Indigenous knowledge of key ecological processes confers resilience to a small-scale kelp fishery

Hannah M. Kobluk1 | Keith Gladstone2 | Mike Reid2,3 | Kelly Brown2,3 | Kira A. Krumhansl4 | Anne K. Salomon1

Abstract
1. Feedbacks between social and ecological processes can lead to sustainable stewardship practices that support ecological resilience among harvested populations. This is evident along the world’s coast lines, where Indigenous knowledge systems have facilitated millennia of human–nature coexistence. However, social–ecological conditions globally are quickly shifting, posing challenges for coastal Indigenous communities where customary harvest of ocean resources, such as kelps, needs to adapt to growing markets, novel climates and changing governance regimes. Consequently, a pressing need exists to determine how specific ecological and social variables drive key dynamics within coupled human–ocean systems.

2. Motivated by the information needs of an Indigenous community on Canada’s Pacific Coast, we co-designed a traditional harvest experiment, field surveys and semi-directed interviews with Indigenous resource users and managers to measure the ecological resilience of the feather boa kelp Egregia menziesii to harvest and determine what environmental variables most affected its recovery. We wove these results with information on current stewardship practices to inform future management of this slow-growing perennial kelp based on Indigenous knowledge and western science.

3. We found that Egregia recovered from traditional harvest levels faster than expected with minimal impact on its productivity because plants sprouted new fronds. In fact, traditional harvest levels of Egregia mimicked natural frond loss. Indigenous knowledge and empirical ecological evidence revealed the importance of individual plant size, site-specific seawater temperature and wave exposure in driving Egregia recovery. Indigenous stewardship practices reflected these ecological relationships in the practice of selecting large plants from sites with healthy patches of Egregia. While we documented key social controls of harvest, current self-reported harvest levels of kelp fronds were two times greater than the stated social norm, but only 1.2 times greater in terms of kelp biomass.
INTRODUCTION

Contemporary evidence suggests that management and conservation interventions linking ecological and social processes outperform those that do not (Cinner et al., 2016; Gill et al., 2017; Gutiérrez et al., 2011; Schultz et al., 2015). For example, tightly coupled feedbacks between social and ecological processes can lead to sustainable stewardship practices that support a species' ecological resilience to harvest (Liu et al., 2007; Ostrom, 2009), that is its recovery rate following this disturbance (Levin & Lubchenco, 2008; Standish et al., 2014). This is because harvest decisions, such as where, when, how much and by what means, influence resource recovery trajectories, which can, in turn, influence a harvester's behaviour. When tightly coupled over long periods of time, the reciprocal feedbacks between harvest decisions and resource recovery rates provide a mechanism for learning and adapting (Fitzhugh et al., 2019). However, external disturbances such as emerging markets, new governance regimes and novel climate shocks can disrupt these feedbacks and lead to overharvesting (Lyver & Tyliaikakis, 2017). Consequently, only through the integrated study of coupled social–ecological systems (SES), where these feedbacks are embedded within a larger, complex adaptive system (Berkes et al., 2003; Berkes & Folke, 1998), can we begin to understand and manage these interactions to support system-wide, social–ecological resilience, that is the capacity of an interdependent system of people and nature to absorb disturbances, learn, reorganize and adapt as to retain its same function, structure and feedbacks (Holling, 1973; Walker et al., 2004).

A deep pre-history of integrated, system-wide approaches to natural resource management exists among Indigenous and place-based communities around the world (Berkes, 2012; Cinner & Aswani, 2007; Jackley et al., 2016; Lepofsky & Caldwell, 2013; Stephenson et al., 2014). This can be attributed to accumulated knowledge of how ecological conditions, social practices and their interactions affect the sustained use of resources over generations (Berkes, 2012; Kimmerer, 2013; Simpson, 1999). This knowledge–practice–belief complex (Berkes, 2012) referred to as Indigenous Knowledge, includes beliefs about how people fit into ecosystems, emergent codes of conduct with 'more-than-human' beings (Simpson, 1999), patterns of resource use, management and conservation that evolve as an expression of these relationships (Lepofsky & Armstrong, 2018; Lepofsky & Caldwell, 2013), and the body of knowledge resulting from enacting these practices (Berkes et al., 2000; Simpson, 1999). It is these systems of knowledge and practice that often promote sustained relationships with place (Artelle et al., 2018). This is well documented, among the world's coastal oceans, where these adaptive knowledge systems have facilitated millennia of human–nature coexistence and social–ecological resilience despite harvest pressure and changing environmental conditions (Corbett et al., 2008; Costa-Pierce, 1987; Rose et al., 2016; Toniello et al., 2019; Turner et al., 2000; Williams, 2016).

Within temperate coastal oceans, oral histories and archaeological evidence dating back millennia point to the longstanding relationship between people and kelp, species of seaweeds in the order Laminariales. Kelps were used as food, medicine, fishing line and storage in Chile and along the Pacific Coast of Canada for over 14,000 years (Dillehay et al., 2008; Erlandson et al., 2007; Turner, 2001). In more recent years, in addition to continued subsistence and small-scale harvests, global markets for seaweeds broadly and kelp specifically have been expanding, posing new opportunities and challenges to coastal communities world-wide (Buschmann et al., 2014; Nayar & Bott, 2014). Kelps are targeted for harvest due to their fast growth rates (Mann, 1973), high levels of biomass and a strong capacity to recover from disturbances (Dayton et al., 1992). For example, recent research on small-scale fisheries of grey weed Lessonia nigrescens and giant kelp Macrocystis pyrifera showed no detectable effects of even intermediate harvest rates on kelp populations and kelp-dependent fish assemblages (Krumhansl et al., 2017; Vásquez et al., 2012). However, in some cases, industrial-scale commercial kelp harvest of these well-documented foundation species (Dayton, 1972) has been shown to negatively affect kelp reproductive potential (Geange, 2014; Reed, 1987) and recruitment (Thompson et al., 2010), as well as kelp-dependent species, including people, through the loss of habitat and prey (Druehl & Breen, 1986; Krumhansl et al., 2017; Lorentsen et al., 2010). The harvest of kelp biomass therefore presents a trade-off between economic opportunity and system-wide...
social–ecological resilience. Fortunately, traditional harvest practices have been shown to facilitate high plant recovery rates (e.g., Turner, Lepofsky, et al., 2013) and support local food security and livelihoods, thereby minimizing these trade-offs.

Along the northwest coast of North America, the feather boa kelp *Egregia menziesii* (Figure 1a) is an ecologically important seaweed that is culturally valuable to coastal Indigenous peoples, including the Haiłzaqv (Heiltsuk First Nation) on the central coast of British Columbia (BC), Canada. *Egregia* is a perennial kelp found in wave swept rocky intertidal and shallow subtidal habitats from northern Baja to south central Alaska (Abbott & Hollenberg, 1976).

Ecologically, *Egregia* acts as a source of habitat and food for a diversity of fish and invertebrates, and shapes intertidal community composition by scouring substrate (Hughes, 2010). It is grazed by a diversity of herbivores and influenced by a diversity of factors such as wave exposure, ocean temperature and the presence of other kelps (Black, 1974, 1976; Friedland & Denny, 1995; Gordon & De Wreede, 1978; Paine, 2002). Culturally, when *Egregia* is used as a substrate to collect eggs of spawning Pacific herring *Clupea pallasii*, it is locally referred to as yáka (yagia; Figure 1b), and is an important gift, food, ceremonial and trading item for the Heiltsuk and First Nations along the northwest coast of North America. The harvest of *Egregia* is embedded in systems of Indigenous knowledge and practice and managed via ancestral laws and protocols known as Ėvi’las (Gvi’ilas; Figure 1c).

With the need for new livelihood opportunities among coastal Indigenous communities in BC, and the opportunity presented by expanding global markets (Campbell et al., 2016; Ehlers, 2016), interest in developing a small-scale commercial harvest of *Egregia* yáka emerged within the Heiltsuk community. However, traditional and local knowledge of *Egregia*’s slow growth rates led to community concern that this species of kelp may not be able to sustain commercial harvest levels. Therefore, prior to pursuing commercial opportunities, Heiltsuk resource users and managers wanted to first improve their understanding of *Egregia*’s recovery rates following traditional harvest methods and determine why kelp in some areas appear to recover more quickly than in other areas. This research therefore, was motivated by traditional resource users and managers aiming to gather information that would later allow them to balance the trade-off between increased livelihood opportunities and the ecological resilience of a culturally important kelp. Because this trade-off is embedded within broader social–ecological conditions that are quickly shifting due to climate change (Savo et al., 2017; Whitney et al., 2020), novel markets (Bennett et al., 2019; Campbell et al., 2016; Ehlers, 2016), new governance agreements with Canada’s Federal fisheries agency (Fisheries & Oceans Canada, 2019) and international declarations aiming to uphold the rights of Indigenous Peoples to access and manage traditional resources (TRC, 2015; UNGA, 2007), evaluating it demands an understanding of the broader social–ecological system (Figure 1c).

To inform the sustainable harvest of *Egregia* specifically and our understanding of the social–ecological system within which this harvest practice is embedded, we gathered data on the recovery of *Egregia* following traditional harvest (i.e. ecological resilience of *Egregia*) and the social–ecological factors affecting it. By braiding western science and Indigenous knowledge, we asked (a) What is the recovery rate of *Egregia* following traditional harvest in terms of biomass re-growth, frond elongation and new frond production; (b) What environmental conditions most affect recovery and (c) What ancestral management and stewardship practices are currently being used in the harvest of *Egregia*?

**FIGURE 1** (a) Fronds of the intertidal feather boa kelp *Egregia menziesii* are used by coastal Indigenous people as (b) a substrate to collect Pacific herring *Clupea pallasii* eggs, a traditional food called yáka (yagia). (c) Key components (rectangles), external disruptions (ovals), internal drivers (green text) and functional relationships (arrows), including direct links (solid arrow) and feedback (dashed arrows) that comprise the yáka social–ecological system and small-scale fishery (photos by A. Salomon, H. Kobluk).
Based on previous research, we predicted that harvested *Egregia* plants would have reduced growth compared to unharvested plants due to meristem removal (at the distal end of the fronds; Figure S1) and *Egregia*'s slow growth relative to other perennial kelps. Based on the intermediate disturbance hypothesis (Connell, 1978; Grime, 1973), we predicted that wave exposure and *Egregia* biomass recovery would have a dome-shaped relationship where optimal recovery would occur at intermediate magnitudes of wave exposure (Demes et al., 2013; Friedland & Denny, 1995). We also anticipated a dome-shaped, nonlinear response to disturbance by grazers (Black, 1976; Paine & Vadas, 1969). Moreover, we expected that ambient kelp density would have a negative effect on recovery due to density-dependent competition for light and nutrients (Black, 1974). Similarly, we anticipated a negative effect of increased seawater temperature, which is associated with reduced nutrient availability (Gordon & De Wreede, 1978; Krumhansl et al., 2017). Socioculturally, we surmised that ancestral stewardship practices for *Egregia* would reflect Heiltsuk practices of limited harvests and cultural protocols of reciprocity and respect (Artelle et al., 2018; Brown & Brown, 2009; Housty et al., 2014). Finally, we anticipated that these cultural protocols would be reflected in the amount and method of harvest, as well as the selection of individual *Egregia* plants.

### 2 | METHODS

#### 2.1 | Knowledge co-production

This paper was co-produced through a process that equitably engaged Indigenous resource users and managers in the research from its inception. The original need for this research was identified by a Heiltsuk kelp harvester (co-author K Gladstone) who brought it to Heiltsuk stewardship and aquatics managers (co-authors K Brown and M Reid) and university researchers (co-authors A Salomon and K Krumhansl). Together, we conceptualized the project by way of in-person meetings and conference calls. At the request of Heiltsuk co-authors, researchers held an initial, pre-field season meeting with the Indigenous stewardship office staff, and a community workshop (led by co-author H. Kobluk) to build trust among all system actors and hone our research questions, site selection and methods to best reflect the research interests of the managers, kelp harvesters and broader Heiltsuk community. After those meetings, traditional knowledge interviews were requested by the stewardship director to ensure Indigenous knowledge and western science were both included in future kelp management plans. Funding and logistics were jointly provided through academic streams and the stewardship office. Finally, the results of the work were shared and reviewed at community presentations and in meetings with stewardship office staff to hone our interpretation of the results. The co-authors on this paper reflect this knowledge co-production process and the intellectual contributions of all partners. This research process built on >10 years of research partnerships and reflects the lessons learned, relationships, trust and camaraderie that grew over that time.

#### 2.2 | Study area

We experimentally harvested *Egregia* at five rocky intertidal sites along the central coast of British Columbia in the traditional territory of the Heiltsuk First Nation (Figure S2) during the spring growing season (April 2017). Sites were selected based on recommendations from Indigenous natural resource managers and harvesters that were known for being areas of high *Egregia* abundance and common harvesting areas. Specific study sites were chosen to reflect variation in wave exposure, accessible sloping bedrock outcrops and contiguous beds of *Egregia* above mean low water.

At each site, a 30 × 2 m horizontal belt transect was placed through *Egregia* habitat at approximately the same tidal height (~1 m above chart datum). Within this belt transect, we conducted a harvest experiment, measured sea surface temperatures and estimated grazer and ambient kelp densities.

#### 2.3 | Harvest experiment

To test the effects of the traditional (Heiltsuk) harvest practice, we randomly selected 9–15 *Egregia* plants\(^1\) within our belt transect. We tagged every frond on each plant at the branch point using numbered tubing and measured each frond from origin to distal end (1 cm accuracy). We randomly imposed a harvest treatment on 6–10 plants and left the rest as un-harvested controls. For each harvested plant, we clipped 25% of the fronds (≥45 cm) 45 cm above the holdfast, mirroring the Heiltsuk traditional practice of partial harvest. The clipped ends of fronds were then measured (max length) and weighed (grams wet weight) to establish length–weight regressions later used to estimate in situ biomass. To measure *Egregia* recovery/growth, we re-measured the length of all tagged and new untagged fronds 99–114 days later (July 2017).

We calculated six plant-level recovery metrics between sampling intervals. (a) Net biomass production (\(g_{\text{final}} - g_{\text{initial}}\) day\(^{-1}\)) using biomass estimates from our length–weight regression (\(y_i = 0.29462x_i^{1.28818}\); pseudo \(R^2 = 0.84\); \(n = 219\) fronds). (b) Net frond production, not accounting for lost fronds (fronds\(_{\text{final}} - \text{fronds}_{\text{initial}}\) day\(^{-1}\)). (c) Net frond elongation, not including negative measures (similar to Blanchette et al., 2002; cm\(_{\text{final}} - \text{cm}_{\text{initial}}\) day\(^{-1}\)). Plus all metrics were relativized by initial measure. As these measures are based on net difference between sampling intervals, we account for tissue loss experienced during the study period and measures are likely underestimates of total growth.

#### 2.4 | Environmental drivers

##### 2.4.1 | Temperature

We measured ambient intertidal temperature every 5 min for the duration of the study period using loggers (0.001 precision, ±0.2°C

---

\(^{1}\)While *Egregia* is a not a 'plant' taxonomically but a macroalga in the order Laminariales, plant is commonly used as a colloquial term to mean one individual thallus or macroalga.
accuracy) affixed along a transect ~1 m above chart datum. We tested loggers for consistency and deployed a set that yielded the smallest difference among readings (0–0.07°C). We divided temperature data into exposed air and subtidal seawater temperatures based on when transects were submerged using the nearest observed tidal height data. We averaged all readings for the duration of the study to calculate both mean seawater and air temperature, and ran models to assess the evidence for their relative effects on biomass recovery. The effect of seawater temperature on recovery had more empirical support than air temperature; thus, we included it in our global environmental models.

2.4.2 | Grazer and ambient kelp densities

To estimate the densities of dominant herbivores and kelps at each site, we counted strongly interacting grazers (Katharina tunicata, Strongylocentrotus droebachiensis, Strongylocentrotus purpuratus and Mesocentrotus franciscanus) and kelps (Alaria marginata, Macrocystis pyrifera, Saccharina sessilis, Saccharina groenlandica, Costeria costata and Egregia menziesii) in eight 1 m² plots randomly stratified within our 30 x 2 m belt transect by dividing the transect horizontally into two strata.

2.4.3 | Wave exposure

We calculated a relative exposure index (REI) for each site over the study period based on Krumhansl and Scheibling (2011):

\[
REI = \sum_{i=1}^{16} \left( V_i \times W_i \times F_i \right),
\]

where \( V_i \) is the average monthly wind speed (km/hr), \( W_i \) is the wind frequency and \( F_i \) is the fetch (km) from the 4th direction (north, north northeast, northeast, east northeast, etc., in 16 increments of 22.5°). Wind data were accessed from Environment Canada (https://climate.weather.gc.ca/historical_data/search_historic_data_e.html).

2.5 | Indigenous knowledge interviews

We interviewed Egregia experts in the nearby Heiltsuk community of Bella Bella in May 2018 (Figure S2). Expert describes a person who has knowledge of Egregia harvesting practices, including harvesters (present or in the past), elders/knowledge holders and aquatic resource managers. We selected experts based on recommendations by the aquatics manager and through chain-referral by other interviewees (Huntington, 2000). To determine realized Egregia harvest rates, variables that influenced recovery post-harvest, and Heiltsuk stewardship practices, we conducted a quantitative survey combined with semi-directed interviews. This process, and the materials used, were approved by Simon Fraser University’s office of research ethics.

To quantify the magnitude and variation in subsistence harvest rates of Egregia, we asked harvesters to identify the percent of fronds they typically harvest using diagrams depicting different harvest rates (Figure S3). To quantify local observations of the factors that influence Egregia recovery rates, we asked harvesters to rank the relative importance of environmental variables using a Likert-type scale (Boone & Boone, 2012) where respondents selected a rank from 1 (not important) to 7 (extremely important). We first asked harvesters to identify variables and then presented them with a standardized list of variables analogous to those measured in our ecological experiment. These rankings were relativized and median ranks were presented (Boone & Boon, 2012). In an effort to converge on conclusions about dominate driving variables from these two unique sources of evidence (i.e. scientific consilience (Wilson, 1998)), we plotted both sets of environmental variables by their order of importance and presented them side by side. For open-ended questions (Appendix S2) about stewardship practices, including where, when and how people harvest, responses were categorized into dominant themes following a thematic analysis approach (Braun & Clarke, 2012). Because not all participants answered each question, sample sizes varied per question.

2.6 | Statistical analysis

To determine the relative strength of evidence for the effect of harvest on Egregia, we took an information theoretic approach. We compared multiple candidate models that included treatment (harvest, control), site and their interaction as fixed effects. We used both gross and net (i.e. relativized) measures of growth to account for the effect of initial plant size in driving model outcomes. We built generalized linear models (GLZ) using a Gaussian error distribution for models of relative biomass recovery because biomass data were normally distributed. We used a Gamma error distribution for models of relative frond production and relative frond elongation because these data were positive and continuous.

We built an additional series of GLZ to assess the strength of evidence for key environmental drivers in influencing recovery of harvested Egregia plants. We selected individual predictor variables based on a priori hypotheses about Egregia growth (Burnham & Anderson, 2002) gleaned from previous research (Black, 1974, 1976; Demes et al., 2013; Friedland & Denny, 1995; Gordon & De Wreede, 1978). We used a Gaussian error distribution for models of biomass and relative biomass recovery, and a Gamma error distribution for models of frond production and relative frond elongation because these data were positive and continuous.

All models were fit using maximum likelihood and alternative candidate models were compared using small-sample-corrected Akaike’s information criterion (AICc) standardized to most parsimonious model to produce ΔAICc and normalized Akaike weights (w; Burnham & Anderson, 2002). Empirical support for a model was taken to be when the next most parsimonious model had a ΔAICc.
value $>2$. For environmental drivers, we compared all model subsets (no interactions) and model averaged a set of (‘top’) candidate models ($\Delta AIC_c < 4$) using the MuMln package in R (Bartoń, 2020). We selected this threshold ($\Delta AIC_c < 4$) to facilitate comparison of all fixed effects across models and knowledge types while still selecting for models with some empirical support ($w_i > 0$). Regression coefficients were calculated using conditional averages and relative variable importance (RVI), the sum of model Akaike weights ($w_i$) in which those variables were found (Burnham & Anderson, 2002). Predictor variables were assessed for co-linearity using correlation coefficients ($<0.5$) and variance inflation factors (VIFs; $<10$, Quinn & Keough, 2002). Variables were centred and scaled (by one standard deviation) to facilitate comparison between fixed effects (Schielzeth, 2010). Residuals were inspected to ensure data met assumptions of normality and homoscedasticity. We tested for normality with the Shapiro–Wilk test. For net biomass recovery, we completed analyses with and without two outliers and found no difference in findings. Moreover, field notes indicated that these outliers were within Egregia’s natural range of variation. Consequently, outliers were kept for all subsequent analyses.

3 | RESULTS

3.1 | Effect of harvest

Relative biomass production over the duration of our experiment was most strongly influenced by site ($\Delta AIC_c = 0.0$, $w_i = 0.80$, Table 1A). There was a fivefold difference in relative biomass production between sites, which ranged from 0.8% day$^{-1}$ to 3.9% day$^{-1}$ (Figure 2a). Across sites, net biomass ranged from 11.72 to 42.79 g of Egregia produced per day, which translates into 1,201–4,395 g produced over the 3.5-month study period.

Across all sites, harvested and un-harvested control plants were similarly productive (3.1% day$^{-1}$). We found little support for an effect of harvest treatment on relative biomass recovery and no evidence for an interaction between site and harvest treatment ($w_i = 0.0$, Table 1A). We found similar results for relative frond elongation, with strong evidence for an effect of site ($w_i = 0.79$, $\Delta AIC_c = 2.65$, Figure S4; Table S1) and no evidence for an effect of treatment ($\Delta AIC_c > 2$, Figure S4; Table S1).

While we aimed to harvest 25% of the fronds (>45 cm) from each experimental plant, on average we removed 22% ($\pm SD$, median = 24%, Figure 2b). When converted to biomass, we experimentally harvested 41% ($\pm 11$ SD, median = 39%, Figure 2c) of the ‘harvestable’ (fronds >45 cm) biomass of each plant due to the selection of larger fronds to mimic traditional harvest protocols. Both the level of fronds and biomass harvested fell within the range of natural loss experienced by un-harvested plants (fronds 0% to 50%, mean = 19% $\pm 19$ SD, Figure 2b; biomass 0%–48%, mean = 10% $\pm 14$ SD Figure 2c). Self-reported subsistence harvest levels (mean 49% $\pm 13$% SD, median = 50%, Figure 2b) were 2.2 times higher than our experimental number of fronds removed that was designed to mimic traditional harvest levels, but only 1.2 times (20%) greater when examined as the amount of biomass harvested. Experts expressed that the amount they harvest per plant varies with weather conditions and associated ease of harvesting, as well as the age/length of the plant.

3.2 | Environmental drivers of kelp recovery

Initial biomass, seawater temperature and wave exposure explained 69% of the variation in net kelp biomass recovery post-harvest (Table 1B) and this pattern was consistent across all measures of kelp growth.

3.2.1 | Initial size

We found strong evidence that initial biomass of harvested individuals had a precise, positive effect on net biomass recovery, frond elongation and frond production post-harvest (RVI = 1, Table 1B; Figure 3a; Figure S5). The amount of biomass recovered increased with initial biomass (Figure 4a), and frond production increased with higher numbers of initial fronds (Figure S5). Experts ranked pre-harvest size as the lowest driver of kelp recovery rate post-harvest (median ranking = 0.57; Figure 3b).
3.2.2 | Seawater temperature

We found strong evidence that seawater temperature had a negative effect on *Egregia*'s biomass recovery (RVI = 1, Table 1B; Figure 3a), relative biomass recovery (RVI = 1, Table 1B; Figure S5), frond production (RVI = 0.8, Table 1B; Figure S5) and frond elongation rate (RVI = 1, Table 1B; Figure S5). Additionally, experts ranked seawater temperature as the most important ecological driver of kelp recovery (median rank = 0.86, Figure 3b). Across our five sites, mean seawater temperature ranged from 11.52°C (±0.01 SE) to 12.53°C (±0.02 SE). We observed a 7.4 times greater median biomass recovery and 3.4 times greater median relative biomass recovery at coolest compared to warmest sites (Figure 4b,d).

### TABLE 1

| Model | K | n | LL   | AICc | ΔAICc | Wᵢ | R²   |
|-------|---|---|------|------|-------|-----|------|
| **(A)** |     |   |      |      |       |     |      |
| **Relative biomass production** |     |   |      |      |       |     |      |
| Site  | 6  | 47 | 135.86 | -257.6 | 0 | 0.8 | 0.4 |
| Treatment + Site | 7  | 47 | 135.86 | -254.8 | 2.77 | 0.2 | 0.4 |
| Treatment + Site + Treatment:Site | 11 | 47 | 138.22 | -246.9 | 10.71 | 0 | 0.46 |
| Intercept | 2  | 47 | 124.24 | -244.2 | 13.4 | 0 | 0 |
| Treatment | 3  | 47 | 124.34 | -242.1 | 15.5 | 0 | 0 |
| **(B)** |     |   |      |      |       |     |      |
| **Biomass recovery** |     |   |      |      |       |     |      |
| Initial size + SST + Exposure | 5  | 31 | -122.07 | 256.5 | 0 | 0.47 | 0.69 |
| Initial size + SST | 4  | 31 | -124.39 | 258.3 | 1.78 | 0.19 | 0.64 |
| Initial size + SST + Exposure + Grazer density | 6  | 31 | -121.98 | 259.5 | 2.92 | 0.11 | 0.69 |
| Initial size + SST + Exposure + Kelp density | 6  | 31 | -122.07 | 259.6 | 3.1 | 0.1 | 0.69 |
| Initial size + SST + Kelp density | 5  | 31 | -123.85 | 260.1 | 3.57 | 0.08 | 0.65 |
| **Relative biomass recovery** |     |   |      |      |       |     |      |
| Grazer density + SST + Exposure | 5  | 31 | 93.82 | -175.2 | 0 | 0.5 | 0.44 |
| SST + Kelp density | 4  | 31 | 91.18 | -172.8 | 2.42 | 0.15 | 0.34 |
| Grazer density + SST + Exposure + Kelp density | 6  | 31 | 94.08 | -172.7 | 2.58 | 0.14 | 0.45 |
| Grazer density + SST + Kelp density | 5  | 31 | 92.22 | -172 | 3.2 | 0.1 | 0.38 |
| Grazer density + SST | 4  | 31 | 90.46 | -171.4 | 3.86 | 0.07 | 0.31 |
| **Frond production** |     |   |      |      |       |     |      |
| Initial fronds + SST | 4  | 31 | 14.92 | -20.3 | 0 | 0.31 | 0.42 |
| Initial fronds + SST + Exposure | 5  | 31 | 16.22 | -20 | 0.27 | 0.27 | 0.47 |
| Initial fronds | 3  | 31 | 12.68 | -18.5 | 1.83 | 0.12 | 0.33 |
| Initial fronds + SST + Kelp density | 5  | 31 | 15.37 | -18.3 | 1.97 | 0.12 | 0.44 |
| Initial fronds + SST + Grazer density + Exposure | 6  | 31 | 16.82 | -18.1 | 2.15 | 0.11 | 0.49 |
| **Frond elongation** |     |   |      |      |       |     |      |
| Initial size + SST | 4  | 31 | -107.42 | 224.4 | 0 | 0.3 | 0.69 |
| Initial size + SST + Exposure | 5  | 31 | -106.27 | 224.9 | 0.56 | 0.22 | 0.71 |
| Initial size + SST + Kelp density | 5  | 31 | -106.43 | 225.3 | 0.88 | 0.19 | 0.71 |
| Initial size + SST + Grazer density + Exposure | 6  | 31 | -105.19 | 225.9 | 1.51 | 0.14 | 0.73 |
| Initial size + SST + Grazer density | 5  | 31 | -107.26 | 226.9 | 2.54 | 0.08 | 0.69 |

Notes: Models with varying numbers of parameters (K) were compared using log–likelihood (LL), small-sample bias-corrected Akaike’s Information Criterion (AICc), ΔAICc differences (ΔAICc), normalized Akaike weights (Wᵢ) and Rsquared (R²). All models for model set (A) shown, top 5 models for model sets (B) shown.
3.2.3 | Grazer density

For models of biomass and frond recovery that included initial biomass as a fixed effect, we found relatively little evidence for an effect of grazer density, and the effect was imprecise (i.e. parameter SE crosses zero; RVI = 0.11; RVI = 0.25, Figure 3a; Figure S5, respectively). While experts ranked grazer density second-to-last among the drivers included in this study (pre-harvest size was ranked the least important driver), the absolute ranking of this driver is still relatively high (median rank = 0.71, Figure 3b).

We found that grazer density had a relatively strong positive effect on relative biomass recovery post-harvest (RVI = 0.84, Table 1B; Figure 4c). Mean grazer density estimates ranged from 0 to 7.75 individuals/m$^2$ ($\pm$2.21 SE). We observed a similar effect of grazer density...
on relative frond elongation (RVI = 0.87, Figure S5), but a weaker and variable effect on relative frond production (RVI = 0.36, Figure S5).

### 3.2.4 Wave exposure

We found a relatively important negative effect of wave exposure on biomass recovery (RVI = 0.71, Figure 3a; Table 1B), relative biomass recovery (RVI = 0.66, Figure S5; Table 1B) and relative frond elongation (RVI = 0.87, Figure S5). The effect of wave exposure on frond production was less important than initial number of fronds and seawater temperature, and this effect was variable (RVI = 0.43, Figure S5). Experts ranked wave exposure as an important driver of kelp biomass recovery, similar to that of seawater temperature (median rank = 0.86, Figure 3b).

### 3.2.5 Ambient kelp density

We found relatively little strength of evidence for an effect of ambient kelp density on growth post-harvest across all metrics of growth, such as biomass recovery (RVI = 0.19, Figure 3a), relative biomass recovery (RVI = 0.4, Figure S5) and frond production (RVI = 0.19, Figure S5; Table 1B). Kelp stipe densities at experimental sites ranged from 7.38 (±1.59 SE) to 52.25 stipes/m² (±18.45 SE). Experts ranked ambient kelp density to be somewhat important for recovery post-harvest (median rank = 0.75) above grazer density and pre-harvest size (Figure 3b). In interviews, *Egregia* harvest experts also identified sunlight, air temperature, ‘seeding’ (i.e. new growth emerging from unused pieces of *Egregia* fronds that are discarded), sea otters and storms as important environmental drivers of kelp recovery post-harvest. These drivers are not included in figures as the rankings for each only came from <9% of respondents.

### 3.3 Stewardship practices

We interviewed 22 local experts, who self-assessed their knowledge of Heiltsuk food fisheries, harvest and stewardship practices at 4.57 (±0.13 SE) out of 5, and at 4.05 (±0.18 SE) out of 5 for yáka harvest and stewardship practices. Of all (n = 22) participants, 91% were men and 9% were women. Participants ranged from 36 to 88 years old with an average age of 60. When asked how many years they had been harvesting and/or holding knowledge of yáka, our experts had on average 37.5 years of experience, with a range of 12–72 years. Some respondents had more knowledge of yáka processing (specifically women respondents) or broader knowledge of stewardship practices in general (Elders), whereas current harvesters could speak more to modern-day practices and trends. Within the context of the community, we interviewed 18/26 (69%) people identified as kelp experts as well as an additional 4/12 (33%) of names received through chain referral for a total of 22/38 (58%) people.

#### 3.3.1 Harvest method

Compared to ecological drivers (shown in Figure 3), harvest method was ranked as the most-important driver of recovery (median = 1).

![**FIGURE 5**](stewardship_practices.jpg)

**FIGURE 5** Traditional harvesting and stewardship practices of *Egregia* including (a) plant selection criteria, (b) harvesting techniques used to ensure sustainable use and (c) harvest location (grey denotes why location would change), with representative Indigenous knowledge quotes (photos by A. Salomon & H. Kobluk; photo of C. Newman used with consent)
Traditional harvest methods encompassed plant selection based on individual- and population-level characteristics of *Egregia*, specific removal techniques and harvest location.

### 3.3.2 | Plant characteristics

Kelp fishers selectively harvest based on large plant size (68%), healthy plants (47%), high quantity and quality of blades (42%) and/or the health of a particular ‘patch’ of *Egregia* (11%; Figure 5a). Experts that identified ‘long fronds’ (grouped with large size) as a characteristic of choice expressed that ‘long’ meant a range from 1.5 to 6 feet (mean 4.19’, median of 4.5’).

### 3.3.3 | Harvesting practices

Nearly all harvesters (91%) stated the importance of leaving the holdfast of *Egregia* during harvest to ensure sustainable use. Other practices include taking only what you need (from a plant) and leaving some fronds behind (41%), assessing the amount of *Egregia* in a patch (and take what you need without impacting that patch; 23%). Cutting fronds instead of ripping them (23%) and leaving small fronds for regeneration (9%) were also identified practices (Figure 5b).

### 3.3.4 | Harvest location

Sixty-eight percent of harvesters return to the same general harvest area every year while 21% go to different areas. People conditionally change where they harvest depending on the proximity to giant kelp (*M. pyrifera*) beds (another harvested kelp) and/or herring spawning areas (37%), weather and tide conditions (26%) and/or the health of *Egregia* in an area (26%; Figure 5c).

### 3.3.5 | yáka uses

Participants harvest *Egregia* for use in the yáka fishery. Yáka is most often given to family or others in the community (64%), used for personal consumption (50%), traded (36%) and used for cultural events (14%). One participant harvests yáka commercially (5%).

### 4 | DISCUSSION

By braiding western science and Indigenous knowledge, our results reveal social-ecological processes that affect the ecological resilience of a culturally important kelp species that is the basis of a small-scale Indigenous food fishery on the northwest coast of North America. Specifically, we found that the traditional harvest practices of removing 25% of the fronds of individual *Egregia* plants had minimal impact on its productivity and in fact mimicked the natural loss of fronds that occurs over the growing season (Figure 2a,b). Moreover, we found a convergence of evidence, from independent sources, revealing the dominant variables driving kelp recovery. Specifically, Indigenous knowledge of the ecological variables driving kelp recovery and empirically collected evidence of these same variables revealed that plant size, site-level seawater temperature and to a lesser extent wave exposure were the variables that most influenced *Egregia* recovery following harvest (Figures 3 and 4a,b, Table 1B). Stewardship practices reflect these ecological relationships in the practice of selecting large plants from healthy patches of *Egregia* (Figure 5a). Here, a co-designed harvest experiment and field surveys alongside Indigenous knowledge improved our understanding of the ecological and social variables affecting the ecological resilience of this kelp to harvest, and the broader social norms and customary management practices in which these interactions are embedded.

### 4.1 | Traditional harvest practices mimic natural loss

The foremost management challenge facing most harvested populations is determining what harvest technique and level of biomass removal supports recovery and sustained use. Counter to our predictions, we found no detectable effect of traditional harvest practices on *Egregia* biomass production (Figure 2a, Table 1A). Surprisingly, this moderate level of harvest (25% of fronds/plant cut above the holdfast) falls within the natural range of frond loss we observed over the same period (Figure 2b). As *Egregia* is a multi-frond kelp, the partial harvest technique allowed for new fronds to sprout from the remaining stipes. Both the level of natural frond loss we observed (median 17% frond loss), as well as our target level of harvest (25% frond removal/plant), are within recorded rates of frond loss for *Egregia* elsewhere (Demes et al., 2013), indicating we could expect a comparable effect of a similar harvest elsewhere. The congruence between the customary practice of harvesting 25% of *Egregia*’s fronds and the natural loss of fronds implies the accumulation of Indigenous knowledge of a fundamental ecological process driving the dynamics of this kelp and the application of the knowledge to support kelp recovery and sustained use.

From a biological standpoint however, mimicking natural levels of frond loss may not always provide a benchmark for ecologically resilient kelp harvest. Kelp tissue erosion varies spatially and temporally and in response to levels of human and non-human impact (Krumhansl & Scheibling, 2011). Kelp harvest can also exceed production due to processes that decrease kelp tissue health (e.g. epifaunal overgrowth and mesoherbivore grazing) leading to biomass loss over time (Krumhansl & Scheibling, 2011). Lastly, as is the case here, when larger fronds are targeted for harvest even when customary harvest rates are followed, the total biomass of kelp harvested may exceed the biomass of natural frond loss because a range of frond sizes could be affected depending on the mechanism...
The ability of kelp to recover from harvest may therefore be a function of harvest amount and technique as well as ecological processes at a particular harvest site.

Although we detected minimal impacts of harvest on the scale of individual plants, the ecological resilience of Egregia, like other species of harvested kelps, could vary across multiple spatial and temporal scales and have both population- and ecosystem-level implications. For example, M. pyrifera biomass recovers rapidly following small-scale harvest (Krumhansl et al., 2017) but previous work has shown that harvest can result in a 68% decrease in generation of reproductive blades in this species (Geange, 2014), which could have long-term implications for population persistence. Additionally, the removal of kelp biomass from the ecosystem can impact associated ecological communities through a reduction in habitat and food, either directly grazed or entering food webs through detrital pathways (Krumhansl & Scheibling, 2012).

We specifically looked at individual recovery of biomass after 25% of individual plant fronds were removed, but concern that harvest intensity could increase with growing commercial interest in this species remains (Figure 1c). In fact, stated subsistence harvest rates (Figure 2b) suggest this may already be happening. While Egregia’s future population persistence in the presence of Indigenous harvest that has been ongoing for generations seems likely, this may not be the case should harvest rates and spatial extent expand. For instance, one expert first began harvesting 72 years ago (F. Reid interview May 2018) and two more described learning from their grandparents (A. Duncan, W. Housty interviews May 2018), which suggests that kelp has sustained harvest over time. Yet, commercialization and increased participation in this harvest might reduce the ecological resilience of this kelp and the social–ecological resilience of the entire fishery. In fact, it was this concern that sparked our study. ‘There’s not a whole lot of it [Egregia], and if we indiscriminately harvest it there’s gonna be none left’ (Anonymous interview May 2018). The discrepancy between self-reported harvest levels of fronds and our harvest experiment meant to mimic traditional harvest practices (Figure 2b) illuminates the implications of how external disturbances, such as novel national and international markets, can disrupt local people’s ability to harvest according to their traditional protocols (Figure 1c). In this case, as with coupled human–ocean systems worldwide, these external shocks can erode adherence to customary norms and lead to aberrant behaviour such as overharvesting (Lyver & Tylianakis, 2017). Further work would be required to examine potential individual-, population- and ecosystem-level effects of increased harvest levels and any practices associated with a larger-scale commercial harvest.

4.2 Multiple lines of evidence reveal plant size and seawater temperature influence kelp recovery

The size of an individual within a population has been shown to influence growth and resilience to disturbance (e.g. Audzijonyte et al., 2015; Claessen et al., 2000). Similar to previous work on kelps (Rothman et al., 2006) including Egregia (Black, 1974) that showed larger plants grow faster, we found that larger plants recovered more biomass post-harvest (Figures 3a and 4a). This could be due to greater photosynthetic capacity of larger fronds, or alternatively, size escape from the effects of crowding (Black, 1974). However, we did not find support for an effect of ambient kelp density on biomass recovery likely because densities were low over the range we measured.

Paradoxically, initial plant size did not emerge as an important driver of recovery from expert knowledge (Figure 3b). Yet, experts described the deliberate use of size selective harvesting practices such that only large, robust plants were selected for harvest (Figure 5a). This was a social norm codified in a harvest practice, whereas our experimental harvest intentionally targeted a range of plant sizes to test the effect of size on recovery. The experiential nature of expert knowledge meant that expert assessment of key variables affecting kelp recovery was based primarily, if not entirely, on larger plants targeted by harvest. While we found an important effect of plant size on recovery rates in our ecological models, these findings are based on randomly selected plants that represent a range of sizes. Thus, this paradox may be due to the respective divergent sample populations upon which Indigenous knowledge and ecological observations were made. In fact, traditional harvesting practices already reflect the importance of plant size that emerged from our experimental findings. Furthermore, experimental findings and Heiltsuk Indigenous knowledge of the relative influence of multiple environmental conditions that most promote Egregia recovery post-harvest were ranked in the same order of importance (Figure 3). This convergence of evidence from independent data sources reflects the broader notion of scientific consilience, when multiple yet sovereign data sources are used to draw strong conclusions (Wilson, 1998).

Temperature and nutrients are important and interrelated factors well known to influence the persistence of kelps in space and time (Bell et al., 2015; Dayton, 1985; Dayton et al., 1999; Pérez-Matus et al., 2017). Temperature drives kelp geographical distribution and abundance (Dayton et al., 1992; Lüning, 1990), and warming temperatures can affect physiological processes (Harley et al., 2012). Seawater temperature is also tightly coupled with nutrient availability, with cooler more nutrient-rich water driving higher density, growth and recruitment of kelp (Bell et al., 2015; Dayton et al., 1999; Parnell et al., 2010; Pérez-Matus et al., 2017). As predicted, we observed a negative effect of seawater temperature on biomass recovery, notably over a small range (11.52°C ± 1.78 to 12.53°C ± 3.10 SD), similar to what was observed for harvested M. pyrifera in the region (Krumhansl et al., 2017). Within British Columbia, negative effects on growth and photosynthesis have been observed in Egregia at temperatures higher than 10°C (Gordon & De Wreede, 1978), possibly indicating that the temperatures over our study period were exceeding thermal optimum for physiological functioning. Alternatively, a link between sea surface temperature and nitrate has been observed in California (Dayton et al., 1999; Parnell et al., 2010), therefore...
given strong seasonal patterns of upwelling in northern coastal waters of BC (Okeley et al., 2014), our observed effect of temperature may in fact be a signal of tightly coupled factors. Our data, however, do not allow us to disentangle these effects. In addition to effects on growth, warmer temperatures and low nutrients can lead to tissue degradation (Krumhansl & Scheibling, 2011; Rothäusler et al., 2009). Whatever the mechanism, sea water temperature is an important consideration for both harvested kelp biomass and quality and suggests that future harvest could be directed to cold water refuges.

4.3 Waves and grazers ‘prune’ kelp

Many studies have shown that kelps are highly influenced by a host of different environmental factors other than temperature (Cavanaugh et al., 2011; Dayton, 1985; Dayton et al., 1999; Parnell et al., 2010), which pose additional considerations for harvest management. For instance, increased wave exposure can negatively affect kelp biomass through tissue erosion and dislodgement (Bell et al., 2015; Cavanaugh et al., 2011; Krumhansl & Scheibling, 2011) but can also support rapid recovery and increased production in comparison to more sheltered sites (Graham et al., 1997; Pedersen et al., 2012). This suggests a nonlinear relationship between kelp size and wave exposure. *Egregia* is known for its adaptations to survive in wave-disturbed environments, including robust holdfasts and ‘self-pruning’ (Demes et al., 2013; Friedland & Denny, 1995). Given this, we hypothesize that the negative effect of wave exposure we observed (Figure 3a) may only be capturing part of a nonlinear, hump-shaped relationship. As traditional harvest practices target larger plants, consideration of wave exposure is important, as indicated by the relatively high ranking of wave exposure by local experts (Figure 3b).

Grazers are also an important driver in kelp ecosystems (Byrnes et al., 2013; Duggins, 1980; Foreman, 1977), yet in our analysis they did not emerge as an important driver of recovery for net measures. This finding challenges our original hypothesis that grazers would reduce the size and amount of biomass. Contrary to our hypothesis, we observed a positive relationship between grazer density and proportional growth (Figure 4c). Previous studies have shown that grazed *Egregia* fronds are more likely to break (Haggerty et al., 2018), and once broken, more branches grow from the main frond or holdfast (Black, 1976). Given this, it is possible that grazers in this study were stimulating growth of new fronds similar to ‘pruning’ plants on land. While we focused on the most strongly interacting kelp forest grazers in this area (*Katharina tunicata, Strongylcentrotus droebachensis, S. purpuratus and Mespocentrotus franciscanus;* Paine, 1992), the presence of other interacting grazers that we did not document such as limpets of the family Lottiidae and amphipods, known to impact frond strength of *Egregia* (Burnett & Koehl, 2018), may have had a numerical effect on kelp productivity that went undetected.

The ecological conditions that influence kelp production do not operate independently (Dayton, 1985; Dayton et al., 1999), rather they tend to interact (e.g. Filbee-Dexter et al., 2016; Wernberg et al., 2010). Climate change, for example, can alter the ecological conditions important to kelp and thus harvest outcomes. While current kelp harvest practices appear robust with minimal impact on individual kelp recovery metrics, temperature had a relatively strong negative effect even over a small range (1°C). This disproportionate effect of temperature indicates that the outcomes of this harvest may not be stable under the warming seawater conditions associated with climate change. There is also the potential for interactive effects between stressors, such as commercial harvest and climate change. However, even within the context of large-scale global change, local scale factors dominate as important drivers of kelp dynamics (Krumhansl et al., 2016), which underscores the importance of local management systems including customary practices. With growing interest in wild and farmed seaweed harvest globally and rising ocean temperatures, our study highlights the importance of site-specific conditions, specifically temperature, in driving recovery as well as how social and ecological processes can support kelp recovery rates.

4.4 Value of social-ecological research in informing kelp fisheries amid global change

Commercial interest in seaweed harvesting and aquaculture is growing quickly throughout North America and world-wide as part of the upsurge of interest in developing the ‘blue’ economy, that is the sustainable use of ocean resources for economic growth (Bennett et al., 2019; Ehlers, 2016). This is in part due to the low carbon footprint, health benefits and culinary interests in seaweeds, as well as its potential to locally ameliorate acidified waters in polyculture applications with shellfish such as oysters, clams and mussels (Duarte et al., 2017; Mac Monagail et al., 2017). However, along temperate coastlines world-wide, tensions exist due to the growing numbers of large-scale commercial seaweed harvest and aquaculture activities operating in the same ocean spaces as smaller-scale Indigenous and artisanal harvests, often with divergent values, incompatible management objectives and thus clashing management systems (Gelcich et al., 2006; Krumhansl et al., 2017; Thompson et al., 2010). Additionally, western approaches to marine conservation, such as the establishment of no-take marine reserves, which exclude human use, conflict with the practices, values and sovereign rights of Indigenous Peoples (Bennett, 2018; Turner, Berkes, et al., 2013).

Lastly, marine heat waves seem to be driving, in part, the decline or collapse of some kelp forest ecosystems (Rogers-Bennett & Catton, 2019), exacerbating these tensions. Scientists, policymakers, natural resource managers, Indigenous communities and non-Indigenous communities are striving to enhance their understanding and develop equitable frameworks to address complex resource management and value-laden issues facing our coastal oceans. Developing a deeper understanding of fisheries as social-ecological systems, and illuminating characteristics that confer their resilience, is especially important in light of quickly emerging international markets and rapid climate change.
4.5 Indigenous harvest practices reflect ecological processes

Emerging ethnographic and archaeological evidence suggests that many Indigenous harvesting practices have been shaped by millennia of experimentation, observation, adapting and the development of social norms—characteristics well known to confer social–ecological resilience (Biggs et al., 2012)—so as to maintain or enhance production and sustain use of resources over time (Cinner & Aswani, 2007; Fitzhugh et al., 2019; Groesbeck et al., 2014; Stephenson et al., 2014; Toniello et al., 2019; Turner & Peacock, 2005). The suite of customary kelp harvesting practices described here, emergent from Indigenous knowledge, reflects multiple conditions for kelp recovery. As described above, harvesters primarily select kelp based on size (Figure 5a), which is complementary to our finding that larger plants recover more biomass post-harvest (Figure 4a). Therefore, whether intentional or not harvesters are selecting for plants that are more ecologically resilient to harvest. Additionally, partial harvest and the technique of leaving the plant’s holdfast attached to the rock (Figure 5b) allow for individual plant regeneration based on observed branching abilities of Egregia (Black, 1976) and population-level persistence given the source of spores that remain post-partial harvest. Lastly, returning to the same area every year (Figure 5c) suggests the ability to monitor perennial patches of kelp, such as Egregia, for harvest effects and build up a time series of observation from local harvest locations. Restricting the harvests of marine species to specific areas is a common practice among coastal First Nations along the north-eastern Pacific. These systems of contingent proprietorship of ocean spaces by family clans means harvesters were, and still are, held accountable for the sustained use of resources in these areas over time (Powell, 2012; Troper, 2003).

Overall, we surmise that customary management practices and social norms rooted in Indigenous knowledge promote system-wide social–ecological resilience of this place-based Indigenous kelp fishery. Although we show empirically how a particular harvest practice might confer ecological resilience of a kelp species to harvest (i.e. recovery rate), social–ecological resilience is an emergent system property that reflects social, ecological and management processes (Figure 1c, Ostrom, 2009). Critically, the goals that guide management processes in any system reflect the values, norms and underlying cosmology of a society (Lertzman, 2009). For the Heiltsuk Nation, their customary law and knowledge, known as Ġvił̓ às, guide relationships to place and promote reciprocity, responsibility and respect towards the natural world (Brown & Brown, 2009; Housty et al., 2014). So while we measured recovery rates to harvest, our results cannot be isolated from the social norms and broader cultural context of Heiltsuk Ġvił̓ às, which are an example of the deep place-based values of Indigenous Peoples that play a role in sustaining environments and societies over time (Artelle et al., 2018).

Environmental degradation, socio-economic transformation and loss of intergenerational knowledge, however, are common challenges eroding traditional practices faced by Indigenous communities world-wide (Berkes et al., 2000; Brown & Brown, 2009; Simpson, 1999). As described by Hilistis ‘Not only was there disruption in the transmission of the teaching of the practice of harvesting...it’s much easier to go trapping and hunting in the band [grocery] store’ (Hilistis Interview May 2018). When local people’s ability to harvest according to their traditions is disrupted so is community kinship, and adherence to customary norms can decline, which can lead to overharvesting (Lyver & Tylianakis, 2017). Interviewees describe the high financial cost of going out harvesting (E Newman interview May 2018) and the perception that some people are improperly harvesting Egregia (R. Johnson, R. Carpenter Jr. Interviews May 2018), which may reflect both loss of knowledge and barriers to the continued transmission of knowledge. Moreover, declines in resource abundance and resulting changes in their spatial distribution means that people need to harvest outside of their customary family use areas. This erosion of knowledge and customary practices could help explain why reported subsistence harvest is higher than the level of traditional harvest used to inform our experiment (Figure 2b), and also signals how external disruptions like environmental changes and economic markets can alter the feedbacks between harvester and kelp. External disruptions to traditional harvesting systems, including climate change and centralized colonial laws (Figure 1c; Simpson, 2004; Turner & Turner, 2008), are emblematic of challenges to Indigenous communities and customary management across the globe.

Scientific consilience allows for a broader depth of understanding of conservation and management problems. This is reflected in the parallel notion of ‘two-eyed seeing’ that mobilizes Indigenous and western scientific knowledge specifically (Reid et al., 2021). Here we show, through respectful and community-engaged research (see Adams et al., 2014), how weaving western science and Indigenous knowledge together can yield a stronger picture of the variables that affect the ecological resilience of a kelp to harvest and the social–ecological resilience of a traditional food system. This, in turn, provides a richer evidence base for decision making and policy (Alexander et al., 2019; Reid et al., 2021). While this approach is not without its challenges (see Nadasdy, 1999; Simpson, 2004), we provide an example of co-produced ‘research that arises from place’ that attempts to centre Indigenous knowledge throughout our scientific understanding and strives for equitable power in knowledge production throughout the research process. Research that arises from place (instead of being imposed on a place) is rooted in local culture, knowledge and management priorities, it benefits and involves the local community making it relevant, applicable and perceived as legitimate by the community where it is based. Locally driven knowledge co-production provides an avenue to democratize the science and practice of natural resource management and conservation (Salomon et al., 2018), support self-determination, and move towards more ecologically safe and socially just operating space (Bennett, 2018; Raworth, 2012).
ACKNOWLEDGEMENTS
This research was conducted in collaboration with the Heiltsuk Integrated Resource Management Department (HIRMD). Funding was provided by HIRMD, an SFU Engagement Grant, an NSERC Discovery and CFI grant to A.K.S. We thank J. Brown, R. Brown, A. Peers Jr., T. Prinzing, J. Burt, M. Thompson, S. Ouchi, E. Slade and K. Gladstone for field support. We thank our 22 interview participants for their time, trust and the gift of their knowledge. We thank Dr Karina Nielsen, an anonymous reviewer and our editors for their constructive feedback that greatly improved this work. We also thank J. Moore for the use of his words ‘research that arises from place’.

CONFLICT OF INTEREST
The authors declare no conflict of interest.

AUTHORS’ CONTRIBUTIONS
A.K.S., K.A.K., K.B., M.R. and K.G. conceived the research idea; all authors contributed to research design; H.M.K. and A.K.S. collected the data; H.M.K. performed the data analysis; H.M.K. and A.K.S. wrote the manuscript, and all authors edited the manuscript.

DATA AVAILABILITY STATEMENT
Ecological experiment data: Dryad Digital Repository https://doi.org/10.5061/dryad.59zw3r26r (Kobluk et al., 2021). Given data sharing agreements with First Nations partners and concerns around intellectual property, specific permission from the Heiltsuk Nation is required to access data from interviews (contact hmkobluk@gmail.com).

ORCID
Hannah M. Kobluk https://orcid.org/0000-0001-6942-2955

REFERENCES
Abbott, I. A., & Hollenberg, G. J. (1976). Marine algae of California. Stanford University Press.

Adams, M. S., Carpenter, J., Housty, J. A., Neasloss, D., Paquet, P. C., Service, C., Walkus, J., & Darimont, C. T. (2014). Toward increased engagement between academic and indigenous community partners in ecological research. Ecology and Society, 19(3). https://doi.org/10.5751/ES-06569-190305

Alexander, S. M., Provencher, J. F., Henri, D. A., Taylor, J. J., Lloren, J. I., Nanayakkara, L., Johnson, J. T., & Cooke, S. J. (2019). Bridging Indigenous and science-based knowledge in coastal and marine research, monitoring, and management in Canada. Environmental Evidence, 8(36), https://doi.org/10.1186/s13750-019-0181-3

Artelle, K. A., Stephenson, J., Bragg, C., Housty, J. A., Housty, W. G., Kawharu, M., & Turner, N. J. (2018). Values-led management: The guidance of place-based values in environmental relationships of the past, present, and future. Ecology and Society, 23(3). 35. https://doi.org/10.5751/ES-10357-230335

Audzijonyte, A., Fulton, E. A., & Kuparinen, A. (2015). The impacts of fish body size changes on stock recovery: A case study using an Australian marine ecosystem model. ICES Journal of Marine Science, 72(3), 782-792. https://doi.org/10.1093/icesjms/fsu185

Bartoń, K. (2020). MuMln: Multi-model inference. R package version 1.43.17. Retrieved from https://cran.r-project.org/package=MuMln

Bell, T. W., Cavanaugh, K. C., Reed, D. C., & Siegel, D. A. (2015). Geographical variability in the controls of giant kelp biomass dynamics. Journal of Biogeography, 42, 2010–2021. https://doi.org/10.1111/jbi.12550

Bennett, N. J. (2018). Navigating a just and inclusive path towards sustainable oceans. Marine Policy, 97, 139–146. https://doi.org/10.1016/j.marpol.2018.06.001

Bennett, N. J., Cisneros-Montemayor, A. M., Blythe, J., Silver, J. J., Singh, G., Andrews, N., Caló, A., Christie, P., Di Franco, A., Finkbeiner, E. M., Gelchis, S., Guidetti, P., Harper, S., Hotte, N., Kittinger, J. N., Le Billon, P., Lister, J., López de la Lama, R., McKinley, E., ... Sumaila, U. R. (2019). Towards a sustainable and equitable blue economy. Nature Sustainability, 3. https://doi.org/10.1038/s41893-019-0404-1

Berkes, F. (2012). Sacred ecology: Traditional ecological knowledge and resource management (Third). Routledge.

Berkes, F., Colding, J., & Folke, C. (2000). Rediscovery of traditional ecological knowledge as adaptive management. Ecological Applications, 10(5), 1251–1262. https://doi.org/10.2307/2641280

Berkes, F., Colding, J., & Folke, C. (Eds.). (2003). Navigating social-ecological systems: Building resilience for complexity and change. Cambridge University Press.

Berkes, F., & Folke, C. (1998). Linking social and ecological systems: Management practices and social mechanisms for building resilience. Cambridge University Press.

Biggs, R., Schlüter, M., Biggs, D., Bohensky, E. L., BurnSilver, S., Cundill, G., Dakos, V., Daw, T. M., Evans, L. S., Kotschy, K., Leitch, A. M., Meek, C., Quinlan, A., Raudsepp-Hearne, C., Robards, M. D., Schoon, M. L., Schultz, L., & West, P. C. (2012). Toward principles for enhancing the resilience of ecosystem services. Annual Review of Environment and Resources, 37(1), 421–448. https://doi.org/10.1146/annurev-environ-051211-123836

Black, R. (1974). Some biological interactions affecting intertidal populations of the kelp Egregia laevigata. Marine Biology, 28(3), 189–198. https://doi.org/10.1007/BF00387297

Black, R. (1976). The effects of grazing by the limpet, Acmaea Insessa, on the kelp, Egregia Laevigata, in the intertidal zone. Ecology, 57(2), 265–277. https://doi.org/10.2307/1934815

Blanchette, C. A., Miner, B. G., & Gaines, S. D. (2002). Geographic variability in form, size and survival of Egregia menziesii around Point Conception, California. Marine Ecology Progress Series, 239, 69–82. https://doi.org/10.3354/meps239069

Boone, H. N., & Boone, D. A. (2012). Analyzing Likert data. Journal of Extension, 50(2).

Braun, V., & Clarke, V. (2012). Thematic analysis. In H. Cooper, P. M. Camic, D. L. Long, A. T. Panter, D. Rindskopf, & K. J. Sher (Eds.), APA handbook of research methods in psychology, Vol 2: Research designs: Quantitative, qualitative, neuropsychological, and biological (pp. 57–71). American Psychological Association.

Brown, F., & Brown, Y. K. (2009). Staying the course, staying alive. Coastal First Nations fundamental truths: Biodiversity, stewardship, and sustainability. Biodiversity BC.

Burnett, N. P., & Koehl, M. A. R. (2018). Knots and tangles weaken kelp fronds while increasing drag forces and epifauna on the kelp. Journal of Experimental Marine Biology and Ecology, 508, 13–20. https://doi.org/10.1016/j.jembe.2018.08.003

Burnham, K. P., & Anderson, D. R. (2002). Model selection and multi-model inference: A practical information theoretic approach (Second). Springer.

Buschmann, A. H., Prescott, S., Potin, P., Faugeron, S., Vásquez, J. A., Camus, C., Infante, J., Hernández-González, M. C., Gutierrez, A., & Varela, D. A. (2014). The status of kelp exploitation and marine agronomy, with emphasis on Macrocystis pyrifera, in Chile. In N. Bourgougno (Ed.), Advances in botanical research: Sea plants (Vol. 71, pp. 161–188). Academic Press. https://doi.org/10.1016/B978-0-12-408062-1.00006-8
