

Diverse knowledge systems reveal social–ecological dynamics that inform species conservation status

Lynn Chi Lee¹ | Joe Thorley² | Jane Watson³ | Mike Reid⁴ | Anne Katherine Salomon⁵

¹School of Resource and Environmental Management, Simon Fraser University, Burnaby, British Columbia, Canada

²Poisson Consulting Ltd., Nelson, British Columbia, Canada

³Biology Department, Vancouver Island University, Nanaimo, British Columbia, Canada

⁴Heiltsuk Integrated Resource Management Department, Bella Bella, British Columbia, Canada

⁵School of Resource and Environmental Management, Simon Fraser University, Burnaby, British Columbia, Canada

Correspondence

Lynn Chi Lee, School of Resource and Environmental Management, Simon Fraser University, 8888 University Drive, Burnaby, BC V5A 1S6, Canada.

Email: lynn_chi_lee@sfu.ca

Funding information

Natural Sciences and Engineering Research Council of Canada; Pew Charitable Trusts; Hakai Institute, Tula Foundation; Canada Foundation for Innovation; Fisheries and Oceans Canada; Simon Fraser University

Editor

Abstract

Understanding changes over historical timescales is essential to gauge conservation status of a species. Modern ecological data typically neglect past magnitudes of change, which fortunately can be evaluated by bridging disparate knowledge sources. We synthesized zooarchaeological, historical, traditional, and western science knowledge to document changes in relative abundance of key species in Canada's northern abalone social–ecological system (SES) from the Holocene to present. Integrated models fit to traditional and western science data revealed 3.7% annual population decline from 1940s to 2010s for large abalone, although traditional knowledge density estimates were 9.5× higher than those derived from western science. Abalone are presently scarce compared to the mid-1900s, but more abundant than before the early 1800s, calling their endangered status into question. Linking multiple knowledge sources can build SES understanding, facilitate power sharing, and support ecologically sustainable and socially just conservation outcomes.

KEYWORDS

integrated Bayesian analysis, marine historical ecology, multiple evidence base, northern abalone, sea otter, shifting baselines, social–ecological system, species at risk, traditional knowledge, western science knowledge

1 | INTRODUCTION

Conservation science increasingly acknowledges the need to understand social–ecological system (SES) change over historical timescales to gauge a species' true conservation status. This long view is needed to account for magnitudes of change before modern ecological data that usually span only years or decades. A myopic view can lead to erroneous conclusions about species status and trends because of shifting baselines where each generation accepts what they grew up with to be normal, without knowledge of past abundances and conditions (Pauly, 1995).

Multiple knowledge sources are increasingly synthesized to reconstruct historical SESs (e.g., Early-Capistran et al., 2018; Saenz-Arroyo, Roberts, Torre, & Carino-Olvera, 2005; Salomon, Tanape, & Huntington, 2007; Thurstan et al., 2015). For example, zooarchaeological and isotopic evidence showed how fishing pressure changed size, abundance, and diet of California sheephead wrasse over 10,000 years (Braje et al., 2017). Zooarchaeological and ethnographic data from Canada's west coast suggested high Pacific herring abundances for millennia, declining only within the last century of commercial fishing (McKechnie et al., 2014). Historical accounts (e.g., explorers' ship logs) provide snapshots of

This is an open access article under the terms of the Creative Commons Attribution License, which permits use, distribution and reproduction in any medium, provided the original work is properly cited.

© 2018 The Authors. Conservation Letters published by Wiley Periodicals, Inc.

cultural lifeways and species abundances over centuries, otherwise unimaginable today (Saenz-Arroyo, Roberts, Torre, Carino-Olvera, & Hawkins, 2006). Traditional knowledge (TK) offers place-based understanding grounded in worldviews, practices, and laws learned from intergenerational interactions between people and their environment (Berkes, Colding, & Folke, 2000). This combined knowledge can alter conservation perspectives by broadening the timescale over which social–ecological interactions and species abundances are assessed.

The northern abalone (*Haliotis kamtschatkana*, hereafter abalone), a widespread marine mollusk found in nearshore rocky habitats, is a culturally important species used by coastal indigenous peoples in British Columbia (BC), Canada (First Nations) over millennia for food and regalia (Menzies, 2010; Sloan, 2004). Abalone also supported commercial and recreational fisheries from the 1950s until 1990 when all abalone fisheries were closed due to conservation concerns. Abalone were subsequently designated as threatened in 1999 and uplisted to endangered in 2009 under Canada's *Species at Risk Act* (2002; Fisheries and Oceans Canada, 2012). Sea otters (*Enhydra lutris*), a once-extirpated predator of macroinvertebrates including abalone, were reintroduced to BC from 1969 to 1972, and have since increased in abundance and range. They were listed as endangered in 1978, downlisted to threatened in 1996 and to special concern in 2007 (Sea Otter Recovery Team, 2007). Sea otters are drivers of rocky reef regime shifts, transforming urchin barrens devoid of kelp to kelp-forested reefs by reducing abundance and size of kelp-grazing urchins (Estes & Palmisano, 1974; Watson & Estes, 2011).

Here, we combined TK, ecological surveys, archaeological data, historical records, and fisheries landings to assess abalone SES change over time. This reconstruction identified three ecological regimes and revealed shifting baselines in abalone abundance and size. Considering this multiple evidence-based understanding of historical change, we present an alternative view about abalone's conservation status in Canada today.

2 | METHODS

To reveal SES regime shifts, we synthesized diverse knowledge sources using multiple evidence (Tengo, Brondizio, Elmqvist, Malmer, & Spierenburg, 2014) and triangulation (Jick, 1979) approaches to reconstruct major changes in key abalone SES components in coastal BC from the Holocene to present. To assess finer-scale changes in abalone abundance and size, we focused quantitative analyses within Heiltsuk First Nation traditional territory on BC's central coast (Figure 1a), using TK and western science knowledge (WSK) data from federal monitoring surveys.

2.1 | Coast-wide reconstruction over millennia

For precontact times, we estimated relative abundances of sea otter, urchin, abalone, and kelp (via kelp-associated fish bones, particularly rockfishes, herring, greenlings, and cabezon) using zooarchaeological shell midden analyses (Supporting Information Table S1), assuming human use reflected relative species abundance in the environment. Number of sea otter pelts traded provided an abundance index before and during the maritime fur trade, recognizing many early traded pelts were likely older pelts passed through First Nations generations (Sloan & Dick, 2012; Supporting Information Table S2). After sea otter extirpation, we estimated abalone density change using a published stock-recruitment relationship at 10% natural mortality rate (Zhang, Campbell, & Lessard, 2007; Supporting Information Table S2).

To anchor relative abalone, urchin, and kelp abundances through time, we used density data from contemporary field surveys in three regions of BC in a space-for-time substitution, with sites spanning 0–38 years of sea otter occupation ($n = 60$ sites, six to nine transects/site; see Lee, Watson, Trebilco, & Salomon, 2016). Sites with >10 years of otter occupation represented precontact conditions, and sites with no otters represented conditions decades after otter extirpation. Mean site densities by decade of otter occupation represented change following sea otter reintroduction (Supporting Information Table S2).

2.2 | Regional-scale change over recent decades

To compare proportional trends for abalone, urchin, and kelp with increasing sea otter occupation time by decade and region, we used subtidal data collected between May and September from random transects (Central Coast; $n = 19$ sites, six to nine transects/site; detail in Lee et al., 2016) and permanently marked transects (West Coast Vancouver Island; $n = 7$ sites, five transects/site, 1987–2015; Watson, J., 2016, unpublished data). For proportional change, we calculated mean densities by site, then grand site means by decade of sea otter occupation.

We conducted 10 semi-structured interviews (Bernard, 2013) to document Heiltsuk TK about abalone ecology, traditional use and management, and changes in abundance and distribution of sea otters, urchin, abalone, and kelp (see Supporting Information). The 14 participants (one woman, 13 men) from 39 to 90 years old were identified as abalone experts by the Heiltsuk natural resource department. To assess intertidal populations, we asked experts to reconstruct the number, size, and spatial distribution of abalone within a site over each decade they recalled. Experts placed color-coded, length-classified abalone shells on a table to represent abalone densities within a specified area that we quantified and photographed: extra-large (>120 millimeters

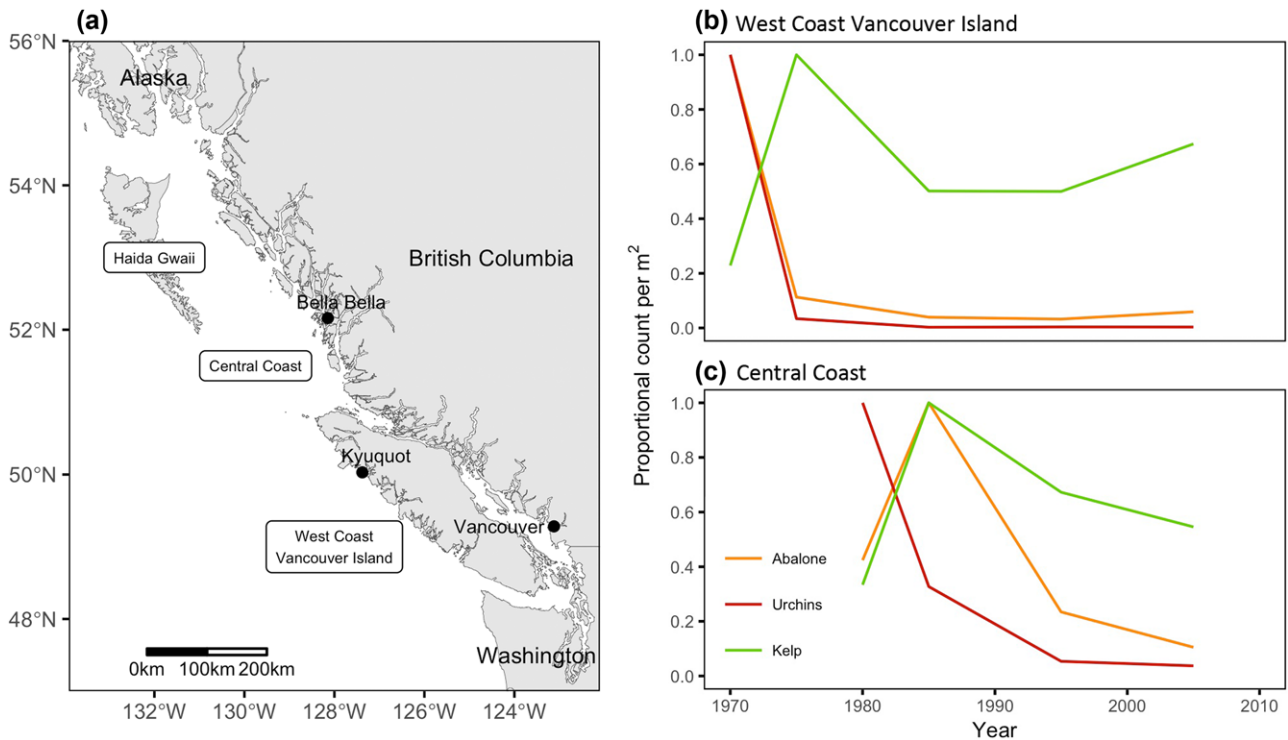


FIGURE 1 (a) Map of the British Columbia coast, including the communities of Kyuquot in Nuu-chah-nulth traditional territory on West Coast Vancouver Island and Bella Bella in Heiltsuk traditional territory on the Central Coast. Sea otters were reintroduced near Kyuquot from 1969 to 1972. A sea otter raft was first documented in Heiltsuk territory in the 1980s. Proportional change in densities of abalone, urchins, and kelp by region: (b) West Coast Vancouver Island and (c) Central Coast. Means of site means from transects within sites are plotted by decade of sea otter occupation

[mm]), large (100–120 mm), medium (70–99 mm), small (50–69 mm), extra-small (30–49 mm), and juvenile (<30 mm). Size classes were predetermined based on biological and fishery-related characteristics (e.g., abalone >70 mm are mature, 100 mm = minimum commercial size limit).

Annual commercial abalone catch data from Canada's federal fisheries agency were aggregated by decade to match TK data scale (Fisheries and Oceans Canada; 1957–1990; Supporting Information Figure S1). Sea otter population estimates were from direct count data (Nichol, Watson, Abernethy, Rechsteiner, & Towers, 2015). The WSK data used in population growth models were from federal abalone population surveys (1980–2016; Fisheries and Oceans Canada, 2016).

2.3 | Abalone population growth models for Heiltsuk territory

We estimated trends in large abalone ≥ 70 mm densities (TK length-classes medium, large, and extra-large) using density-independent exponential population growth models fit to TK and WSK data using Bayesian methods (Supporting Information Boxes S1–S3). Only WSK data were modeled for small abalone <70 mm (TK length-classes juvenile, extra-small, and small) due to few TK data points. Each TK observation represented average abalone density by site by decade. Each WSK observation represented total number of abalone per site

per year. Accordingly, we used a lognormal residual error distribution for TK and negative binomial distribution for WSK data.

For large abalone density, four alternative models were fit assuming constant annual population growth rate and random site effect. The full model estimated separate growth rates (slopes) and initial densities (intercepts) for TK and WSK (Supporting Information Table S4; Supporting Information Box S4). Three reduced models incorporated the same (1) growth rate, (2) initial density, and (3) growth rate and initial density, for TK and WSK.

For small abalone, two population growth rate models were fit with random site effect. The full model included a step change in growth rate (Supporting Information Table S8; Supporting Information Box S6) and the reduced model did not. Step change timing was fixed at 2004 based on preliminary modeling with no random site effect (Supporting Information Table S6; Supporting Information Box S5).

Model support was determined by Akaike weight (w_i ; Burnham & Anderson, 2002) based on the Wanatabe–Akaike Information Criterion (Watanabe, 2010). Posterior distributions were estimated from 4,000 Markov Chain Monte Carlo samples thinned from the second halves of four chains (Kery & Schaub, 2011). Model convergence was confirmed by ensuring potential scale reduction factor, \hat{R} , ≤ 1.05 for each parameter (Kery & Schaub, 2011). Model performance was

confirmed by examination of residual plots. Models were fit using STAN (Carpenter et al., 2017) and analyses run in R version 3.4.2 (R Core Team, 2015), with the smbr package (Muir & Thorley, 2018).

3 | RESULTS

Our results suggested that rate, magnitude, and spatial distribution of SES changes along BC's coast varied over the past 250 years with temporal and spatial differences in extirpation and recovery of sea otters (Figure 2). In areas reoccupied by sea otters, abalone and urchin densities declined by >75% within 1–5 years, then persisted at low densities. Kelp stipe density increased for ~6 years after otters arrived, then declined and stabilized at densities higher than reefs without otters (Figure 1b,c; Lee et al., 2016; Watson & Estes, 2011). Abalone and urchin densities stabilized by 10 years of sea otter occupation, representing site conditions at high otter abundance. Archaeological evidence suggested abalone persisted at relatively low abundances and sea otters at relatively high abundances prior to European contact.

The short, intense commercial abalone fishery left a profoundly reduced abalone population coast-wide (Figure 2b). The central coast commercial fishery from 1970s to 1980s corresponded with abalone declines observed by Heiltsuk experts (Figure 3; Supporting Information Figures S1 & S2; Table 1). Concurrent with the fisheries collapse was an increase in the newly reestablished sea otter population (Supporting Information Figure S1). Heiltsuk experts attributed abalone declines to (1) past and ongoing illegal fishing, (2) predation by sea otters, (3) commercial overfishing, and (4) increased predation by river otters and minks no longer being harvested (Supporting Information Table S3). Based on differences in the state of human and ecological communities, we parsed the abalone SES into three regimes: sea otters present, absent, and recovering (Figure 2).

For large abalone, ≥ 70 mm on the central coast, the most supported model ($w_i = 0.55$) included different initial densities and a shared annual population growth rate (Figure 4a,b; Supporting Information Table S10). TK and WSK data similarly supported an annual decline of 3.7% (credible interval [CRI] 2.2–5.2%), while abalone density estimates from TK were 9.5 \times (CRI 5.2–16.5) higher than those from WSK. Densities of small abalone <70 mm based on WSK declined annually at 13.3% (CRI 9.9–16.9%) from 1980 to 2003, then increased at 24.5% (CRI 18.3–31.0%) from 2004 to 2016, mostly because juvenile and extra-small abalone increased (Figure 4d; Supporting Information Tables S9 & S10). TK data for small abalone were insufficient to include in the model (Figure 4c).

TK suggested proportions of large and extra-large abalone declined from 1940s to early 2000s, while that of medium

abalone increased (Figure 5a). Small and extra-small abalone were absent from TK reconstructions until 1970s when they increased in proportion, and juvenile abalone were noted from 2000s onwards (Figure 5a). WSK indicated proportions of large and extra-large abalone increased from 1990s to early 2000s and then declined, while extra-small and juvenile abalone increased nearly sixfold from mid-2000s to mid-2010s (Figure 5b). Finally, proportions of medium and small abalone were consistently high from 1980 to 2016 (Figure 5b).

4 | DISCUSSION

4.1 | SES regime shifts alter abalone abundance

Using multiple lines of evidence (Saenz-Arroyo & Roberts, 2008; Tengo et al., 2014) and a historical ecology (Thurstan et al., 2015) approach, we showed how abalone abundance and size changed in BC from the Holocene to present (Figure 2b). Moreover, we revealed change in social–ecological context not possible through any source alone. Human activities influenced abalone populations over >10,000 years, indirectly through the extirpation and reintroduction of sea otters and directly through fishing (Figure 2; Supporting Information Table S1). Although environmental conditions can affect abalone populations by influencing reproduction, recruitment, growth, mortality, kelp abundance, and disease occurrence (Boch et al., 2018; Micheli et al., 2012; Rogers-Bennett, Dondanville, Moore, & Vilchis, 2010; Saenz-Arroyo & Roberts, 2008), oceanographic shifts did not correlate with red abalone abundance and size over millennial timescales in California (Braje, Erlandson, Rick, Dayton, & Hatch, 2009). Rather, evidence suggested that top-down effects of sea otters and human hunting and fishing strongly influenced historical trends (Braje et al., 2009), similar to mechanisms we illuminate here for BC.

During the *sea otters present* regime, zooarchaeological evidence showed consistently high abundances of sea otter bone, and sporadic low abundances of abalone shell fragments at suitable outer-coast sites (Figure 2b; Menzies, 2015; Orchard, 2007). Although sea otters reduced abalone abundance and size, they indirectly benefitted abalone by promoting expansion of kelp forests that provide food and shelter (Figure 2b; Supporting Information Tables S1 & S2; Lee et al., 2016; Watson, 2000; Watson & Estes, 2011). First Nations hunting from hundreds of villages likely reduced the local abundance and spatial distribution of sea otters, creating a patchwork of ecological conditions (Corbett et al., 2008).

The *sea otters absent* regime resulted from ecological extirpation of sea otters after ~50 years of intense maritime fur trade hunting (Figure 2b; Sloan & Dick, 2012). Concurrently, introduced diseases and trade-related conflicts reduced

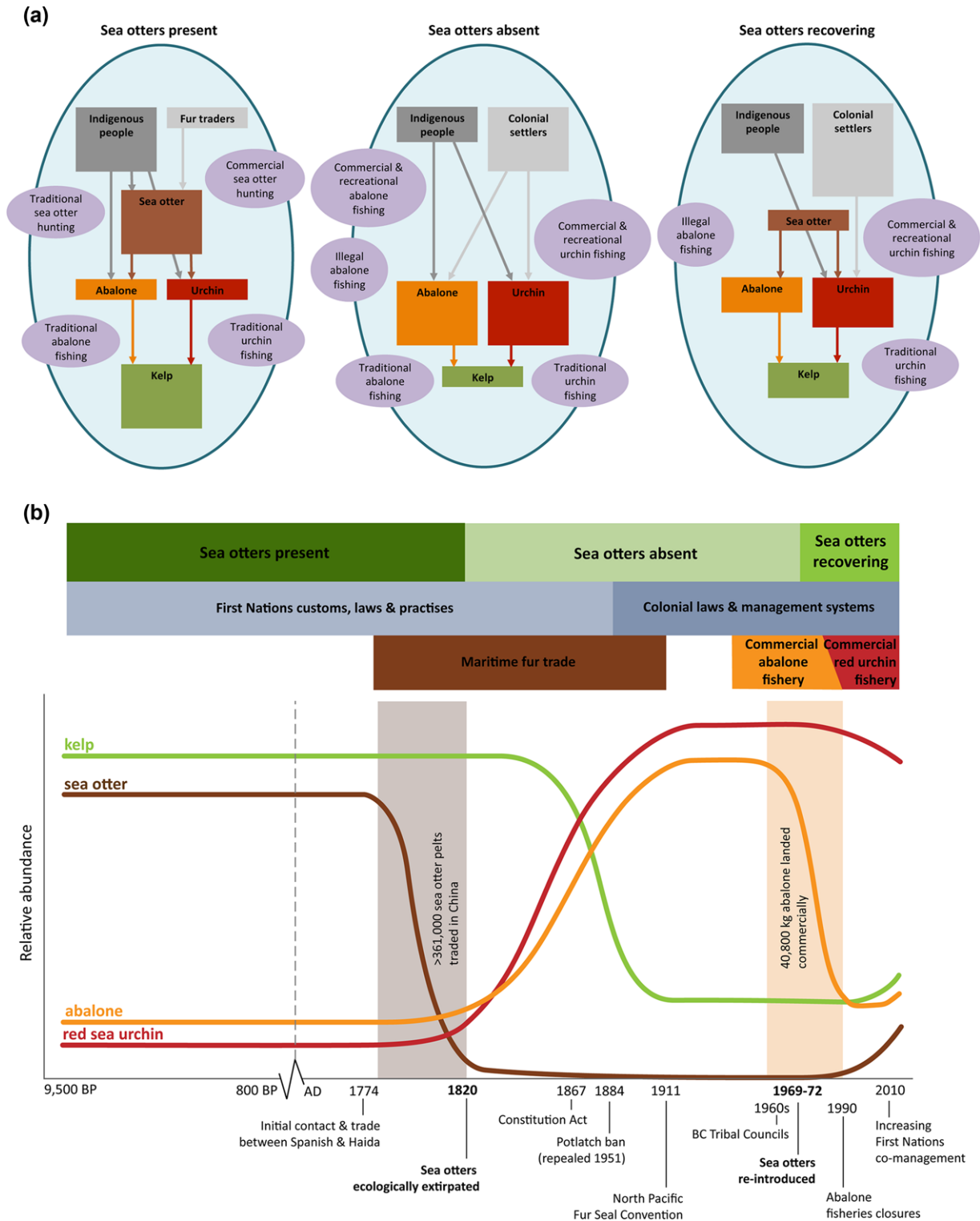


FIGURE 2 (a) Conceptual models showing key components (rectangles) and drivers (ovals) in each of the three British Columbia (BC) abalone social–ecological system (SES) regimes: sea otters present, absent, and recovering. Relative size of key components indicates the directions of change between regimes but not the magnitudes of change, which are much larger than shown. (b) Historical timeline from start of the Holocene to present for the northern abalone SES in BC, highlighting key governance and management systems, events, and resource uses driving system change within the three SES regimes

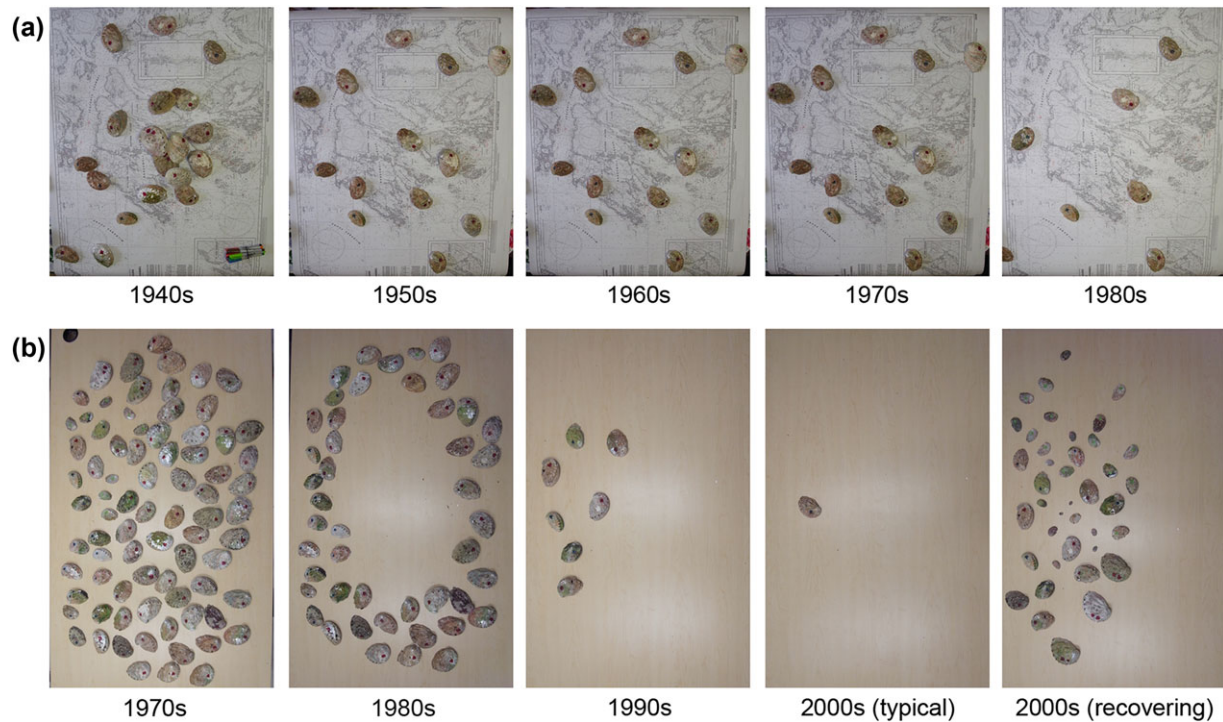


FIGURE 3 Examples of abalone abundance and size reconstructions by decade from Heiltsuk traditional knowledge interviews with: (a) George and Gary Housty from 1940s to 1980s, and (b) Davie Wilson from 1970s to 2000s

TABLE 1 Representative observations of abalone use and ecology by decade from Heiltsuk traditional knowledge interviews

Decade	Representative observations by Heiltsuk abalone experts
1940s	“They were just three, four on top, on top of each other.” (GEH; abalone XL & L size) “... well, these guys are still eating. I went and picked two sacks [of abalone].” (GEH; abalone often picked for meals while out fishing for other seafood)
1950s	“Yah, we just row around the island and pick enough to eat and all these reefs outside here ...” (FCR; picked abalone while working his trapline)
1960s	“... we're usually happy with one [100 lb] sack of it for our winter supply.” (ARR; used to row out to pick abalone in the seine skiff)
Early 1970s	“... my older brother took me out there. He knew the area and he knew there was lots of them out there and we didn't spend much time gathering there so we did other things as well. ... there's seaweed out there, we would grab a little bit of seaweed and do a little bit of jiggling ... but in a short period of time we had a couple of sacks [of abalone] each.” (MKR)
Late 1970s	“This [XL] was the size and it didn't take me very long to, at that particular trip, double back and just pluck them off of the kelp.” In the late 1980s, “I think around three different rocks now to get the same volume or ... the amount of abalone from 1975 ... in that same area.” (MKR)
Early 1980s	“... you have to pick ... start picking before you got off your boat ... the whole rock was just right plugged.” (DNW)
Late 1980s	“You know, you'd have to spend a lot of time walking the rocks the same areas where we used to just go to our little spots and you know you're going to get a bucket there to dump into your sack. If you go out to the same areas now, you're going to have to pick kelp up, leaves, and you're hoping to find one. I think it was probably late eighties when I started to see that change.” (GGH)
1990s	“If I found one, the double red [XL], I'd get a hero's welcome.” (HH)
2000s	“I said, 'look at all these baby ones; it's going to be good for later on.'” (DNW)
2010s	“Not very big. There's lots out there, but they're small.” (Anonymous)

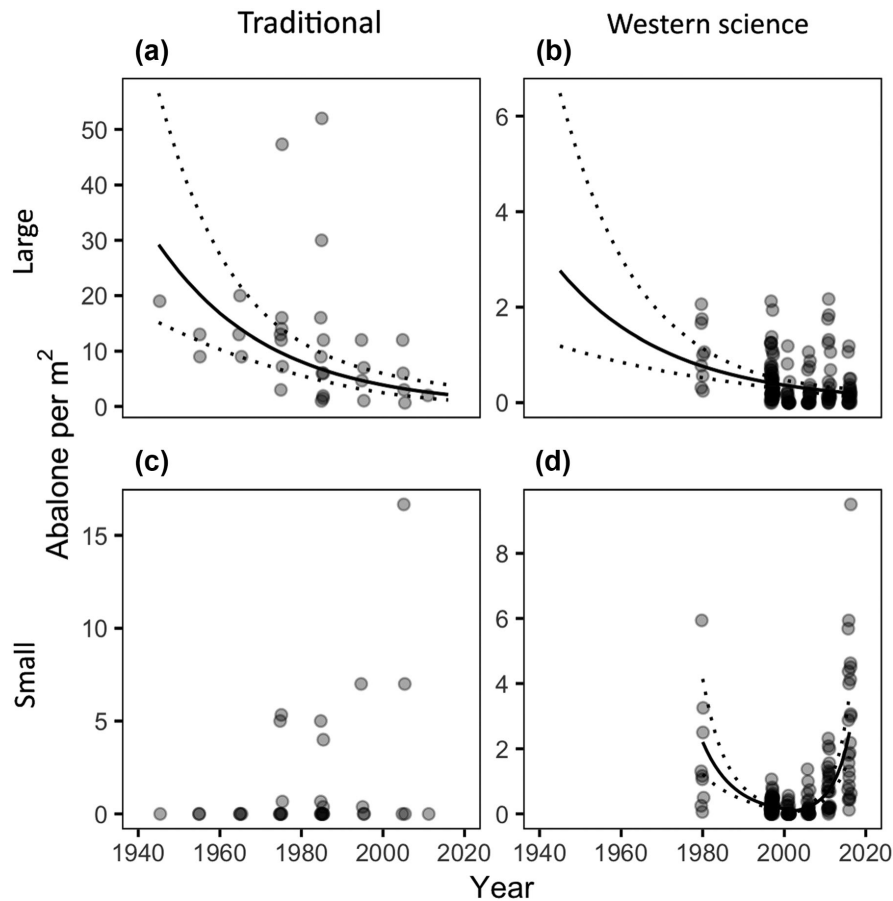


FIGURE 4 Density of large ≥ 70 mm and small < 70 mm abalone: (a, c) by decade from Heiltsuk traditional knowledge interviews, and (b, d) by year of federal fisheries agency population index site monitoring surveys. Black lines represent abalone density estimates from the most supported population growth model for: (a, b) large abalone using data from traditional and western science knowledge, and (d) small abalone using data from western science only. Dotted lines indicate 95% credible intervals. Data points are transparent thus darker areas represent overlapping data points

coastal First Nations populations by $>90\%$, disrupting cultural customs, laws, practices, and traditional economies (Supporting Information Tables S1 & S2; Orchard, 2007). Yet despite escalating imposition of colonial economies, religion, policies, and laws, traditional fisheries practices persisted through generations, demonstrating high cultural resilience (Figure 2b; Supporting Information Table S1; Gauvreau, Lepofsky, Rutherford, & Reid, 2017). Over a century of sea otter absence facilitated macroinvertebrate population growth beyond previous abundances, flipping ecosystem conditions to more large herbivores and less kelp (Figure 2b; Supporting Information Tables S1 & S2). Hyper-abundant macroinvertebrates, the ecosystem condition now perceived as normal, fuelled development of modern shellfish fisheries.

The current *sea otters recovering* regime initiated local and regional ecosystem shifts from urchin to kelp-dominated in the 1970s on Vancouver Island's west coast and in 1980s on the central coast (Figure 1b,c). Despite overall declines due to sea otter predation, abalone can persist at relatively high densities under suitable site conditions during initial years of

sea otter occupation (Figure 1c; Lee et al., 2016). Increases in abalone density, albeit small, can also occur decades after otter occupation (Figure 1b; Watson, unpublished data). Factors such as direct and indirect effects of sea otter predation, substrate complexity, and wave exposure interact to create the spatial and temporal patchwork that defines self-sustaining abalone populations that coevolved with sea otters (Lee et al., 2016; Watson, 2000). Today, cultural resurgence is strengthening First Nations traditional food harvest, governance, and assertion of title and rights to their traditional territories.

4.2 | TK and WSK broaden views of abalone trends

Our novel integrated modeling of TK and WSK data allowed us to simultaneously quantify uncertainty in both data sets and provide broader understanding of recent decadal-scale changes (Figure 4a,b). We contribute to growing literature highlighting the utility of traditional and local experiential knowledge in documenting species abundance and trends. For example, local knowledge-based abundance trends for

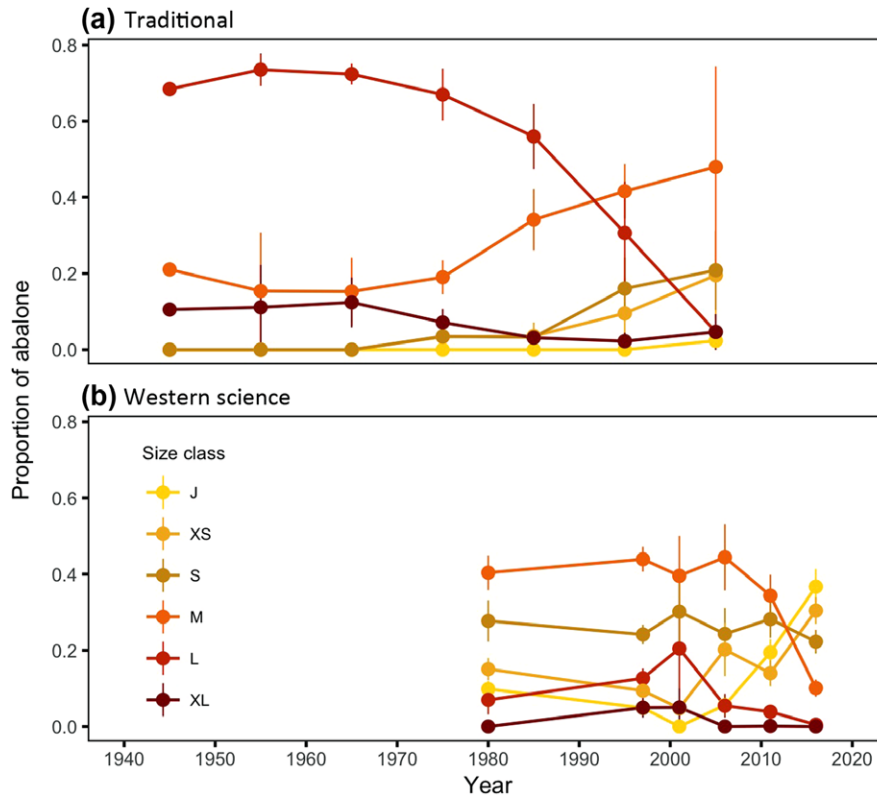


FIGURE 5 Proportion of abalone in each length-class in Heiltsuk territory: (a) by decade from traditional knowledge interviews, and (b) by year from federal fisheries agency population index site monitoring surveys

harbor seal, Pacific herring, and lingcod in Puget Sound corroborated those from western science, supporting similarly derived rockfish abundance trends (Beaudreau & Levin, 2014) and in Mexico, abalone fishers' knowledge correlated well with historical landing records, legitimizing trends from both sources (Saenz-Arroyo & Revollo-Fernandez, 2016).

Similarities and differences in population growth models enabled us to consider the benefits and biases of integrating knowledge sources. Whereas both knowledge sources revealed declining trends in large abalone, density estimates from TK were nearly 10× higher than from WSK. This difference likely reflects ecological context and sampling bias. Without sea otters, abalone densities and size are highest in low intertidal/shallow subtidal areas (Lee et al., 2016) where Heiltsuk harvest abalone. Federal abalone monitoring surveys extended into subtidal habitat (Fisheries and Oceans Canada, 2016) where abalone densities decline with depth (Lee et al., 2016). High spatial variability in abalone density correlated with environmental variables (Lee et al., 2016) and was evident in TK data.

Similarly, differences in abalone size structure between knowledge sources may result from recall bias, social norms, and sampling error. Traditional harvesters likely recalled abundances of larger, targeted abalone more readily than smaller nonharvested sizes, also explaining the paucity of small abalone in earlier decades. Harvesters were taught to

take larger abalone: “We were told, ‘Let it grow up to this size [large] before you take it home.’” (Howard Humchitt, personal communication, Jan 25, 2012). Sampling error may apply to earlier WSK data that focused on larger commercial fishery-sized abalone. Both data sources reflected increasing juvenile abalone recruitment through 2000s, albeit at different magnitudes (Figures 4c,d and 5a,b).

Our results highlight the need to consider qualitative aspects of TK when interpreting quantitative results, particularly where few data points are available, which occurred at the start (few elder experts) and end (few people looking for abalone) of the time series. Whereas the integrated models indicated declining large abalone densities from 1940s to present, Heiltsuk elders remembered stable densities from 1940s to 1960s (Figures 3 and 4a; Supporting Information Figure S2). In other studies, local knowledge holders recalled higher abundances compared to western science, and different abundance estimates based on knowledge holder's age and how knowledge was acquired (Beaudreau & Levin, 2014; Saenz-Arroyo et al., 2005). Future Bayesian analyses could incorporate qualitative observations and estimates of cognitive bias via informative prior distributions.

Further, collaboration between First Nations communities and academia to codesign research projects with outcomes that benefit communities and conservation broadly are increasing (Salomon et al., 2018). Such collegial relationships

will help shift management and decision-making toward true comanagement (Nadasdy, 1999). In this study, acknowledging Heiltsuk research protocols, retaining proprietary TK rights within the community, and co-conducting interviews were key to project success (also see Gauvreau et al., 2017).

4.3 | Reevaluating species conservation status

Knowledge of historical change is essential to set appropriate conservation targets. For many species, past abundances are poorly known. Historically higher abundances and greater range distributions are often not accounted for, resulting in acceptance of lower current abundances. In Mexico, declining trends from historical reconstruction of Gulf grouper fish abundance promoted conservation, whereas increasing trends from modern scientific data prompted consideration of increased catch quotas (Saenz-Arroyo et al., 2005). For East Pacific green turtle populations that collapsed from overfishing, reconstructing three centuries of fisheries data identified the timeframe most likely to represent appropriate conservation targets (Early-Capistran et al., 2018). Finally, knowledge of historically higher black abalone distribution and abundance assisted with restoration site selection (Braje, Rick, Erlandson, Rogers-Bennett, & Catton, 2016).

Understanding baselines shifts is key to assessing species status and trends. Under Canada's *Species At Risk Act* (2002), a species' status is gauged against its abundance and distribution over the past 10 years or three generations, whichever is longer (Mace et al., 2008). The generation time for northern abalone is a decade, therefore current abundances are gauged against a late 1900s baseline when abalone abundance was high rather than the 1700s and 1800s when it was low, leading to an inflated view of abalone extinction risk. Under the current baseline criteria, northern abalones are now considered endangered. Yet mounting evidence from global case studies illustrates how human activities have shifted baselines (Hicks, Crowder, Graham, Kittinger, & Le Cornu, 2016), limiting the value of static and temporally arbitrary baselines to judge conservation status.

Understanding long-term changes in SESs allows us to envision alternative futures. For example, shell middens in areas with sea otters and red abalone in California showed widely variable yet persistent abalone abundances over 8000 years (Braje et al., 2009), suggesting traditional abalone fisheries can be sustained in absence of commercial fisheries. Today, younger generation First Nations are disconnected from abalone: "I took my granddaughter out ... showed her abalone and she said, 'What do you do with these?'" (Davie Wilson, personal communication, Jan 24, 2012). Elders have been deprived of abalone for decades: "I got that much [abalone] and that old lady was so happy. She damn near hugged me to death ..." (Heiltsuk expert, personal commu-

nication, Jan 27, 2012). If northern abalone are not truly at risk of extinction, the conservation value of maintaining traditional abalone fisheries closures should be reevaluated and weighed against the social costs.

This broader understanding of abalone population dynamics suggests that current local-scale abundances may allow for sustainable small-scale traditional abalone fisheries. Reconstructing changes in this and other complex SESs using multiple knowledge sources can build common understanding, share power, and highlight leverage points to foster ecologically sustainable and socially just outcomes.

ACKNOWLEDGMENTS

NSERC, Hakai Institute, SFU graduate scholarship and DFO Species at Risk grants supported LL under SFU Ethics permit 2011s0805. NSERC, Canadian Foundation for Innovation, Hakai Institute and Pew Foundation grants to AKS funded this research. Giaxsixa (thanks) to collaborators Jennifer Carpenter, Harvey Humchitt, and Gary Wilson; co-interviewer *Gitla* (Elroy White); abalone experts Gus Brown, Bill Gladstone Sr., George and Gary Housty, Howard Humchitt, Sonny Hunt, Mike Reid, Tony and Emma Reid, Fred Reid, Davie Wilson, and three others who generously shared their time and knowledge. Experts named and quoted gave their consent. We thank colleagues for thoughtful reviews.

REFERENCES

- Beaudreau, A. H., & Levin, P. S. (2014). Advancing the use of local ecological knowledge for assessing data-poor species in coastal ecosystems. *Ecological Applications*, *24*, 244–256.
- Berkes, F., Colding, J., & Folke, C. (2000). Rediscovery of traditional ecological knowledge as adaptive management. *Ecological Applications*, *10*, 1251–1262.
- Bernard, H. R. (2013). *Social research methods: Qualitative and quantitative approaches* (2nd ed.). Thousand Oaks, CA: Sage.
- Boch, C. A., Micheli, F., AlNajjar, M., Monismith, S. G., Beers, J. M., Bonilla, J. C., ... Woodson, C. B. (2018). Local oceanographic variability influences the performance of juvenile abalone under climate change. *Scientific Reports*, *8*. <https://doi.org/10.1038/s41598-018-23746-z>
- Braje, T. J., Erlandson, J. M., Rick, T. C., Dayton, P. K., & Hatch, M. B. A. (2009). Fishing from past to present: Continuity and resilience of red abalone fisheries on the Channel Islands, California. *Ecological Applications*, *19*, 906–919.
- Braje, T. J., Rick, T. C., Erlandson, J. M., Rogers-Bennett, L., & Catton, C. A. (2016). Historical ecology can inform restoration site selection: The case of black abalone (*Haliotis cracherodii*) along California's Channel Islands. *Aquatic Conservation-Marine and Freshwater Ecosystems*, *26*, 470–481.
- Braje, T. J., Rick, T. C., Szpak, P., Newsome, S. D., McCain, J. M., Smith, E. A. E., ... Hamilton, S. L. (2017). Historical ecology and the conservation of large, hermaphroditic fishes in Pacific Coast kelp forest ecosystems. *Science Advances*, *3*, e1601759.

- Burnham, K. P., & Anderson, D. R. (2002). *Model selection and multimodel inference: A practical information-theoretic approach*. New York, NY: Springer-Verlag.
- Carpenter, B., Gelman, A., Hoffman, M. D., Lee, D., Goodrich, B., Betancourt, M., ... Riddell, A. (2017). STAN: A probabilistic programming language. *Journal of Statistical Software*, 76(1). <https://doi.org/10.18637/jss.v076.i01>
- Corbett, D. G., Clausey, D., Clementz, M., Koch, P. L., Doroff, A., Lefevre, C., & West, D. (2008). Aleut hunters, sea otters, and sea cows: Three thousand years of interactions in the western Aleutian Islands, Alaska. In T. C. Rick & J. M. Erlandson (Eds.), *Human impacts on ancient marine ecosystems: A global perspective* (pp. 43–75). Berkeley and Los Angeles, CA: University of California Press.
- Early-Capistran, M. M., Saenz-Arroyo, A., Cardoso-Mohedano, J. G., Garibay-Melo, G., Peckham, S. H., & Koch, V. (2018). Reconstructing 290 years of a data-poor fishery through ethnographic and archival research: The East Pacific green turtle (*Chelonia mydas*) in Baja California, Mexico. *Fish and Fisheries*, 19, 57–77.
- Estes, J. A., & Palmisano, J. F. (1974). Sea otters: Their role in structuring nearshore communities. *Science*, 185, 1058–1060.
- Fisheries and Oceans Canada. (2012). *Action plan for the Northern Abalone (Haliotis kamtschatkana) in Canada (Species at Risk Act Action Plan Series)*. Ottawa, Canada: Author.
- Fisheries and Oceans Canada. (2016). *Review of dive survey methods for Northern Abalone in British Columbia* (Canadian Science Advisory Secretariat Science Response 2016/044). Nanaimo, Canada: Author.
- Gauvreau, A. M., Lepofsky, D., Rutherford, M., & Reid, M. (2017). “Everything revolves around the herring”: The Heiltsuk-herring relationship through time. *Ecology and Society*, 22, 10.
- Hicks, C. C., Crowder, L. B., Graham, N. A. J., Kittinger, J. N., & Le Cornu, E. (2016). Social drivers forewarn of marine regime shifts. *Frontiers in Ecology and the Environment*, 14, 253–261.
- Jick, T. D. (1979). Mixing qualitative and quantitative methods—Triangulation in action. *Administrative Science Quarterly*, 24, 602–611.
- Kery, M., & Schaub, M. (2011). *Bayesian population analysis using WinBUGS: A hierarchical perspective*. London, England: Academic Press.
- Lee, L. C., Watson, J. C., Trebilco, R., & Salomon, A. K. (2016). Indirect effects and prey behavior mediate interactions between an endangered prey and recovering predator. *Ecosphere*, 7, e01604.
- Mace, G. M., Collar, N. J., Gaston, K. J., Hilton-Taylor, C., Akçakaya, H. R., Leader-Williams, N., ... Stuart, S. N. (2008). Quantification of extinction risk: IUCN's system for classifying threatened species. *Conservation Biology*, 22, 1424–1442.
- McKechnie, I., Lepofsky, D., Moss, M. L., Butler, V. L., Orchard, T. J., Coupland, G., ... Lertzman, K. (2014). Archaeological data provide alternative hypotheses on Pacific herring (*Clupea pallasii*) distribution, abundance, and variability. *Proceedings of the National Academy of Sciences of the United States of America*, 111, E807–E816.
- Menzies, C. R. (2010). Dm sibilhaa'nm da laxyuubm Gitxaala: Picking abalone in Gitxaala territory. *Human Organization*, 69, 213–220.
- Menzies, C. R. (2015). Revisiting “Dm sibilhaa'nm da laxyuubm Gitxaala (Picking abalone in Gitxaala territory)”: Vindication, appropriation, and archaeology. *BC Studies*, 187, 129–153.
- Micheli, F., Saenz-Arroyo, A., Greenley, A., Vazquez, L., Montes, J. A. E., Rossetto, M., & De Leo, G. A. (2012). Evidence that marine reserves enhance resilience to climatic impacts. *Plos One*, 7, e40832.
- Muir, C., & Thorley, J. (2018). *smbr: Analyses using STAN*. Retrieved from <https://doi.org/10.5281/zenodo.1162382>
- Nadasdy, P. (1999). The politics of TEK: Power and the “integration” of knowledge. *Arctic Anthropology*, 36, 1–18.
- Nichol, L. M., Watson, J. C., Abernethy, R., Rechsteiner, E., & Towers, J. (2015). *Trends in the abundance and distribution of sea otters (Enhydra lutris) in British Columbia updated with 2013 survey results* (Canadian Science Advisory Secretariat Science Advisory Report 2015/043). Nanaimo, Canada: Fisheries and Oceans Canada.
- Orchard, T. J. (2007). *Otters and urchins: Continuity and change in Haida economy during the Late Holocene and maritime fur trade periods* (Doctoral dissertation). Department of Anthropology, University of Toronto, Toronto, Canada.
- Pauly, D. (1995). Anecdotes and the shifting baseline syndrome of fisheries. *Trends in ecology & evolution*, 10, 430.
- R Core Team. (2015). *R: A language and environment for statistical computing*. Vienna, Austria: R Foundation for Statistical Computing.
- Rogers-Bennett, L., Dondanville, R. F., Moore, J. D., & Vilchis, L. I. (2010). Response of red abalone reproduction to warm water, starvation, and disease stressors: Implications of ocean warming. *Journal of Shellfish Research*, 29, 599–611.
- Saenz-Arroyo, A., & Revollo-Fernandez, D. (2016). Local ecological knowledge concurs with fishing statistics: An example from the abalone fishery in Baja California, Mexico. *Marine Policy*, 71, 217–221.
- Saenz-Arroyo, A., & Roberts, C. M. (2008). Consilience in fisheries science. *Fish and Fisheries*, 9, 316–327.
- Saenz-Arroyo, A., Roberts, C. M., Torre, J., & Carino-Olvera, M. (2005). Using fishers’ anecdotes, naturalists’ observations and grey literature to reassess marine species at risk: The case of the Gulf grouper in the Gulf of California, Mexico. *Fish and Fisheries*, 6, 121–133.
- Saenz-Arroyo, A., Roberts, C. M., Torre, J., Carino-Olvera, M., & Hawkins, J. P. (2006). The value of evidence about past abundance: Marine fauna of the Gulf of California through the eyes of 16th to 19th century travellers. *Fish and Fisheries*, 7, 128–146.
- Salomon, A. K., Lertzman, K., Brown, K., Wilson, K. B., Secord, D., & McKechnie, I. (2018). Democratizing conservation science and practice. *Ecology and Society*, 23, 44.
- Salomon, A. K., Tanape, N. M., & Huntington, H. P. (2007). Serial depletion of marine invertebrates leads to the decline of a strongly interacting grazer. *Ecological Applications*, 17, 1752–1770.
- Sea Otter Recovery Team. (2007). *Recovery strategy for the sea otter (Enhydra lutris) in Canada (Species at Risk Act Recovery Strategy Series)*. Vancouver, Canada: Fisheries and Oceans Canada.
- Sloan, N. A. (2004). Northern abalone: Using an invertebrate to focus marine conservation ideas and values. *Coastal Management*, 32, 129–143.

- Sloan, N. A., & Dick, L. (2012). *Sea otters of Haida Gwaii: Icons in human–ocean relations*. Skidegate, Canada: Gwaii Haanas Archipelago Management Board & Haida Gwaii Museum.
- Tengo, M., Brondizio, E. S., Elmqvist, T., Malmer, P., & Spierenburg, M. (2014). Connecting diverse knowledge systems for enhanced ecosystem governance: The multiple evidence base approach. *Ambio*, *43*, 579–591.
- Thurstan, R. H., McClenachan, L., Crowder, L. B., Drew, J. A., Kittinger, J. N., Levin, P. S., ... Pandolfi, J. M. (2015). Filling historical data gaps to foster solutions in marine conservation. *Ocean & Coastal Management*, *115*, 31–40.
- Watanabe, S. (2010). Asymptotic equivalence of Bayes cross validation and widely applicable information criterion in singular learning theory. *Journal of Machine Learning Research*, *11*, 3571–3594.
- Watson, J. C. (2000). The effects of sea otters (*Enhydra lutris*) on abalone (*Haliotis* spp.) populations. *Canadian Special Publication of Fisheries and Aquatic Sciences*, *130*, 123–132.
- Watson, J. C., & Estes, J. A. (2011). Stability, resilience, and phase shifts in rocky subtidal communities along the west coast of Vancouver Island, Canada. *Ecological Monographs*, *81*, 215–239.
- Zhang, Z., Campbell, A., & Lessard, J. (2007). Modeling northern abalone, *Haliotis kamtschatkana*, population stock and recruitment in British Columbia. *Journal of Shellfish Research*, *26*, 1099–1107.

SUPPORTING INFORMATION

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

How to cite this article: Lee LC, Thorley J, Watson J, Reid M, Salomon AK. Diverse knowledge systems reveal social–ecological dynamics that inform species conservation status. *Conservation Letters*. 2018;e12613. <https://doi.org/10.1111/conl.12613>