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RESEARCH ARTICLE

Predicting regional cumulative effects of future development on coastal ecosystems to support Indigenous governance

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Abstract

1. To achieve better biodiversity outcomes and match local governance capacity, cumulative effects assessment frameworks that combine Indigenous and western knowledge to predict future development impacts on biodiversity are needed.
2. We developed a spatial future-focused model informed by inclusive elicitation and strategic foresight to assess the regional cumulative effects of development on ecosystem health across the land and sea. We collaborated with three First Nations on the Central Coast of British Columbia, Canada, enabling Indigenous priorities, knowledge and values to drive the process, from the choice of priority ecosystem components (including salmon, herring, seabirds and bears), to identifying future development scenarios (based on forestry, energy/mining, tourism and salmon aquaculture sectors). Bayesian networks were populated with empirical data and expert judgement elicited from knowledge holders to predict the cumulative effects of current and future pressures on species and ecosystems.
3. Under current conditions, the lowest probability of persistence was predicted for Pacific salmon (37%), followed by Pacific herring (43%). Under future conditions, the greatest declines in species health were associated with the intense development of mining, tourism and forestry, with up to a 54% decline from the current baseline health estimates predicted for Marbled Murrelets and old-growth forest.
4. Future outcomes for overall ecosystem health were predicted to be worst in scenarios with high future forestry activities (>60% decline in some areas). The continuation or development of all four industries resulted in an 8% decline overall in ecosystem health across the Central Coast. In contrast, predicted ecosystem health in the tourism economy scenario increased up to 15% in some marine areas, primarily driven by the removal of salmon aquaculture and forestry activities.
5. *Synthesis and applications*. Our study demonstrates an inclusive, regional approach to assessing the cumulative effects of future development on coastal species. The novel participatory tools and predictive framework draw upon and interweave multiple forms of knowledge, enabling Indigenous values to drive the process, and appropriately integrate Indigenous knowledge into regional cumulative effects

assessment. Our interactive web application provides First Nations partners access to all outputs, supporting Indigenous-led governance and in situ ecosystem-based management of their lands and water.

KEYWORDS
Bayesian network, cumulative impacts, ecosystem-based management, expert knowledge, Great Bear Rainforest, salmon, scenario planning

1 | INTRODUCTION

Proactive approaches to conservation decision-making that anticipate problems before they escalate are crucial in this increasingly human-dominated world, where human activities are driving rapid species decline and ecosystem collapse (Díaz et al., 2019). Understanding biodiversity responses to interacting and changing human activities, or 'cumulative effects', is necessary to plan for sustainable development and manage for disturbances where possible to terrestrial, freshwater and marine ecosystems. However, predicting cumulative effects on biodiversity is challenging due to uncertainties in species responses to multiple disturbances, and the complex interactions within multi-use landscapes. This challenge is particularly potent in coastal areas where transboundary species depend on healthy land, freshwater and marine environments (Levi et al., 2012). Cumulative effects assessments must account for past, present and anticipated future impacts that have and will accumulate from other activities in a given region (CCME, 2014). Despite the recognition that cumulative effects assessments (CEAs) can be more effective if they encompass broad regional considerations (Clogg et al., 2017; Connelly, 2011), current approaches often focus on single site-specific projects and ignore other human activities that may impact a region (Eckert et al., 2020) (but see Harriman & Noble, 2008; Noble, 2008).

CEAs have traditionally been driven by colonial governments through western science frameworks, falling short in their incorporation of the values and knowledge of local decision-makers and knowledge holders, such as Indigenous governments (Canter & Ross, 2010; Clogg et al., 2017; Duinker & Greig, 2006), due in large part to exclusive methodologies and narrow scope (Adams et al., 2023; Clogg et al., 2017; Eckert et al., 2020). These shortfalls are common throughout Canada, where Indigenous governments have generations of place-based knowledge and hold decision-making authority over their territories in areas where Crown governments also claim jurisdiction (e.g. Yahey v. British Columbia, 2021). Although some improvements in CEAs have been made (Hodgson et al., 2019), the exclusion of Indigenous sovereignty and Indigenous knowledge limits the effectiveness of CEAs in capturing comprehensive impacts across a region, and also overlooks the cultural and socio-economic considerations important in assessing the impacts and consequences of cumulative effects for local people and ecosystems. Inclusive approaches using two-eyed seeing and coproduction have recently emerged that address these historical limitations by explicitly integrating Indigenous interests, values and knowledge and western perspectives within CEA in Canada (Mantyka-Pringle et al., 2017; Staples, 2022).

Strategic foresight is a method for long-term planning that can help anticipate possible risks and opportunities in the future by including expert knowledge (Cook et al., 2014; Cornish, 2004). By systematically considering a range of possible or probable futures and their consequences for current and future decisions, foresight can help address uncertainties, including those associated with cumulative effects, and avoid undesirable outcomes for biodiversity (Cook et al., 2014; Sutherland & Woodroof, 2009; Therivel & Ross, 2007). Foresight approaches such as scenario planning and horizon scanning can help identify the type and location of future activities driving species decline (Cook et al., 2014; Peterson et al., 2003). Where consented to and offered, Indigenous and local knowledge can contribute expertise and increase the capacity for precise predictive foresight analysis (Berkes et al., 2000; Roué & Nakashima, 2002).

Bayesian networks (BNs) are decision-support tools that are well suited for predicting how multiple pressures combine to affect species persistence (i.e. the ability of the species to sustain itself and fulfil its ecological role (Mantyka-Pringle et al., 2014) and distribution (e.g. Martin et al., 2015)). These tools bridge the gap between quantitative and qualitative knowledge systems by expert knowledge (e.g. local or traditional ecological knowledge, western science) and empirically derived data, aiding deeper and more inclusive ecological understanding (Marcot et al., 2001). Although other tools can include expert knowledge, BNs have several advantages, including their capacity to demonstrate likely outcomes of complicated ecosystem interactions, and explore the effects of uncertainty on management decisions (Ban et al., 2014; Marcot et al., 2006).

We developed a spatial future-focused framework for regional CEA, explicitly driven by Indigenous priorities and values, to predict how future development scenarios may affect the health of interconnected ecosystem components and regional ecosystem health across the land and sea. We defined health as the ability of interconnected 'ecosystem components' (species and habitats) to persist at levels necessary to fulfil their ecological and cultural role over 25 years. We inform our quantitative predictive modelling framework using an elicitation approach developed by Adams et al. (2023) for cumulative effects assessments, informed by the guiding principles of respecting Indigenous sovereignty and regional autonomy. We illustrate the framework by assessing the cumulative effects of four industry sectors (salmon aquaculture, energy/mining, forestry and tourism) on seven interconnected species across the Central Coast region of the Great Bear Rainforest in BC, Canada. In this region, ongoing planning processes are required to balance short-term economic opportunities with ecosystem-based management (EBM) (CFN & BC, 2016; Diggon et al., 2021). In collaboration with decision-makers and knowledge holders from the Kitasoo Xai'xais, Nuxalk and Wuikinuxv First Nations, we employ strategic foresight methods (horizon scanning and scenario planning; Glenn & Gordon, 2009) to integrate information about the region's past, present and future over 25 years (Dortmans, 2005). Using a future-focused spatial BN model based on elicited local and Indigenous knowledge (Marcot et al., 2006), we predict how the cumulative effects of four alternative development scenarios may influence species health and ecosystem health. We use the results to evaluate spatial management options across various sectors at a regional scale and provide relevant outputs for regional decision-makers.

2 | MATERIALS AND METHODS

2.1 | Region of focus

Our work spans the homelands of the Heiltsuk, Kitasoo Xai'xais, Nuxalk and Wuikinuxv First Nations in an area popularly referred to as the 'Great Bear Rainforest' (Figure 1). The region is co-managed by Indigenous, provincial and federal governments under the principles of EBM (Price et al., 2009). Interconnections among the well-being of lands and waters and of First Nations people are deeply established in this region; however, these have been and continue to be impacted by human activities post-colonization, such as commercial harvesting of forests, fish and minerals.

Approximately 3500 people live in the Central Coast region of the Great Bear Rainforest. Bella Coola, Bella Bella, Ocean Falls, Wuikinuxv village, Shearwater and Klemtu are the main communities, which differ greatly in size and capacity for resource stewardship and economic development. The Central Coast communities have depended primarily on the logging and fishing industries in the recent past (Supporting Information S1.1). Logging is now managed through an EBM framework under the Great Bear Rainforest agreements and Nations are engaged in the oversight of forestry companies, including their own. While logging remains important, local economies are diversifying to focus on tourism (primarily in Bella Coola, Shearwater and Klemtu), salmon aquaculture (only around Klemtu) and other service sectors. Tourism has grown faster than regulation across the coast (pers. comm. Evan Loveless, Kitasoo Xai'xais Stewardship Authority, 2022). Kitasoo Xai'Xais Nation is now issuing its own tenures and agreements with companies and regulating the size and density of tour operators to minimize impacts and maximize tourism opportunities. Activities and development taking place on land or in the marine environment require approval through Nation referral processes, including those for energy and mining. Mining claims and exploration activities are escalating across BC, including planning processes and tenures being issued in the Great Bear region (Government of British Columbia, 2024).

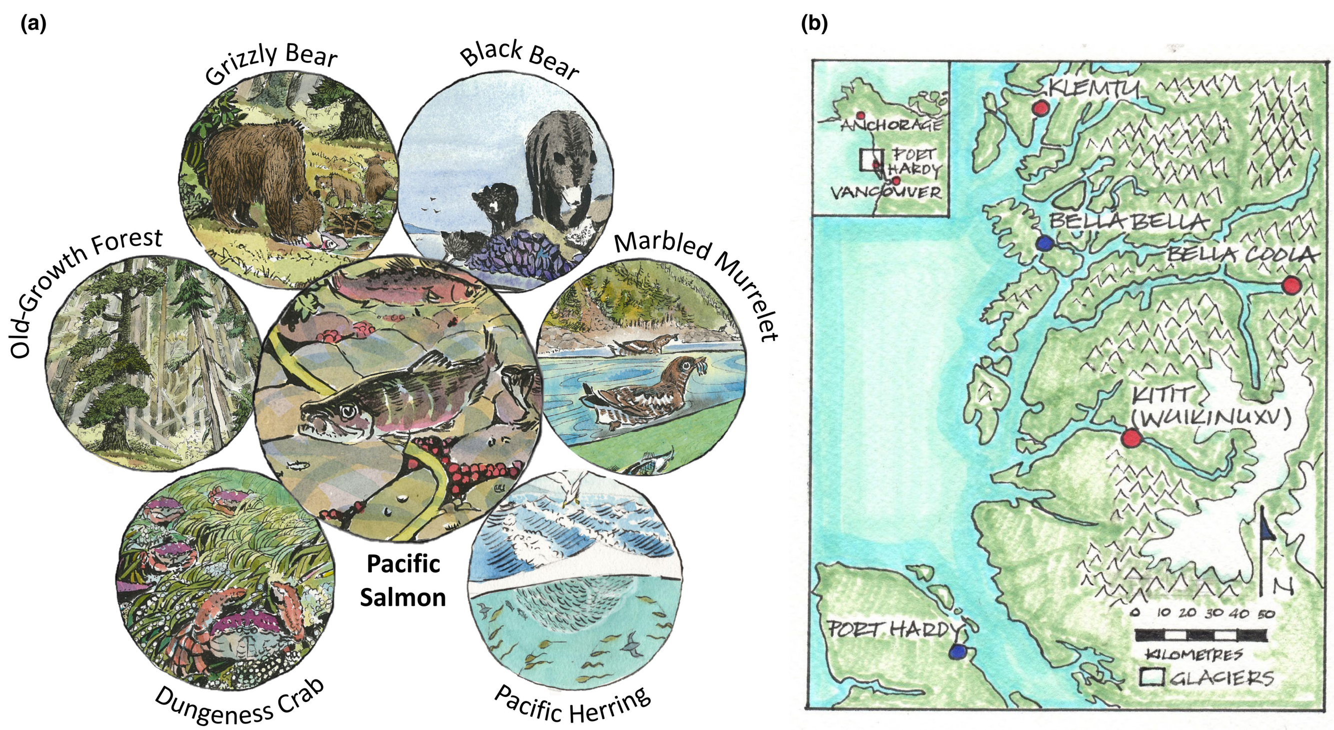


FIGURE 1 (a) Interconnected valued ecosystem components, selected by Nations; and (b) study area of the Central Coast, BC (artwork by Briony Penn).

2.2 | Cumulative effects assessment framework

2.2.1 | Engaging diverse knowledge holders

We obtained written collaboration consent from Central Coast First Nations governments at the outset of this work, and from the Nations who live and steward the region, the Kitasoo Xai'xais, Nuxalk and Wuikinuxv First Nations and their Stewardship Departments, who agreed to enter into this work with our team (see Adams et al., 2023 for more information, UBC Human Ethics H20-00874 and Supporting Information S2). Members of our research team had training and experience built from community-based practice with these communities, bringing the lessons, responsibilities and accountabilities stemming from those relationships to this project. As such, Indigenous sovereignty and stewardship authority were of key value to this project. Staff from each Nation guided the prioritization and focus of this work, the selection of valued ecosystem components, and the identification of anticipated future developments that form the basis of predicted future cumulative effects (Figure 2, see Section 3 below).

We worked with expert knowledge holders across the Great Bear region to identify cumulative effects and predict their impacts on focal species (Figure 2, Supporting Information S2). We used a snowball approach to identify diverse knowledge holders founded in relationships held by our research team or collaborators within each Nation, including Indigenous community members and Nation staff, regional tenure holders (e.g. fishing guides, commercial fishermen), biologists and managers from Crown governments and academic research scientists. We first prioritized data, perspectives and priorities from Indigenous knowledge holders' through inclusive expert elicitation workshops in the Nations' communities (Supporting Information S2.1). Other regional experts were then invited to contribute knowledge and expertise through a secondary expert elicitation process. In total, we had 53 respondents, which falls in the upper values of the suggested size of pools for expert elicitation, which range from as few as three (Clemen & Winkler, 1999) to as many as 60 (Doria et al., 2009). However, experts only responded for species for which they held knowledge. At a species level, the number of respondents ranged from 10 to 38.

2.2.2 | Selecting regionally relevant ecosystem components

We worked with Nation stewardship staff to select specific valued species and habitats to focus our assessment on, hereafter called 'ecosystem components'. Seven ecosystem components were chosen—Pacific salmon (*Oncorhynchus* spp.), old-growth forest patches (made up of tree species within the Coastal Western Hemlock biogeoclimatic zone), grizzly bears (*Ursus arctos horribilis*), black bears (*Ursus americanus*), Dungeness crab (*Cancer magister*), Pacific herring (*Clupea pallasii*) and Marbled Murrelets (*Brachyramphus marmoratus*) (Figure 1). Although there are other species that depend on or link to salmon ecosystems in this region (Tulloch et al., 2022), these were the ecosystem components chosen by knowledge holders as the highest priority for conservation and/or management in the region. These species are all closely connected via direct or indirect trophic linkages (Tulloch et al., 2022), and so we considered them together as a representation of the ecosystem as a whole (Walsh, Pendray, et al., 2020). We developed detailed spatially explicit habitat importance maps for each ecosystem component (Supporting Information S1.1). We also elicited information on past, present and anticipated future pressures influencing the health of each ecosystem component, which fed into influence diagrams (see Figure S1 for an example). This was achieved through a series of semi-structured conversations with Indigenous knowledge holders, supplemented with interviews with species experts, a thorough literature review, and the collation of available spatial data on human activities and species distributions.

To ensure spatial outputs for our project represented the scale of potential spatial management used by local communities, we generated a land-sea planning unit layer combining distinct subwatersheds ($n=801$; derived from the BC Freshwater Atlas (Gray, 2010)) and marine fishing subregulation areas ($n=123$; Pacific Fishery Management Areas, Fisheries and Oceans Canada).

2.2.3 | Using strategic foresight to anticipate future development based on local knowledge

We used horizon scanning to design future development scenarios for the predictive model (Glenn & Gordon, 2009). Horizon scanning is a key strategic foresight tool for collecting and organizing diverse streams of information on potential environmental threats and opportunities (Cook et al., 2014) that can help anticipate future environmental issues and plan for the unpredictable (Sutherland et al., 2015). We asked knowledge holders to identify a range of foreseeable futures and to specify industries with the potential for future expansion or reduction in the region in the short term (25 years). We shortlisted these industries based on their ability to be managed at a local or regional scale. Through this process, we identified four industry sectors and associated human activities in the region—salmon aquaculture, forestry, energy and tourism (Tables S1 and S2). This approach simplifies the management process by assuming management occurs at an industry level (e.g. expansion of logging throughout the region means that all logging activities are affected), rather than at the level of individual activities. Although there are other human activities and associated pressures in the region, these are either not directly manageable by First Nation governments (e.g. climate change, natural biological processes) or are unlikely to increase in the near future (e.g. fisheries, due to declining stocks).

Only activities classified as within the four sectors with existing spatial information were included in the BN (Tables S1 and S2). Activities were mapped to a standardized 1 km^2 grid of the study area (CRS BC Albers, EPSG:3005) and then aggregated by sector using thresholds ('none', 'low', 'moderate', 'high', Table 1) at

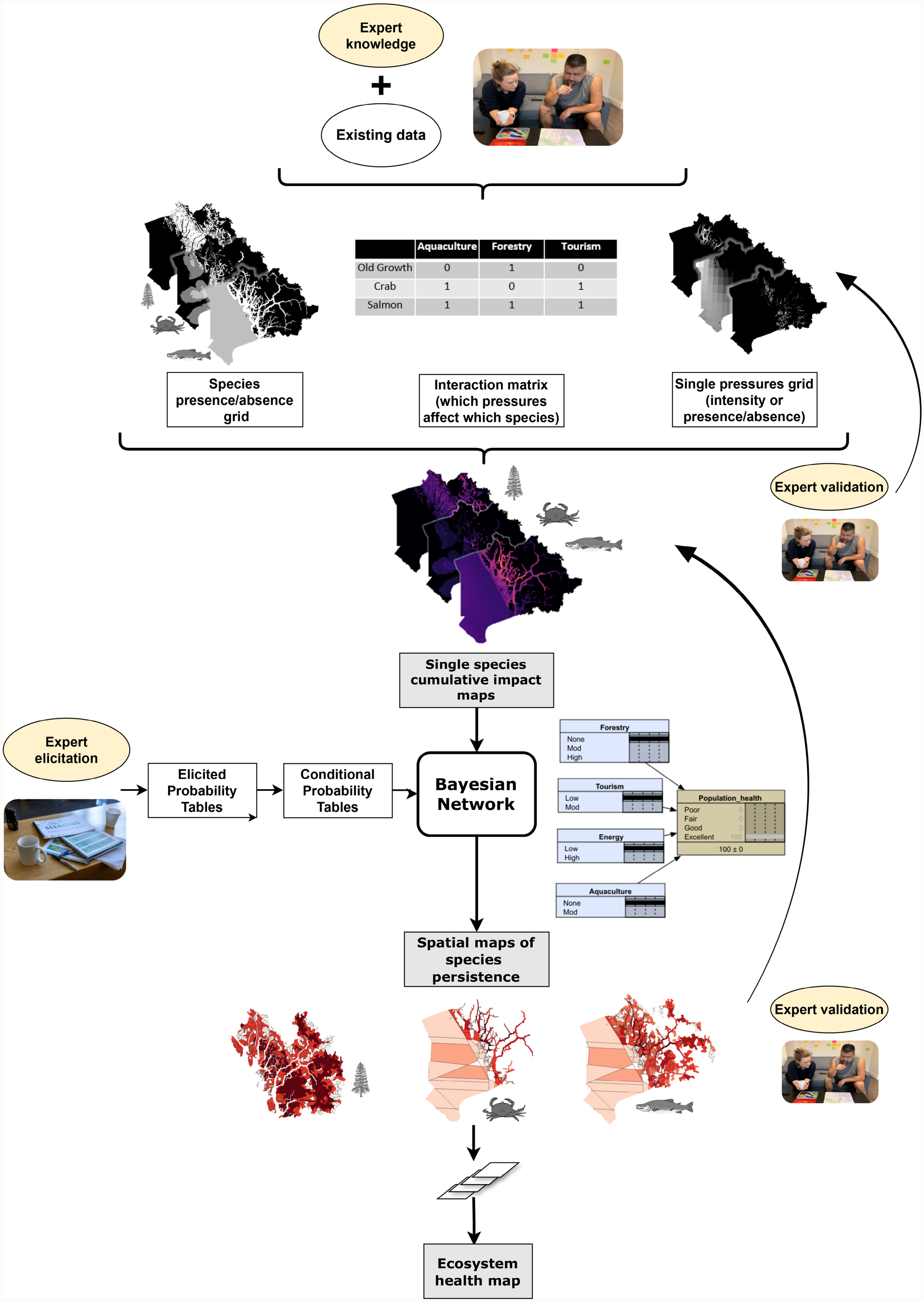
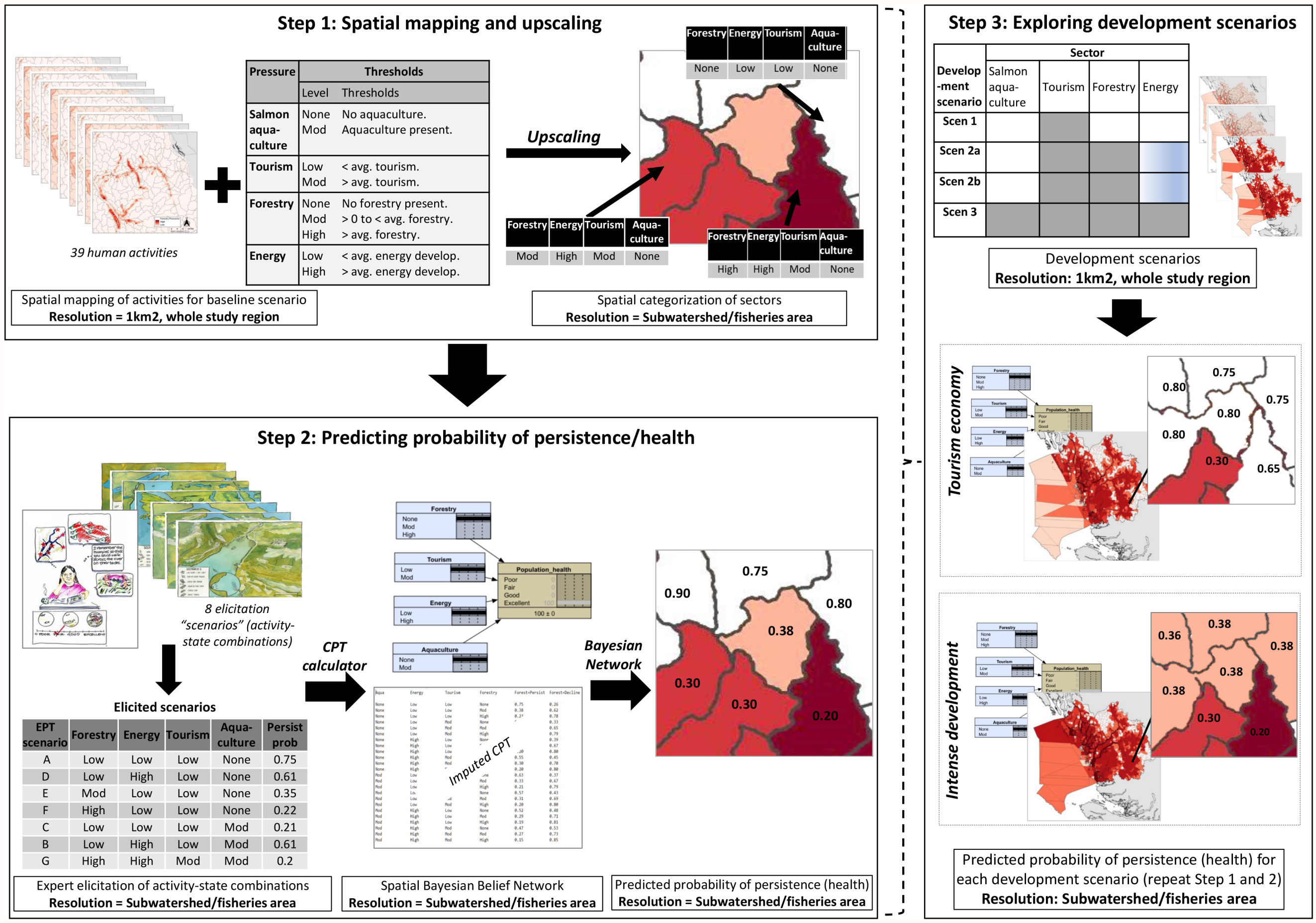


FIGURE 2 Cumulative effects assessment framework, from predictions made by diverse knowledge holders during inclusive expert elicitation workshops, to developing the final spatial maps of species persistence (three examples shown here, for old-growth forest, crab and salmon), and ecosystem health map (combination of all species persistence maps). Expert knowledge was used to inform the Bayesian network and predictions of current and future ecosystem health, select species or ecosystem components, develop species distribution maps and influence diagrams, identify the location of historical human activities and formulate development scenarios, with expert validation occurring at all mapping stages.

TABLE 1 Future development scenarios explored with the Bayesian network model (see Table S2 for the spatial data used within each scenario and the interaction matrix for each ecosystem component), and threshold criteria used to generate low, moderate or high levels of each activity within subwatersheds/fisheries subareas (see Figure 3 for a process diagram detailing how industries are switched on and off in the Bayesian network).

	Thresholds		Development scenario			
Pressure	Levels	Thresholds	Scenario 1—tourism economy only	Scenario 2a—renewable resources with salmon aquaculture	Scenario 2b—renewable resources without salmon aquaculture	Scenario 3—intensive development
Salmon aquaculture	None	No presence of aquaculture		■		■
	Mod	>0 presence of aquaculture		■		■
Tourism	Low	< average tourism	■	■	■	■
	Mod	> average tourism	■	■	■	■
Forestry	None	No forestry present		■	■	■
	Mod	>0 and < average forestry		■	■	■
	High	> average forestry		■	■	■
Renewable energy	Low	No renewable energy or hydro projects		■	■	■
	High	Presence of renewable energy or hydro projects		■	■	■
Non-renewable energy	Low	< average energy development				■
	High	> average or presence of mining				■

Note: Grey boxes represent those industries included in each scenario.



EPT scenario	Forestry	Energy	Tourism	Aquaculture	Persist prob
A	Low	Low	Low	None	0.75
D	Low	High	Low	None	0.61
E	Mod	Low	Low	None	0.35
F	High	Low	Low	None	0.22
C	Low	Low	Low	Mod	0.21
B	Low	High	Low	Mod	0.61
G	High	High	Mod	Mod	0.2

FIGURE 3 Process used to spatially link elicited information from experts to the Bayesian network (BN), which predicted species health at the planning unit (subwatershed/fisheries subarea) resolution. Expert knowledge was interpolated using a conditional probability table (CPT) calculator to predict the state of ecosystem components given all combinations of activities in each individual planning unit. Development scenarios switched on different activity layers, and then the resulting activity combinations were modelled using the BN to predict ecosystem component health within each planning unit.

the scale of the planning layer (subwatersheds and fisheries subareas) (Figure 3; Table 1). To map total activities spatially, the sum of normalized human activities (input nodes) for each of the four industries (salmon aquaculture, energy, forestry and tourism) was calculated for each subwatershed ($n=801$) and marine activities summed within each fisheries subregulation area ($n=123$), first for all historical and current activities. We created one combined data frame for the entire region using these values, and set these values as our baseline states (Figure 3). Our approach to mapping activities was iterative, whereby spatial maps were presented back to communities for validation, and adjusted based on input received (Figure 2).

Using horizon scanning, we designed three future development scenarios to explore changes in the spatial distribution of predicted ecosystem health given different development priorities. Future development scenarios were mapped at the scale of the study region, using data describing future planned activities related to each industry sector (Table S2). Each scenario switched on or off sectors (and associated activity spatial layers, Table S2), according to different development priorities (Table 1). We ran two additional forestry-only scenarios to test the sensitivity of the predictive BN model (Step 4) to alternative timber harvest regimes, comparing the base timber supply model (SELES Spatially Explicit Landscape Event Simulator (Fall et al., 2001)) to a novel timber supply model specially developed for the region (Lochhead et al., 2022) (Supporting Information S1.2).

2.2.4 | Predicting ecosystem health using a Bayesian network

To capture the current state of ecosystem components in the region (hereafter 'baseline' scenario) and predict future health, we elicited predictions from regional experts at the subwatershed/fisheries subarea resolution, which informed the outputs of a BN (Supporting Information S2.1; Adams et al., 2023). We followed the guidelines of Marcot et al. (2006) and Johnson et al. (2010) when developing the BN. The BN predicted the persistence of ecosystem components as well as overall 'ecosystem health' at the scale of individual subwatersheds and fisheries subareas. Ecosystem health was defined as the average combined predicted persistence of those seven ecosystem components.

In a BN, variables are depicted as nodes in the network. Mechanistic relationships between parent nodes and child nodes are shown as links or arcs. Our input nodes were activities identified as manageable by local First Nation governments (aggregated by industry sector). The spatial data on human activities within each industry (salmon aquaculture, energy, forestry and tourism) were variables in our model (Figure 3). For example, the states of various forestry activities drive the state of the intermediate node variable 'forestry development intensity', and subsequently the output node 'population health' (Figure S2). We defined mechanistic relationships between nodes using an interaction table of binary relationships (0,1) between human activities and ecosystem component impacts (Table S1), populated using information from influence diagrams and expert interviews (Step 2). We modelled interactions among nodes in the BN as conditional probability distributions, which measure the probability of an event given that another event has occurred. The conditional probabilities for the BN were stored in a conditional probability table (CPT), representing all activity-state combinations of the parent nodes (Supporting Information S1.3). Activity-state combinations were based on the spatial distribution and intensity of each activity across the Central Coast, with thresholds for low, moderate or high levels of the combination of activities in each industry sector at the planning layer resolution (subwatershed/fisheries subarea; Table 1).

Conditional probabilities that are elicited from experts are called elicited probability tables (EPTs). EPTs contain only a subset of activity-state combinations, due to the large number of potential combinations of human activities in each planning unit, and the need to minimize the questions asked of experts. The activity-state combinations within each planning unit for the EPT were chosen using a Delphi approach (O'Hagan, 2006) by selecting specific states: (1) the best-case (all parent nodes (the four industries) in their most favourable states), (2) the worst-case (all parent nodes in their least favourable states) and (3) cases where only one parent node is not in its most favourable state (Cain, 2001). The EPTs were populated during a series of structured group workshops with Indigenous knowledge holders and online surveys (see Supporting Information S2.3 for the workshop booklet and accompanying scenario booklet, from Adams et al. (2023)) between June and November 2021. Each expert independently estimated the probability of persistence for each ecosystem component for the subset of activity-state combinations required for the EPT (Supporting Information S2.3; Table S3). We calculated an unweighted average to determine the mean response elicited from the experts for each ecosystem component to populate the EPT. By taking an unweighted average, we avoided difficulties concerned with rating the comparative 'accuracy' of each expert's knowledge about each ecosystem component (Einhorn et al., 1977). We assumed the experts' ability to provide this measure was contained within the expert data, since experts only provided responses to ecosystem components for which they were confident (Supporting Information S1.4). The remainder of the activity-state combinations (Table S3) were then imputed using the CPT calculator (Cain, 2001) (Supporting Information S1.3).

2.2.5 | Spatial visualization of predicted ecosystem component health and ecosystem health

We began with the spatial baseline layers, calculating the average level of each activity across subwatersheds and fishing regulation areas to use as a relative benchmark for categorizing the industry intensity levels across the Central Coast (Table 1). For each future scenario, we recalculated the average values of future and current activities (Figure 3). The average values under different futures were then compared against the original baseline average value for each activity to estimate which areas were vulnerable to increased human activities, forming the threshold inputs for each future development scenario (Table 1; Table S4; Supporting Information S1.5).

We used R (version 4.0.5; http://www.r-project.org/) to develop the BN, taking as input the data frame containing the spatial information for each development scenario, ecosystem component presence or absence in each planning unit, and the average values for each interpolated CPT (Figure 2; Figure S2). We performed these steps for each of the development scenarios and each ecosystem component to compare the probability of persistence for the ecosystem component spatially. We again presented draft spatial maps of persistence back to the communities for checking and validation, and to adjust thresholds accordingly (Table S4). We then combined the outputs for all ecosystem components to calculate how future ecosystem health, defined as the average persistence across all ecosystem components in each planning unit, would change at local and regional scales for each development scenario. To facilitate interrogation of the spatial outputs, we developed an online user interface that enables exploration of maps that show changes in the probability of persistence of focal species/ecosystem components and overall ecosystem health given current human activity levels (i.e. baseline) and development scenarios (https://ubcconservationdecisionslab.shinyapps.io/ccce_app_cc/). This was developed using the shiny package (Chang et al., 2022) in R v. 4.0.5 (R Core Team, 2023). The project culminated in a final in-person community presentation and review of outputs, where future expansion of the research was also discussed.

3 | RESULTS

We identified 39 human activities across the Central Coast's marine and terrestrial environments that had spatial information and could be categorized into one of the four industry categories—salmon aquaculture, forestry, energy/mining or tourism (Table S1). At the activity-state level, planning units with high forestry activities in them had the lowest ecosystem health compared to other activity-state combinations based on the estimates from the experts, and interpolation by the CPT calculator, regardless of the states of the other activities. We present findings for the three development scenarios ranging from least extractive (tourism economy) to most extractive (intense development) below (sensitivity test results in Supporting Information S1.3).

3.1 | Baseline scenario

Under current conditions, the predicted probability of persistence across the entire region (average across all planning units) was lowest for Pacific salmon (37%), followed by Pacific herring (43%), while bears had the highest predicted persistence (black bears = 57%, grizzly bears = 50%) (Table S5). Predicted ecosystem health, defined as the average probability of persistence across all ecosystem components, was 46% across the Central Coast (Table S5). Predictions for ecosystem health at a planning unit scale ranged from 18% to 79% (Table S7). Spatially, regions with higher predicted health were those currently experiencing the lowest pressures from forestry and energy/mining, including remote regions on the land and islands (Figure 4). In general, offshore areas had a higher probability of persistence than on the land, except for ocean areas where current energy infrastructure and vessel lanes overlapped with marine species distributions (Pacific salmon, Pacific herring, Dungeness crab) (Figure 4). Inshore habitats generally had a lower probability of persistence than offshore, with the lowest expected ecosystem health expected in the northern coastal waters of Queen Charlotte Sound due to the high levels of marine traffic coupled with salmon aquaculture.

3.2 | Scenario 1—Future ecotourism economy

Under an ecotourism economy (Table 1), the predicted probability of persistence increased from current conditions in select coastal waters by up to 15% for Pacific herring, and up to 18% for Pacific salmon (Figure 5), largely due to the removal of salmon aquaculture in the north (Table S6). Other species with increases in predicted probability of persistence in these areas were Dungeness crab (10%) and Marbled Murrelets (4%). At a regional level, an economic

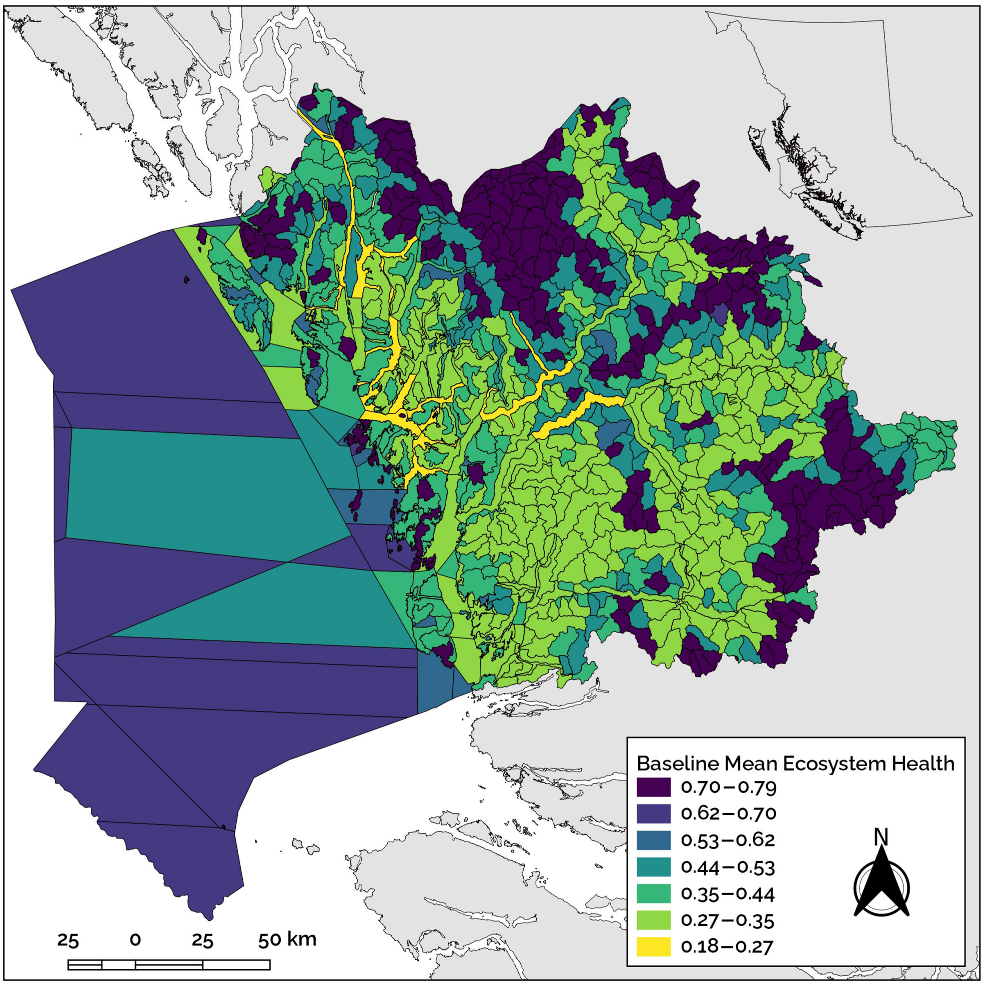


FIGURE 4 Probability of good ecosystem health estimated by the Bayesian network, representing the combined average persistence for all ecosystem components in each planning unit (subwatersheds or fisheries subareas) given current human activity levels (baseline scenario). The lightest colour indicates highest mean predictions of ecosystem health (corresponding to the best condition), with darkest colors the lowest mean predictions (corresponding to the worst condition, given status quo).

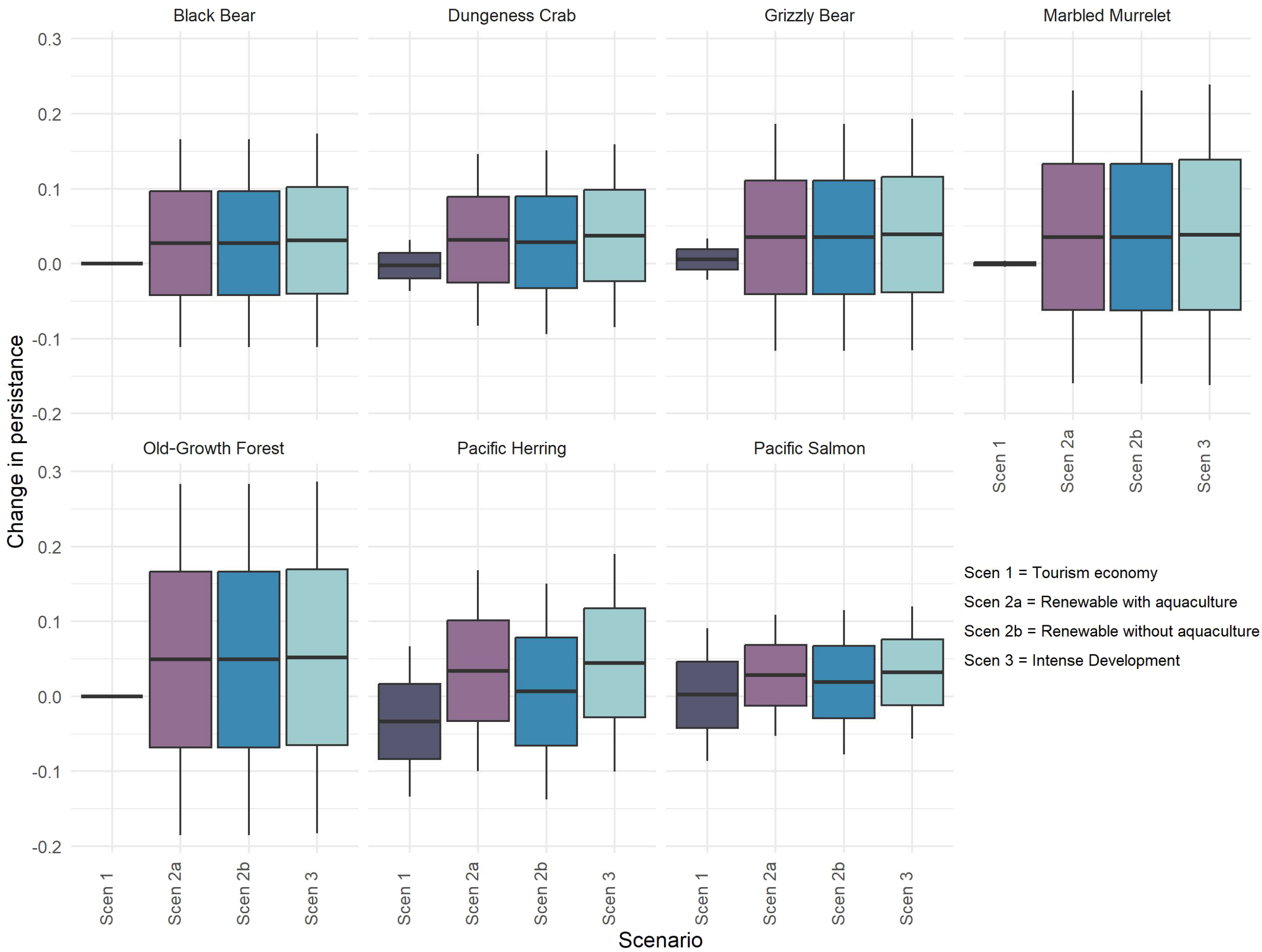


FIGURE 5 Boxplots of the average predicted probability of persistence for each ecosystem component across all planning units. The black line represents the mean, lower and upper hinges correspond to the standard deviation and whisker end points represent mean plus two standard deviations. Colours are used to visually differentiate scenarios.

pathway that prioritized ecotourism alone had optimal outcomes for Pacific herring, which increased in expected persistence across the region by 4% (Figure 5) (Table S6a). No change in the average probability of persistence was predicted for black bears or old-growth forest (Table S6). Ecosystem health overall improved by 1% across the region in this scenario, although in the coastal waters of the north, the average increase was up to 11% (Figure 6). Some declines in ecosystem health of up to 4% from the baseline state were observed in the northern subwatersheds (Figure 6).

3.3 | Scenario 2—Future renewable resource development

Expanding ecotourism development to include other sectors of the economy that rely on renewable resources such as forestry, renewable energy and salmon aquaculture (Scenario 2a; Table 1) resulted in a 5% average decline in old growth at a regional scale (to 40% probability of persistence), followed by grizzly bears (4% decline to 49%) (Figure 5; Table S6). Declines in predicted probability of persistence at the subwatershed scale were greatest for old-growth forest and Marbled Murrelets (54% decline for both, Table S6), with relatively large but spatially concentrated changes in predicted probability of persistence for bears also (up to 44% reduction for grizzlies and 40% for black bears). Dungeness crabs were least impacted in this scenario, with a maximum predicted decline in the persistence of 17%. Average predicted ecosystem health declined by almost 4% across the board from current conditions to 43% at a regional scale (Table S6). In contrast, once salmon aquaculture was removed (Scenario 2b), the average predicted probability of persistence returned to baseline levels for Pacific herring (43%), with increases in persistence similar to those under an ecotourism economy at a planning unit scale for Pacific herring, Pacific salmon, Dungeness crab and Marbled Murrelets in the north. Average ecosystem health across the region was marginally higher when salmon aquaculture was removed (44%) than included (Table S7), although some coastal fisheries management areas in the north showed up to 11% increase in ecosystem health with the removal of aquaculture (Figure 6).

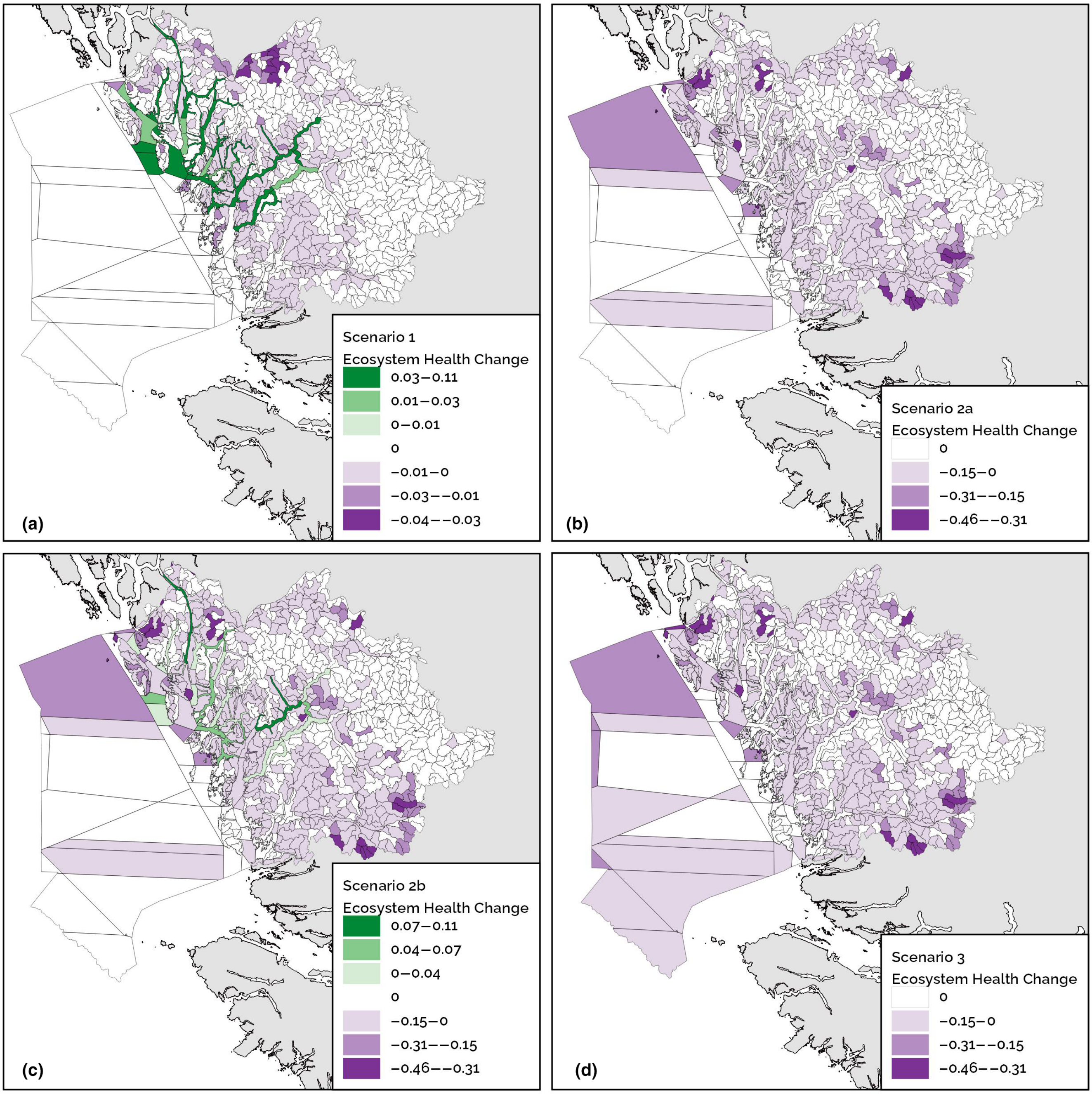


FIGURE 6 Changes in ecosystem health in each planning unit (subwatersheds or fisheries subareas) estimated by the Bayesian network for each development scenario relative to the baseline scenario—(a) tourism economy (Scenario 1), (b) renewable resources with salmon aquaculture (Scenario 2a), (c) renewable resources without salmon aquaculture (Scenario 2b) and (d) intense development (Scenario 3). Green shading represents an average improvement in ecosystem health in the planning unit, versus purple shading, which indicates a decline in predicted ecosystem health. Spatial visualizations of the probability of persistence for ecosystem components are available for interrogation in a Shiny App (https://ubcconservationdecisionslab.shinyapps.io/ccce_app_cc/).

3.4 | Scenario 3—Intensive economic development

The final scenario added the future expansion of mining and non-renewable energy sources such as oil and gas exploration, infrastructure and shipping (Table 1; Table S2). For individual ecosystem components, Pacific salmon had the lowest average predicted probability of persistence across the region at 34% (ranging from 16% to 60% in some planning units), followed by Pacific herring at 39% (Figure 5). Only species dependent on ocean environments were predicted to have greater declines in health compared to Scenario 2 (Table S6b). Although the greatest declines at the planning unit resolution from baseline conditions were predicted for Marbled Murrelets and old-growth forest (up to 54% decline), these were similar to declines predicted for Scenario 2, Table S6.

Black bears had the highest average predicted probability of persistence under this scenario at 54% (Figure 5). Under this scenario, ecosystem health had the greatest declines at the planning unit resolution (46%, Table S6), and averaged across the region (8% reduction to 44%) compared to all other scenarios (Table S7). Spatially, marginal declines were observed in the far north-east subwatersheds of Kitasoo Xai'xais, and some offshore fisheries subareas (Figure 6).

4 | DISCUSSION

Charting new development pathways that lead to positive and sustainable outcomes for local communities and biodiversity requires future-focused thinking that integrates multiple, diverse perspectives and challenges existing culture and practice (Diamond, 2019). CEAs that directly engage Indigenous knowledge and provide output relevant for First Nations governments not only support communities living with the consequences of cumulative effects, but also uphold commitments many western governments have made via the United Nations Declaration of the Rights of Indigenous Peoples (UNDRIP) (Adams et al., 2023; Eckert et al., 2020), and are a step towards meeting the Convention on Biological Diversity's Global Biodiversity Framework targets around indigenous knowledge (target 21, https://www.cbd.int/gbf/targets/21/). Despite increasing recognition of the effectiveness of regional CEAs grounded in local values, knowledge and experiences (Mantyka-Pringle et al., 2017; Staples, 2022; Weber et al., 2012), environmental impact assessment continues to be shaped by legacies of colonialism and inequality (Larsen et al., 2017). Our Indigenous knowledge-driven approach provides an excellent foundation for participatory analysis of possible management futures for the Great Bear Rainforest and Sea, a culturally and ecologically complex decision-making context.

Our spatially explicit CEA allowed specific locations to be identified across the land and sea where place-based management is needed to prevent negative impacts on valued ecosystem components, and where improvements in health might occur given particular development futures. For example, development pathways that removed salmon aquaculture resulted in ecosystem health improvements across coastal waters, fjords and channels in the north. In contrast, scenarios driven by forestry and extractive energy drove declines in ecosystem health, particularly along valley bottoms and rivers in the west, in the north, where logging activities have been less intense, and offshore waters, where extractive energy may impact marine life. Findings are consistent with recent spatial maps of cumulative degradation to freshwater salmon habitats (Connors, Jones, Honka, et al., 2018). Salmon use coastal streams for spawning and rearing, which attracts carnivores and scavengers that rely on the salmon as a food source (Levi et al., 2020). Many of the most productive and biodiverse temperate rainforests occur in these areas due to the nutrient subsidies provided from the ocean through the returning salmon (Schindler et al., 2003). The reliance of multiple species on these habitats drove lower ecosystem health predictions in those valley bottoms, riparian zones and rivers where the cumulative impacts of combined human activities are greatest currently and are expected to continue in the future, and highlighted where effective regional ecosystem-based management might be needed to combat the 'death of a thousand cuts'.

Despite the acknowledged need for ecosystem-based management, threatened species conservation policies and regulations still largely focus on individual species (Simberloff, 1998). Our calculation of and approach to predicting ecosystem health can be downscaled to guide single-species management, by focusing on those species predicted to have the lowest probability of persistence both now and in the future. For example, salmon and herring had very low baseline predictions of persistence (37% and 43%, respectively) that dropped even lower with the future development of ocean-based and land-based resource extractive industries (Table S6). In other words, there is a high chance (63%) that salmon will no longer be able to sustain themselves or their ecosystem function, and will effectively extirpated, given business as usual human activities. Salmon and herring rely on interconnected pelagic, nearshore and estuarine environments, and as keystone species, they underpin the overall health and function of the coast (Fox et al., 2018; Hyatt & Godbout, 2000). Our predictions support growing evidence of the need for additional conservation strategies for salmon and herring at multiple scales (Chalifour et al., 2022; Walsh, Connors, et al., 2020). Marbled Murrelets also had large local declines predicted (up to 54% in some subwatersheds). This endangered bird species (IUCN 3.1 Classification) is reliant on old growth nesting habitat predicted to be significantly affected by development in the future (up to 54% decline in persistence), as well as ocean and coastal environments that may also experience degradation (BirdLife International, 2020; Hazlitt et al., 2010; Figure 6). Preventing declines of species predicted to worsen with development clearly requires conservative and sustainable management of local forestry and energy, as well as cross-realm management across connected ocean and land environments where threats are overlapping.

Not all sectors operating in the region were included as an explicit lever in the model due to data deficiencies or local management ability, but they were assumed to be interacting in the background of our models. Including different levels of fishing intensity by First Nations communities in future iterations of this model would add value, but the collection of local spatial fisheries data is needed. This approach could provide a recipe to help assess other emerging industries, such as kelp aquaculture, given the dynamic nature of development. Although climate change was raised as a key concern by knowledge holders, the potential effort required by knowledge holders and elicitors to include climate interactions in their predictions prohibited inclusion at this stage. Only slight differences in average predicted ecosystem health were found between development scenarios (Table S7), largely due to setting thresholds based on the relative value within normalized and, in some cases, aggregated pressure layers (Table S4), and averaging predictions across species, which reduced inter-pressure and inter-species variability. Future work could expand the calculation of ecosystem health to account for species functioning and importance within the ecosystem, and use a weighted species–pressure interaction matrix to improve inter-species and cross-scenario variability. For risk-averse planning, this approach could be modified using maximum values from predictions as inputs versus averages. Our thresholds approach has been used previously for undefined benchmarks for salmon (Connors, Jones, Kellock, et al., 2018). Future work could develop thresholds for each species based on biological objectives and/or risk, but for the majority of pressures, empirical benchmarks do not exist, especially those affecting coastal and marine environments. Importantly, our online user interface (RShiny) enables managers and decision-makers to explore all outputs at local and regional scales to inform in situ species-based and ecosystem-based management.

The ability of inclusive approaches to CEA that include shared western and Indigenous perspectives to contribute towards more effective adaptive co-management governance practices and solutions for the resilience and sustainability of ecosystems is increasingly acknowledged (Adams et al., 2018; Mantyka-Pringle et al., 2017; Staples, 2022). To respect the needs and well-being of participating knowledge holders, we chose a flexible analytical framework and facilitation style versus a rigid elicitation structure (see Supporting Information 2.1–2.3; Adams et al., 2023). Ecosystem components and the planning unit resolution were chosen to match the scales of management within the Great Bear Rainforest and Sea (Marine Planning Partnership Initiative, 2015; Province of British Columbia, 2016). Coupling elicited Indigenous knowledge with Bayesian methods enabled the consideration of future landscapes ranging from desirable by local communities (e.g. ecotourism) to highly undesirable (e.g. intense development) and highlighted development pathways leading to the least and worst impacts on valuable species. The best outcomes for future ecosystem health were found with Indigenous ecotourism, which has both conservation and community benefits (Johnston, 2000). Importantly, our future-focused method grounded in local values and knowledge is being used to support Indigenous-led governance of their lands and water. By predicting the future impacts of alternative development pathways on the species and ecosystems that are important to local communities, decisions can be made with the interests of current and future generations in mind.

AUTHOR CONTRIBUTIONS

Vivitskaia J. D. Tulloch, Megan Adams, Tara G. Martin and Stephanie Avery-Gomm conceived the ideas and designed the methodology; Megan Adams, Tara G. Martin, Briony Penn and Vivitskaia J. D. Tulloch designed and conducted the elicitation and collected the data; Vivitskaia J. D. Tulloch, Riley Finn and Mathieu Bourbonnais developed the code and conducted the analysis; Riley Finn and Vivitskaia Tulloch produced the figures; and Vivitskaia J. D. Tulloch led the writing of the manuscript. All authors contributed critically to the drafts and gave final approval for publication.

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CONFLICT OF INTEREST STATEMENT

All authors have no conflict of interest to declare.

DATA AVAILABILITY STATEMENT

We acknowledge the right of Indigenous Peoples to own, control, access and possess data that derive from them, and which pertain to their members, knowledge systems, customs or territories. This research follows the 'CARE' stands principles (Collective Benefit, Authority to Control, Responsibility and Ethics (Carroll et al., 2020)), prioritizing Indigenous self-determination and the protection of Indigenous knowledge, cultures and intellectual property rights. Raw data sources listed in Tables S1 and S2 include publicly available information, but exclude Indigenous proprietary data sources. All outputs are available on the Shiny app https://ubcconservationdecisionslab.shinyapps.io/ccce_app_cc/.

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SUPPORTING INFORMATION

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

Data S1. Supplementary methodology detail, detail on expert elicitation, supplementary tables and figures, and references.

Data S2. Workshop materials.

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