 3. Lasqueti Island (66), 4. Gambier Island (69), 5. Bowen Island (50), 6. Gabriola Island (53), 7. Thetis Island (11), 8. Galiano Island (58), 9. Saltspring Island (185), 10. Mayne Island (23), 11. Saturna Island (32), 12. North (27) & South (9) Pender Islands, 13. Prevost Island (6.74), 14. Tumbo (1.23) & Cabbage (0.04) Islands, 15. Rum Island (0.05) and 16. D'Arcy Island (0.86).

resources for Indigenous communities (i.e. healthy meat, pelt for drums, hooves for ceremony; pers. comm. E. Pelkey; Garibaldi & Turner, 2004; Kelly, 2017). The temporal scope of the decision was set as 10 years, which was deemed a feasible time period to enact strategies and begin to assess impacts. Lastly, decision-makers, titleholders, rightsholders and stakeholders involved in this decision were identified and consulted, including local Coast Salish Nations, Islands Trust, Parks Canada, BC Parks and local parks and conservancies.

### 3.2 | Objectives

Six project objectives were identified by Indigenous and/or Western experts, falling within categories of (1) maximizing benefit (three objectives: maximize well-being (i.e. human and ecological needs), maximize ecosystem function, reduce deer density), (2) maximizing feasibility (two objectives: maximize project uptake, maximize project success) and (3) minimizing cost (1 objective) (Figure 4, Table S1). Expert-elicited benefit and feasibility objectives were defined as the likelihood of the desired outcome being met over the 10-year time period (0%–100%), and costs were in Canadian dollars.

While Western experts initially designed the ecosystem function and deer density benefit objectives, Indigenous experts wished only to provide estimates for an overarching, holistic well-being objective, as deer stewardship is viewed as integrally connected with

Indigenous food and cultural sovereignty, and the well-being of the land encompasses the well-being of its Peoples—a positive, holistic state of physical, mental, emotional, spiritual and cultural health (Grenz, 2024; Tsuji et al., 2023). Therefore, Indigenous experts used the well-being objective, while Western experts provided estimates for all three benefit objectives. Feasibility estimates were only derived from Western experts, but with additional time and compensation, it would be important to elicit Indigenous views.

We acknowledge the potential circularity in asking Indigenous hunters whether more Indigenous hunting is needed to help with connection to land and culture, which is partially defined by Indigenous hunting; however, this framing is needed, as Nations have been systematically disempowered on their own lands. These questions help incorporate notions of social justice and cultural revitalization into a predominately ecologically focused decision framework—a vital viewpoint as restoring Indigenous stewardship is inextricable from restoring Indigenous culture and sovereignty (Claxton & Price, 2019; Dick et al., 2022).

### 3.3 | Alternatives

The initial selection of drafted alternatives was completed by Western experts, and then reviewed and altered by Indigenous experts. The updated version was used in the final iteration of the decision analysis.

Objectives

<b>Objectives</b>	<b>Benefits</b>	<b>Feasibility</b>	<b>Cost</b>
	<p><b>Maximize Wellbeing</b>    Maximize ecosystem function and deer reduction, while supporting Indigenous cultural practices and food sovereignty (0–100% Likelihood)</p> <p><b>Maximize Ecosystem Function</b>    Maximize the cover, richness, and diversity of browsing-sensitive and ecologically and culturally significant native plants within 10 years (0–100% Likelihood)</p> <p><b>Reduce Deer Density</b>    Maximize the likelihood that the strategy will reduce the number of deer (#deer/km<sup>2</sup>) to the level needed to allow ecological recovery (~&lt;8 deer/km<sup>2</sup>) in the Southern Gulf Islands within a timeframe of 10 years (0–100% Likelihood)</p>	<p><b>Maximize Project Uptake</b>    Maximize the likelihood that the strategy will be taken up and funded within 2 years, i.e. have socio-political support for implementation (0–100% Likelihood)</p> <p><b>Maximize Project Success</b>    Maximize the likelihood of success in technically implementing the selected alternative within the 10-year time frame (0–100% Likelihood)</p>	<p><b>Minimize Cost</b></p> <p>Minimize the net present value of the accumulated cost of the project over the 10-year time frame (\$ CAD)</p>

Alternatives

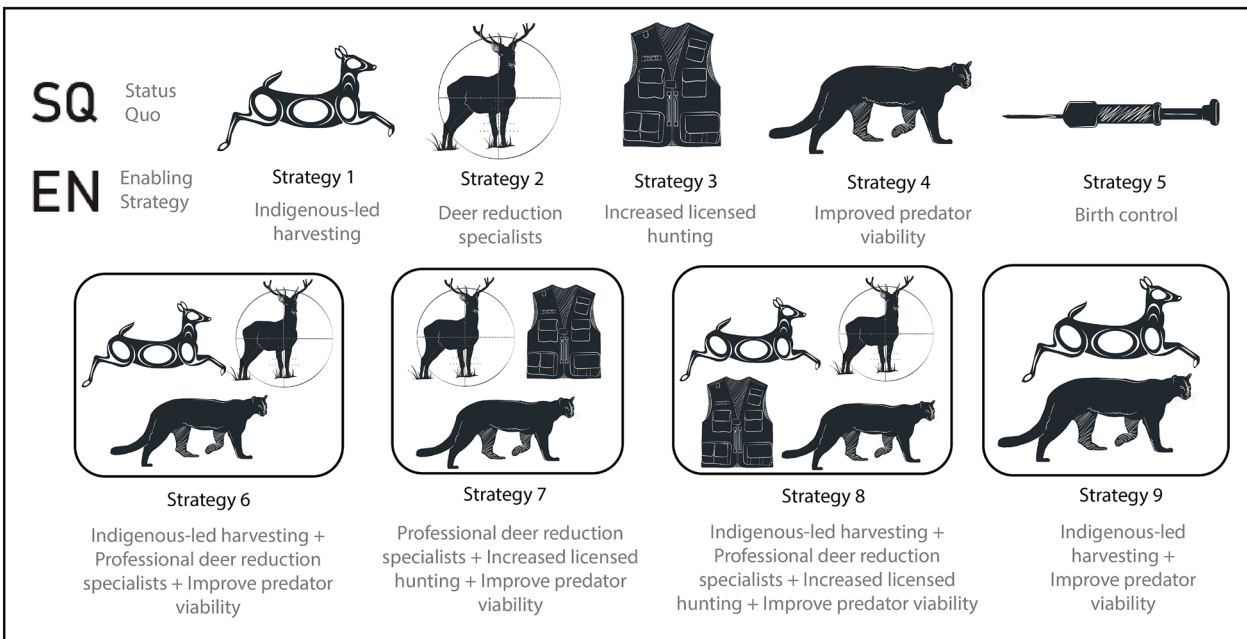


FIGURE 4 Expert-defined objectives and alternatives.

Western experts first discussed and amended an initial list of strategies developed from deer management literature and experience, including various lethal and non-lethal alternatives (Table S2), before selecting the top five strategies for the full decision analysis to minimize elicitation fatigue. Experts voted Indigenous-led hunting (1), deer reduction specialists (2), increased licensed hunting (3), improved predator viability (4) and birth control (5) as the five best strategies to consider for this locale and species (Figure 4, Table S3).

Indigenous-led hunting and deer reduction specialist strategies rely primarily on paid hunters to facilitate deer reduction, although the hunters and protocols vary greatly between the two approaches. The increased licensed hunting strategy relies on motivating hunting by residents without payment. The predator strategy focuses on reducing human-driven predator mortality rather than reintroduction, as the central issue for predators (cougars and wolves) is survival once they colonize an island and therefore relies on education and financial incentive programs. Lastly, the birth control strategy relies on funding veterinarians to administer immuno-contraceptives to

does for reproductive population control. In-depth information on each strategy (i.e. components, costs, assumptions) can be found in Supporting Information.

As combinations of strategies have been shown to improve action efficacy and complementarity, Western experts voted on four combinations of the five strategies to develop portfolio strategies. Western experts also constructed an enabling strategy (EN) (Figure 4), which comprised the education, communication and other activities needed to enable any strategy chosen. Indigenous experts provided feedback on all strategies, adapted specific components of each strategy, defined the Indigenous-led hunting strategy and amended acceptable portfolio combinations.

3.4 | Consequences

We present the quantitative expert elicited and computed consequence values (Table 1). Detailed key qualitative findings revealing

**TABLE 1** Consequence table showing best-guess outcomes of each strategy for each objective for large islands.

Alternatives	Benefits			Feasibility			Cost
	Maximize well-being (0%–100%)	Maximize ecosystem function (0%–100%)	Reduce deer density (0%–100%)	Maximize project uptake (0%–100%)	Maximize project success (0%–100%)	Minimize costs (\$ CAD)	
0. Status quo	3	8	7	80	98	\$ –	
1. Indigenous-led hunt	60	34	37	53	62	\$5,846,782	
2. Professional deer reduction specialists	23	48	64	36	60	\$5,935,636	
3. Increase licensed hunting	14	25	30	51	66	\$3,024,443	
4. Improve predator viability	31	31	36	27	52	\$5,266,113	
5. Birth control	4	32	35	32	38	\$8,825,837	
6. Portfolio 1, 2 & 4	38	59	74	37	52	\$8,217,969	
7. Portfolio 2–4	21	55	67	29	37	\$6,815,685	
8. Portfolio 1–4	30	62	73	35	45	\$8,412,774	
9. Portfolio 1 & 4	69	54	58	39	44	\$6,081,644	

Note: Benefits and Feasibility are estimated in likelihood of achieving outcomes (0%–100%) and averaged across experts, whereas Cost is estimated as the net present-day value of \$CAD spent over 10 years using a 4% discount rate and includes costs for ‘enabling strategies’. The colour-scheme shows which strategies are the most (green) and least (yellow) effective for achieving each objective.

benefits, barriers and scenarios of each strategy are integrated throughout and are available in Supporting Information (Table S4).

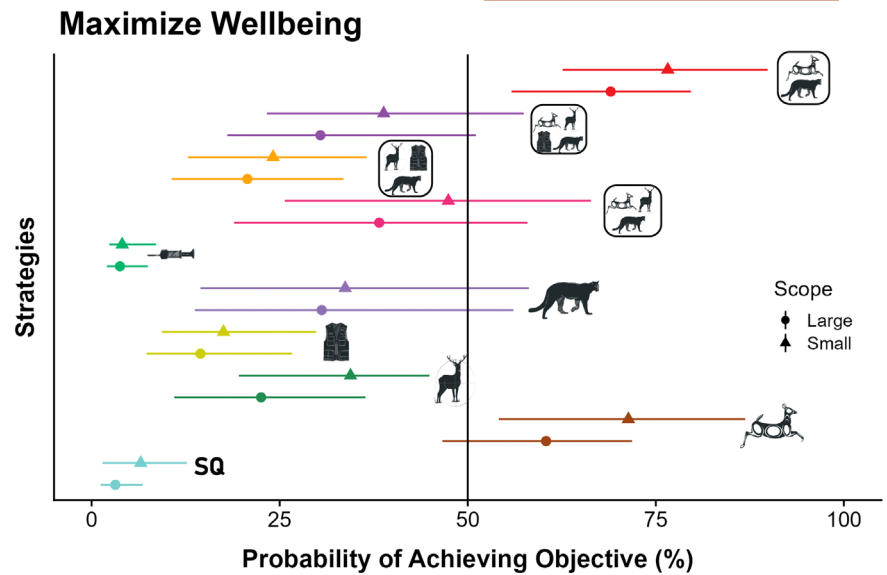
### 3.4.1 | Expert elicitation of benefit and feasibility objectives

Indigenous experts estimated the likelihood of each of the strategies to achieve the ‘maximize well-being’ objective, in which values are for both large- and small- islands contexts (Figure S1, Table S5), while Western experts provided estimates for all benefit and feasibility objectives (Figures S2 and S3, Table S6). Overall, small-island estimates had higher probabilities of achieving objectives than large-island estimates, based on the perceived higher likelihood to reduce deer density and allow recovery. No single strategy had the highest or lowest values across all benefit and feasibility objectives, although ‘improve predator viability’ and ‘birth control’ had relatively low values across objectives. Experts agreed ‘status quo’ will not improve ecosystem function, although non-zero values account for potential natural population regulation through starvation due to exceedance of carrying capacity, or emerging diseases such as chronic wasting disease (transmissible spongiform encephalopathy) and cervid adenovirus.

#### ‘Well-being’ benefit estimates by Indigenous & Western experts

Averaging the ‘well-being’ objective across Indigenous and Western experts, on large islands, ‘Indigenous-led hunting’ (60% [47%–72%]) and ‘Indigenous-led hunting and improved predator viability’ (69% [56%–80%]) were the only strategies with likelihoods >50%, or being able to meet ecological and cultural well-being considerations (Figure 5, Table 1, Table S7). ‘Indigenous-led hunting and improved predator viability’ was the only portfolio strategy deemed not to conflict with Indigenous hunting interests and therefore was most likely to support Indigenous cultural practices and food sovereignty, although experts expressed potential issues due to expected opposition to living with predators. Most other strategies had relatively similar, low values, reflecting experts’ comments that those strategies provided lower benefits to overall well-being. ‘Birth control’ was the only discrete strategy near 0% (4%) across Indigenous and Western experts. Although birth control has been used in nearby territories where hunting is more challenging (Fisher et al., 2025), Indigenous experts were strongly opposed to birth control here for two reasons. First, they viewed it as unethical to repeatedly capture and administer a drug to an animal, and worried about the welfare of the animal during these procedures. Second, they expressed deep concern that administering birth control contaminates the meat and therefore makes the animal unable to be consumed—stated as akin to ‘cultural genocide through the contamination of their food supply’ (K. Thomas). Western expert estimates reflect feedback received from Indigenous experts on their view of ‘birth control’ with regards to animal welfare and cultural and food sovereignty.

**FIGURE 5** Expert's estimates of the likelihood that the 'well-being' objective will be achieved by each strategy for large-(circle) and small-(triangle) island contexts. Each point indicates the average best guess of all experts, with the lines corresponding to the average of experts' standardized worst- and best-case scenario estimates, with point and line colours representing distinct strategies for ease of reference.



*'Ecosystem function' and 'deer density' benefit estimates by Western experts*

'Ecosystem function' and 'reduce deer density' objective estimates by Western experts differed from those of the 'well-being' objective, but relatively aligned with each other—although 'reduce deer density' overall had higher estimated likelihoods the objective could be met and greater agreement among Western experts. Hunting by 'deer reduction specialists' had the greatest agreement for both the 'maximizing ecosystem function' (48% [27%–73%]) and 'reduce deer density' (64% [45%–85%]) objective across large islands, with most Western experts estimating it as the most effective individual strategy, while 'Increasing hunting licences' had the least chance of 'maximizing ecosystem function' (25% [10%–46%]) or 'reducing deer density' (30% [12%–47%]). However, only portfolio strategies had >50% likelihood of achieving both objectives on both large- and small islands, as all discrete strategies—excepting deer reduction specialists for 'reduce deer density'—were estimated to have <50% likelihood of success on large islands, showing combined strategies may be important for large-island contexts.

*'Project uptake' and 'project success' feasibility estimates by Western experts*

Most Western experts had larger uncertainty intervals for feasibility objectives ('project uptake' and 'project success') compared to benefit objectives. Estimates for 'project success' were always higher than those for 'project uptake', highlighting experts' opinions that societal uptake and funding will be a greater challenge than technical implementation. 'Indigenous-led hunting' had the highest likelihood of achieving 'project uptake' across strategies (53% [26%–78%]) and 'increased licensed hunting' had the highest value for 'project success' (66% [47–87]) (large islands), while 'improving predator viability' and 'birth control' had the lowest feasibility values of discrete strategies, highlighting the societal and technical issues these strategies may face in comparison.

3.4.2 | Calculation of cost objective

Best-guess NPV cost estimates, based on deer population models, ranged from \$3 to \$9 million CAD spent across all islands over the 10 years (Table 1, Figures S4 and S5), with 'increased licensed hunting' and 'improved predator viability' being the cheapest, and 'birth control' being the most expensive across all strategies (Supporting Information). As we cannot force residents to hunt or predators to be sufficiently abundant to serve a functional role, costing only reflects best efforts to motivate these conditions, while for 'Indigenous-led hunting', 'professional deer reduction specialists' and 'birth control', the salary and/or Honoraria necessary to theoretically achieve the targeted deer reduction was paid, hence higher costs, larger variability in estimates, and likely greater confidence in estimates. Additionally, all strategies were designed to reduce deer density to the threshold for ecological integrity, making costs likely significantly cheaper than eradication efforts in the short-term. Eradication has exponential costs from diminished search efficiency for the last few deer, although long-term has lower recurrent costs if durably designed (Irvine & Thorley, 2024).

3.5 | Trade-off analyses

Our cost-effectiveness analysis found that for 'well-being', which incorporates Indigenous and Western expert perspectives, 'Indigenous-led hunting' had the highest cost-effectiveness across large-island (3.2 [0.6–15.7]) and small island (320.5 [78.3–1373.3]) contexts (best-guess [worst-case–best-case estimates]) (Table S8, Figure S6). 'Indigenous-led hunting and improved predator viability' had the next highest cost-effectiveness (1.9 [0.3–9] for large and 189 [53.7–739.6] for small) while 'birth control' was effectively zero for 'well-being'.

For 'ecosystem function' and 'deer density', which just incorporated Western experts' estimates, 'increased licensed hunting' had the highest cost-effectiveness scores on large islands (2 [0.3–7.9] for function and 2.5 [0.4–8.2] for density) due to low costs and higher feasibility, while 'professional deer reduction specialists' was considered most effective on small-island contexts (231.2 [52.8–1692.7] for function and 298.6 [69.9–2190.1] for density), though all hunting strategies had relatively high and similar cost-effectiveness. Portfolio strategies were similar in effectiveness, with 'Indigenous-led hunting + professional deer reduction specialists + improve predator viability' having the highest effectiveness [1.2 and 137.1 for ecological function, 1.6 and 176.2 for deer density (large and small)].

We found cost-effectiveness estimates on small-island contexts were ~100× greater than on large-island, with changes in top-ranked strategies between large- and small-islands mostly due to increased feasibility of implementation as a result of reduced size and socio-political barriers on small islands (Figure S6).

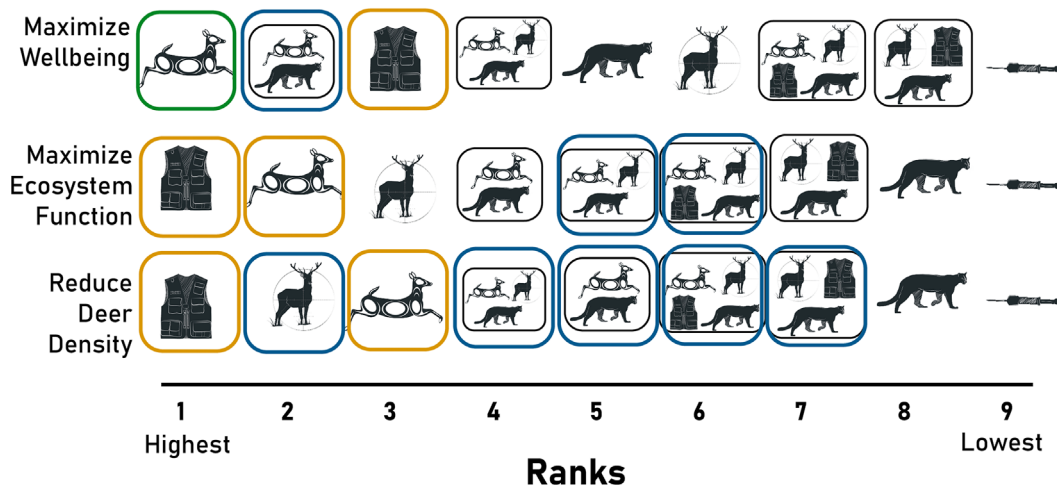
Ranking the strategies by their cost-effectiveness scores for each benefit objective, on large islands, 'Indigenous-led hunting' is ranked highest for 'well-being', but is also second and third highest for 'ecosystem function' and 'deer density'—likely due to the high 'project uptake' and moderate to high benefits (Figure 6). 'Increased licensed hunting' is ranked highest for both ecological objectives—likely due to low cost and high societal acceptance even though benefits are relatively low—as all components are currently weighted equally. 'Professional deer reduction specialists' ranks high for 'ecosystem function' and 'deer density' and lower for 'well-being', while the inverse is true for 'increased predator viability'. 'Birth control' is ranked last across benefit objectives, while portfolio strategies are often ranked moderately, likely due to higher costs as well as some competing interests in benefits with

Indigenous rights. Only 'Indigenous-led hunting' has >50% likelihood of achieving the benefit objective—'maximizing well-being'—while also having >50% likelihood of achieving both feasibility objectives. Small-island contexts have similar results, except that 'professional deer reduction specialists' and 'Indigenous-led hunting + deer reduction specialists + predator viability' also have >50% likelihood of achieving both objectives.

## 4 | DISCUSSION

The issue of hyperabundant herbivores requires timely management action to prevent irreversible loss of keystone species and places globally. The complex nature of the problem, particularly the competing social factors around herbivore management, means there is no one solution. Therefore, using a structured decision-making process employing expert elicitation, population modelling and cost-effectiveness analysis that honours multiple knowledge systems, we estimated how well five discrete and four portfolio deer management strategies would achieve a variety of benefit, feasibility and cost objectives in the Southern Gulf Islands of British Columbia, Canada. We found that 'Indigenous-led hunting' was ranked the most cost-effective when benefits considered well-being of people and place, and was the only strategy deemed >50% likelihood of achieving benefit and feasibility objectives on large-island contexts. On small-island contexts, 'reduction specialists' and the combined strategy of 'Indigenous hunting, reduction specialists and predator viability' also meet these criteria (Table 1, Table S7, Figure 6), highlighting the effectiveness of hunting strategies at recovering well-being.

While the decision outcomes of this analysis are specific to the Salish Sea, the overall approach transcends this region and can be



**FIGURE 6** Effectiveness rankings of all strategies ('Alternatives') for each benefit objective for large-island best-guess estimates, where 1 is the highest ranking and 9 is the lowest. Blue boxes highlight strategies with >50% likelihood of achieving the specific benefit objective, yellow boxes highlight strategies with >50% likelihood of project uptake and success feasibility, and green boxes highlight strategies that meet both constraints.

applied to ecologically and culturally significant keystone places across the globe dealing with hyperabundant herbivores. We share below important takeaways from the application of this approach in the Salish Sea, providing key considerations for both regional and global decision-makers.

## 4.1 | Regional benefits and barriers to deer strategies

We share regional benefits and barriers to enacting deer management highlighted by experts through this process, and while these are framed in relation to the Salish Sea, they echo elements decision-makers are likely to experience elsewhere.

### 4.1.1 | Place-based co-benefits

Many of the strategies were designed with numerous co-benefits in mind that experts deemed essential for increased project success and support, highlighting the need to design strategies rooted in place-based values and needs. Across strategies, reduced deer densities work towards revitalizing oak meadow flora through reduced browsing of these palatable plants, many of which have highly important food, medicinal, material, cultural and spiritual uses in the region (Charlie, 2021; Turner & Hebda, 2012). Preventing density-driven starvation and high disease-risk conditions could also improve deer population health and venison quality (Gortázar et al., 2006). All hunting strategies include meat processing workshops, in which much of the meat will be directed towards local First Nations, increasing food sovereignty and providing a nutritious, environmentally conscious meat source to communities when handled safely. The Indigenous-led hunting strategy funds time for Indigenous youth to get 'out on the land and be able to hunt in a traditional way' (E. Pelkey), takes steps towards revitalizing Indigenous food systems and cultural practices and provides financial support to Indigenous experts (Joseph & Turner, 2020).

### 4.1.2 | Barriers to ecological recovery

Even with the implementation of multiple recovery strategies, the 10-year time-frame will be too short to achieve full ecosystem recovery, as vegetation communities and relationships take longer to recover (Tanentzap et al., 2012). In addition, deer hyperabundance is one of several cumulative stressors, and reducing density alone may be insufficient to achieve full recovery (Benayas et al., 2009). We found that recovery is more likely on small islands within 10 years because of the high potential for quick density reduction, but all experts agreed that additional actions (i.e. native plant restoration and invasive species management) would be required to achieve >90% ecological function across island contexts.

### 4.1.3 | Barriers to hunting

Hunting as a means of reducing deer numbers can be contentious. On small, sparsely populated islands, feasibility of hunting is predicted to be higher than on larger, populated islands, where an opposition to hunting can hinder uptake (Table S6). In addition, deer reduction strategies on large islands will have to be carried out over a longer time-frame, as search time increases as populations decrease and as deer disperse to refuges on private lands where landholders are not amenable to hunting (Iijima, 2017; Irvine & Thorley, 2024). Efficient hunting strategies—particularly licensed recreational hunting—will only have a substantive impact on reducing deer density and ecological recovery if they are designed and implemented with a clear objective of population reduction (e.g. hunting females, increased bag limits, extended hunting season), as reduced density results in reduced hunting success and effort long before recovery thresholds are met (Husheer & Tanentzap, 2024; Irvine & Thorley, 2024). Current regulations in the Salish Sea reduce hunting opportunities and efficiencies in a highly privatized, patchwork landscape, with hunting prohibited within 100 meters of a residence, restricted use or ban of rifles and prohibitions on hunting at night even as deer increase nocturnal activity (Government of British Columbia, 2023, 2024; Tanentzap et al., 2012). For Indigenous-led hunting, the legal right to hunt is treaty-protected on public lands; however, Nations have stated government interference (i.e. racism, violence, arrests) has made Indigenous-led harvests not viable or culturally safe (W̱SÁNEĆ Leadership Council, 2022), expressed as 'they got a lot of flak when they went out there' (E. Pelkey), as have the lack of access and resources due to colonial legacies and ongoing land development. Fortunately, recent initiatives co-developed with Indigenous communities in the region have enabled collaborative solutions to land access and hunting knowledge sharing, and while these initiatives will need expansion to have significant impacts on deer density, they provide much needed hope for the future restoration of this ecoregion (Parks Canada Agency Government of Canada, 2023).

### 4.1.4 | Barriers to non-hunting strategies

The 'improved predator viability' strategy was designed to increase the social acceptance of predators colonizing islands rather than purposefully introducing them, as the underlying issue is whether predators can avoid being shot once they colonize on their own (Pacific Wild, 2023). There was high uncertainty around whether humans would want to co-exist with natural predators, reflected in the lowest 'project uptake' values of all the strategies (Table 1). While public safety and livestock loss are legitimate concerns of increased predator presence, it can be that longstanding cultural attitudes determine predator loss more than reports of increased human-wildlife interactions, and it is both these concerns and attitudes that would need to be proactively addressed

(Marvier, 2023). However, experts expressed that facilitating predator recovery is a long-term strategy and would not meet the 10-year time-horizon in the decision analysis, but could be paired with other strategies. Experts highlighted uncertainties complicating predator strategy evaluation, including how (1) predator recovery translates into prey abundance and ecological impact, (2) predator presence modifies deer behaviours and impacts and (3) predators move between islands (Samhoury et al., 2017).

Birth control is often proposed to manage deer hyperabundance when additive mortality is not desired or feasible. Although birth control has been shown to be an effective tool in certain situations (Massei, 2023), to meet our modelled reduction target, immuno-contraceptives would need to be applied to the majority of adult females every 3 years—an impractical proposition, as search efficiency and population mobility considerations prohibit locating of all does (Gamborg et al., 2020; Irvine & Thorley, 2024). Indigenous experts consulted here expressed that administering birth control to deer is unethical to deer welfare, and worries that it contaminates a critical food source and is therefore an infringement on their rights in their territories. The majority of Western experts also expressed doubts on whether birth control would achieve the long-term deer reductions required for ecological recovery.

## 4.2 | Reflecting on methodological implications

This work provides a methodological framework for bringing together multiple knowledge systems to steward wildlife effectively across worldviews (Hessami et al., 2021; Reid et al., 2021). Instead of incorporating Indigenous scientific knowledge systems and perspectives into those of Western science—perpetuating epistemological inequalities in wildlife management and decision science (Todd, 2016)—the approach honours distinct knowledge systems equitably, tailoring methodological approaches in lateral ways that respect knowledge sharing practices and protocols (Cornassel & T'lakwadzi, 2009; Kimmerer, 2013; Tuhiwai Smith, 2021; Wilson, 2020).

This work highlights the difficulty in, but also the need for, applying these approaches in practice. Honouring Indigenous perspectives and accounting for not only ecological well-being but also human well-being in cost-effectiveness calculations alter the prioritization of strategies, highlighting the importance of including multiple knowledge systems and values in elicitation (Adams et al., 2014; Ban et al., 2018).

However, while we had distinct groups to reduce exposure to harm and allow approaches to iteratively transform in response to expert needs, this process would have been improved upon if all experts could have been brought together safely in a decolonialized manner—facilitating productive cross-cultural discussions and likely accelerating the 4-year process to a 1-to-2-year timeline (Feakins et al., 2024; Tuck & Yang, 2012). Going forward, continued relationship-building, cultural competency training and financial support to bring Indigenous and Western experts together in

a culturally safe manner is recommended (Tuhiwai Smith, 2021; Tujague & Ryan, 2021). Additionally, while we relied on visual approaches primarily for our Indigenous experts, we recommend incorporating visualization-based approaches for Western experts as well—as intricate spreadsheets seemed to exacerbate elicitation fatigue and prolong inconsistencies (Adams et al., 2023; Hemming et al., 2018).

The application of this methodology stressed the distinction between short-term deer management versus long-term deer stewardship strategies. Stewardship approaches—grounded in long-term duty of care—heal human relationality with and responsibility to the land, thereby ensuring strategy effectiveness in the long term. Implementing adaptive, long-term solutions is critical, as populations that are reduced but then left unmanaged will likely rapidly increase to reach pre-managed population levels (Tanentzap et al., 2012; West et al., 2018). However, long-term successful stewardship depends on public support, which requires time and effort to gain in areas in which human relationality with the land has been critically impacted and where external regional and global stressors continue to drive localized hyperabundance of deer (Fernandez-Gimenez et al., 2008). Funding further complicates the issue of support, as different strategies will have different payment mechanisms, and therefore, the issue of who pays and how that is understood by the public influences buy-in. Pilot projects can be used as engagement, mentorship and learning opportunities in the near term, while slowly building the social and financial capital needed to expand projects to larger spatial extents and to support more long-term investment strategies (i.e. training and supporting Indigenous guardians, improving predator viability) (Fernandez-Gimenez et al., 2008).

Lastly, while this methodology can be applied to any area around the globe facing herbivore hyperabundance, the approach must always be grounded in a local, place-based context, centering the knowledge and values of care that have shaped the area over time (Artelle et al., 2018, 2021). The application of this approach relied upon Indigenous and Western decision-makers, experts and analysts from the region, thereby ensuring the decision analysis was strongly rooted in place, and we recommend the same when carrying out this process in practice.

## 4.3 | Accounting for assumptions and uncertainties

The models and results presented here are not designed as final products, but as prototypes that require regular updating when additional information becomes available. Cost estimates had large uncertainty intervals due to assumptions made in the underlying deer population models around (1) deer density and mobility, (2) strategy-specific hunting efficiencies and behavioural impacts and (3) population fitness under low food conditions (Supporting Information). Accounting for these uncertainties influenced the amount of effort required to reduce deer to the target density, greatly impacting the costing of labour components. To address uncertainties and to adaptively manage populations, we need greater real-time estimates

of deer density, and reoccurring assessments of vegetative recovery as metrics of success (Martin et al., 2011). Additionally, deer have complex behavioural responses to management, and a multifaceted approach could be imperative for actions to be adaptive (Iijima, 2017; Irvine & Thorley, 2024). Further research is needed to assess whether the flexibility of combining components from multiple strategies outweighs the increased complexity of implementation, particularly as Indigenous experts highlighted that portfolio strategies might further impinge on their already limited access by increasing competing hunting opportunities (Trask et al., 2019).

#### 4.4 | Future directions

Immediate action to reduce herbivore densities is pivotal, before opportunities to revitalize ecosystems are lost (Beckett et al., 2022; Martin et al., 2011; Martin, Nally, et al., 2012). Our decision analysis approach reveals that solutions to deer hyperabundance that meet both ecological and human well-being objectives are possible in the Salish Sea, but will require collaboration and co-governance between regional decision-makers and titleholders to meaningfully reduce deer densities, recover ecological function and respect Indigenous sovereignty. More broadly, our analysis outlines a process for designing effective, place-based and holistic solutions to address the hyperabundance of herbivores seen across the globe.

#### AUTHOR CONTRIBUTIONS

Sofie McComb, Kephra Beckett and Tara G. Martin served as the research team conducting the entire structured decision-making analysis, involved in the conception of the idea, the methodology design and the collection of all data. Sofie McComb led data analysis and manuscript writing, supported by Kephra Beckett. All other co-authors, as well as Tara G. Martin, served as experts in the structured expert elicitation process, who provided data and feedback throughout the process, contributed critically to the drafts and gave final approval.

#### ACKNOWLEDGEMENTS

We would like to acknowledge all members of Spune'luxutth, W̱SÁNEĆ and Quw'utsun Nations who supported this project with their time and knowledge, as well as Michael Janssen, Erich Kelch and Heather Clarke from Parks Canada, Adam Huggins from the Galiano Conservancy Association and Emily Clark from UBC. This work was supported by Vanier Canada Graduate Scholarships, NSERC Discovery Grants, UBC Liber Ero Chair in Conservation and UBC Graduate Fellowships.

#### CONFLICT OF INTEREST STATEMENT

No conflicts of interest.

#### DATA AVAILABILITY STATEMENT

Our data is publicly archived on Dryad, found at <https://doi.org/10.5061/dryad.b8gtht7rc>. Expert elicitation data are anonymized.

#### CONSENT

All participants served as equitable co-authors of this work, sharing their knowledge and approving iterations in a relational manner based on continuous ethical consent, both written and/or verbal (Behavioural Research Ethics Board approval H19-01635).

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## SUPPORTING INFORMATION

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

**Appendix A.** Supplementary Tables & Figures.

**Table S1.** Six finalized ecological, feasibility, and cost objectives.

**Table S2.** List of initially considered strategies, grouped by general theme, with some of the key literature used in drafting and defining the initial strategies list.

**Table S3.** Brief descriptions & key components for final, expert-defined strategies to best meet objectives.

**Table S4.** Key benefits, barriers, & scenarios findings for each of the strategies considered.

**Table S5.** Indigenous experts' consequence averages with uncertainty intervals for 'Wellbeing' objective.

**Table S6.** Western experts' consequence averages with uncertainty intervals for all elicited objectives.

**Table S7.** Indigenous and Western experts' combined consequence averages with uncertainty intervals for 'Wellbeing' objective.

**Table S8.** Average trade-offs across groups with uncertainty intervals, grouped by benefit objectives.

**Figure S1.** Maximize 'Wellbeing' consequences (Indigenous experts).

**Figure S2.** Average likelihoods of strategies meeting all benefit and feasibility objectives for both island contexts, with standardized 80% confidence intervals, from the 11 Western academic and managerial experts.

**Figure S3.** Individual expert estimates of likelihood of strategies meeting the 'maximize wellbeing' objective for both island contexts, with standardized 80% confidence intervals, from the 11 Western academic and managerial experts.

**Figure S4.** Modeled deer density on large islands.

**Figure S5.** Costing estimates per strategy.

**Figure S6.** Effectiveness scores for all strategies for large- and small-island best-guess estimates.

**Appendix B.** Elicitation Process & Materials.

**Appendix C.** Deer Population Model.

**Appendix D.** Costing.

**Appendix E.** Trade-offs.

**How to cite this article:** McComb, S., Beckett, K., Akerman, T. J., Arcese, P., Bedford, D., Dunwiddie, P., Fisher, J. T., Golumbia, T., Gonzales, E. K., Irvine, R., James, A., Long, E. S., Martin, J.-L., Michel, S., Pelkey, W. E., Sylvester, T. A., Thomas, S. K., Thomas, N., & Martin, T. G. (2025). Decision analysis rooted in Indigenous and Western scientific knowledge identifies cost-effective strategies for managing hyperabundant deer to restore keystone places. *People and Nature*, 00, 1–17. <https://doi.org/10.1002/pan3.70136>