



Declining size and age of rockfishes (*Sebastes* spp.) inherent to Indigenous cultures of Pacific Canada



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ARTICLE INFO

Article history:

Received 30 January 2017

Received in revised form

18 April 2017

Accepted 29 April 2017

Keywords:

Age decline

British Columbia

Indigenous people

Quillback Rockfish

Sebastes

Size decline

Yelloweye Rockfish

ABSTRACT

Yelloweye Rockfish (*Sebastes ruberrimus*) and Quillback Rockfish (*S. maliger*) are important foods in the traditional diets of Indigenous people in coastal British Columbia (BC), Canada. These species are vulnerable to overexploitation because fecundity increases with maternal size or age, yet large-scale fisheries truncate size and age structures. In BC's Central Coast, Indigenous fishers have observed declines in the size and abundance of rockfishes, particularly since the commercial over-exploitation that occurred in the late 1970s and 1980s. To address this conservation concern, we analyzed fishery-independent data collected annually since 2003 by the International Pacific Halibut Commission (IPHC) and the Pacific Halibut Management Association (PHMA). These surveys are coast-wide, yet we focused on data for BC's Central Coast and vicinity. Linear mixed models tested for temporal trends in size and age while controlling for environmental variables. IPHC and PHMA surveys differed in field methodology and were analyzed separately. For Yelloweye Rockfish, fork length declined at average rates of -3.53 mm yr^{-1} (IPHC: 2003–2015) or -4.26 mm yr^{-1} (PHMA: 2006–2015), and age declined at average rates of $-0.73 \text{ yrs yr}^{-1}$ (IPHC: 2003–2012) or $-0.86 \text{ yrs yr}^{-1}$ (PHMA: 2006–2012). The fork length of Quillback Rockfish declined at an average rate of -4.57 mm yr^{-1} (PHMA: 2006–2015). Although rockfish management in BC has become more conservative since the early 2000s, the abundances of Yelloweye and Quillback Rockfish remain at historical low levels. Our results, along with the body of work that precedes them, suggest that loss of reproductive potential associated with size and age truncation could be hampering recovery. Current management criteria, however, are biomass-based and might fail to address this problem. Incorporating old age and large size structures into management objectives could enhance rockfish recovery and help maintain the cultural integrity of Indigenous people who rely on these species.

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1. Introduction

Indigenous people (or First Nations) of British Columbia (BC), Canada, have been harvesting rockfishes (*Sebastes* spp.) for thousands of years (McKechnie, 2007; McKechnie and Moss, 2016). To this day, Yelloweye Rockfish (*S. ruberrimus*) and Quillback Rockfish (*S. maliger*) remain highly prized in traditional diets and provide food security year-round. Prior to colonization, coastal First Nations had large population densities and sophisticated fishing technologies, yet enacted stewardship laws that prevented resource

depletion (Lepofsky and Caldwell, 2013; Trosper, 2003). These laws continue to guide Indigenous conservation practices into the present (e.g. Frid et al., 2016a).

Recognizing the integral role of local resources in First Nation culture, community, and identity, Canada's constitution and federal fishery policies grant Indigenous fisheries for food, social and ceremonial (FSC) purposes priority access to marine resources (DFO, 2007). Fulfilling this legal obligation, however, can be difficult due to competing pressures from commercial and recreational fishers (Frid et al., 2016a, 2016b).

In BC's Central Coast, traditional knowledge holders and fishers from the Heiltsuk, Kitasoo/Xai'xais, Nuxalk, and Wuikinuxv First Nations have observed declines in the size and abundance of Yelloweye and Quillback Rockfish (Frid et al., 2016b), particularly since the 1980s (Eckert et al., 2017). These observations coincide with the

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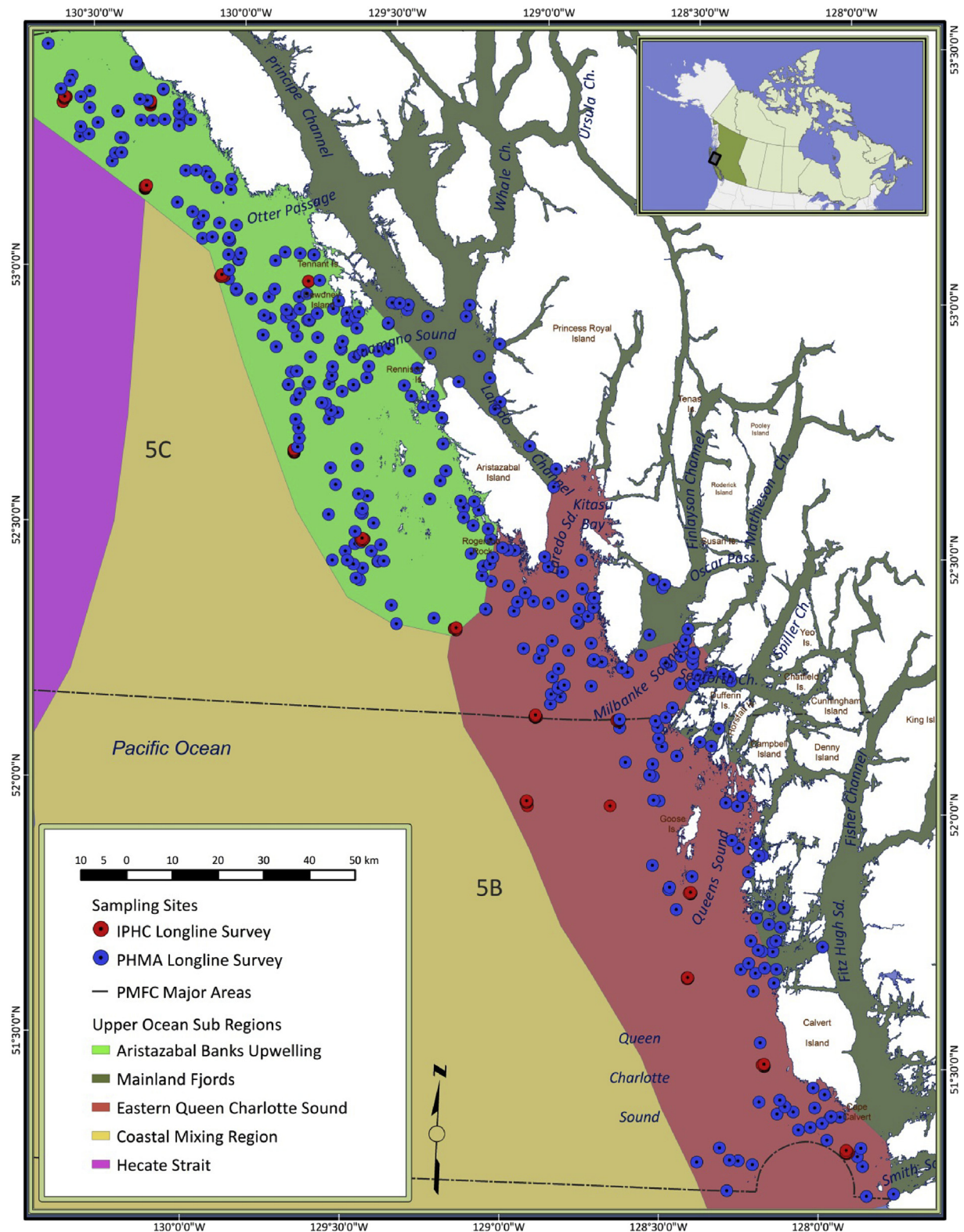


Fig. 1. Study area map, including sampling locations by survey type; ocean subregions, and Pacific Marine Fisheries Commission major areas.

rapid rise of commercial rockfish fisheries that began in the late 1970s and peaked in the early 1990s. Since the early 2000s, federal management of rockfishes has become more conservative, reducing the total allowable catch, establishing spatial fishery closures, and implementing bycatch quotas (Yamanaka and Logan,

2010). These are all notable improvements. Yelloweye and Quillback Rockfish, however, have maximum known lifespans of 121 and 95 years, respectively (DFO, 2012, 2015). Their longevity is associated with slow life history characteristics, implying that both species may require decades to recover from overexploitation

(Berkeley et al., 2004). Notably, for the “outside” fishery management unit of BC (i.e. marine waters to the west and north of Vancouver Island), the most recent median biomass estimates for Yelloweye and Quillback Rockfish are only 18% and 37.7%, respectively, of the corresponding values for 1918 (DFO, 2012, 2015). Accordingly, the Committee on the Status of Endangered Wildlife in Canada assessed Quillback Rockfish as “threatened” in 2008 and Yelloweye Rockfish as a species of “special concern” in 2009 (COSEWIC, 2008, 2009).

Rockfishes in general reach reproductive maturity relatively late in life and their annual fecundity increases with age or size (Berkeley et al., 2004; Hixon et al., 2014). Many species, including Yelloweye and Quillback Rockfish, range from southern California or northern Baja California to western Alaska, and the timing of their life-history events vary with latitude (Love et al., 2002). For Yelloweye Rockfish in the “outside” management unit of BC, recent estimates of age at 50% maturity are 15.2 years for females and 17.5 years for males (DFO, 2015), and the mean age of reproductive females is 32.5 years (COSEWIC, 2008). For Quillback Rockfish in the same area, the most recent estimates are 11 years for age at 50% maturity and 22.8 years for the mean age of reproductive females (COSEWIC, 2009). Fecundity varies exponentially with total length, yet the slope of this relationship varies with species (Dick et al., 2017). In the case of Quillback Rockfish, a 50-cm female is nearly seven times more fecund (765,649 eggs/yr) than a 30-cm female (115,543 eggs/yr) (Model 3a of Dick et al., 2017). We are unaware of published estimates of the length-fecundity relationship for Yelloweye Rockfish, yet females of this species produce between 1.2 and 2.7 million eggs annually (Love et al., 2002).

Rockfishes give birth to live larvae. In BC, larval releases occur March to June for Quillback Rockfish and April to September for Yelloweye Rockfish (Love et al., 2002). For rockfishes in general, older females give birth earlier in the year than younger females (Berkeley et al., 2004; Hixon et al., 2014). (Maternal effects on parturition date, however, have yet to be studied in Quillback and Yelloweye Rockfish.) Maintaining older females in the population, therefore, extends the parturition season, which increases the probability that some individuals will reproduce when environmental conditions favour larval development (Berkeley et al., 2004; Hixon et al., 2014).

Clearly, maintaining old age and large size structures is important for the population productivity of rockfishes (Berkeley et al., 2004; Dick et al., 2017; Hixon et al., 2014). Large scale exploitation, however, may lead to “longevity overfishing”: a situation in which a population loses much of its reproductive potential due to the disproportionate removal of older females (Beamish et al., 2006).

Despite a growing awareness of longevity overfishing by fishery scientists, rockfish in BC are managed based on biomass thresholds (e.g. DFO, 2012, 2015). This approach does not explicitly recognize age and size structures as proxies for reproductive output (Beamish et al., 2006; Dick et al., 2017; O’Farrell and Botsford, 2006) and has been linked to the decline or poor recovery of many species (Hixon et al., 2014; Berkeley et al., 2004).

Fishery independent data are important for detecting shifts in the characteristics of fish stocks. Accordingly, Fisheries and Oceans Canada (DFO) has been collaborating with the International Pacific Halibut Commission (IPHC) since 2003 and the Pacific Halibut Management Association (PHMA) since 2006 to conduct fishery-independent, longline surveys of groundfish in BC. Because these time series do not extend to earlier decades, they cannot capture population changes triggered by the overexploitation that occurred during the late 20th century (see Yamanaka and Logan, 2010). However, they do provide an opportunity to estimate recent changes in the size and age of rockfish.

Accordingly, we analyzed IPHC and PHMA data sets for Yelloweye and Quillback Rockfish in BC’s Central Coast and vicinity (Fig. 1). We tested for temporal trends in age and size while controlling for environmental variables. Through these analyses, we highlight conservation concerns raised by First Nations of BC’s Central Coast, whose cultural integrity and food security is affected by the decline of rockfish species inherent to traditional diets.

2. Methods

DFO provided us with fishery independent data for the sizes and ages of Quillback and Yelloweye Rockfish collected during longline surveys by the IPHC (2003–2015) and the PHMA (2006–2015). These data lacked information on zero catches, and therefore precluded analyses of temporal shifts in relative abundance (i.e. catch-per-unit-effort). Gear, bait and depth distribution, which might affect catchability of different size classes or species, differed between survey types (Table S1; Fig. S1). Also, although both survey types had large spatial overlap, only PHMA surveys covered inside waters (Fig. 1). Therefore, we analyzed each survey type separately. We restricted analyses to Pacific Marine Fisheries Commission major areas 5B and 5C and the following upper ocean subregions (BCMCA, 2011): Aristazabal Banks Upwelling, Eastern Queen Charlotte Sound, and Mainland Fjords (Fig. 1). These areas encompass locations important to Central Coast Indigenous fisheries and adjacent areas to the north used by other First Nations.

We used IPHC and PHMA surveys to analyze temporal trends in the fork length (mm) and age (yrs) of Yelloweye Rockfish. Sample sizes and time series durations were more limited for Quillback Rockfish, allowing only analyses of temporal trends in length from PHMA surveys (Table S2).

We used linear mixed models (LMMs: Zuur et al., 2009) implemented with the ‘lme’ package (Pinheiro and Bates, 2000) in R version 3.2.4, which is widely used in ecological studies to implement linear mixed effects models. For all models, fixed effects consisted of date (number of days since Jan 1, 1970) and depth (m) at which specimens were caught. Date was the principal predictor of interest. Depth has been positively related to age and/or length in other studies (Frid et al., 2016b and references within) and needed to be controlled statistically. Upper ocean subregions were analyzed as random effects to control for broad-scale environmental variability. Visual inspection of quantile-quantile plots, plots of residual versus fitted values, and the correlation matrix were examined to verify model assumptions. Autocorrelation functions of the average residuals from each year were examined to determine that the models were free from temporal autocorrelation. A visual inspection of residuals across space confirmed the lack of spatial autocorrelation.

3. Results

We report results in terms of estimated responses derived from linear mixed models. Variability around these estimates is detailed by 95% confidence intervals in Figs. 2 and 3 and by standard errors for coefficients reported in Table 1.

The fork length of Yelloweye Rockfish declined over time and increased with depth in both data sets (Table 1). In the IPHC data ($N = 1780$) it declined at an average rate of -3.53 mm yr^{-1} , dropping from 589.63 mm in 2003 to 547.25 mm in 2015 at the median depth of sampling (94 m) (Fig. 2a). In the PHMA data ($N = 4179$) it declined at an average rate of -4.26 mm yr^{-1} , dropping from 560.13 mm in 2006 to 521.81 mm in 2015 at median depth (60 m) (Fig. 2b). Within a given year, specimens from the IPHC survey tended to be larger than those from the PHMA survey (Fig. 2a and b).

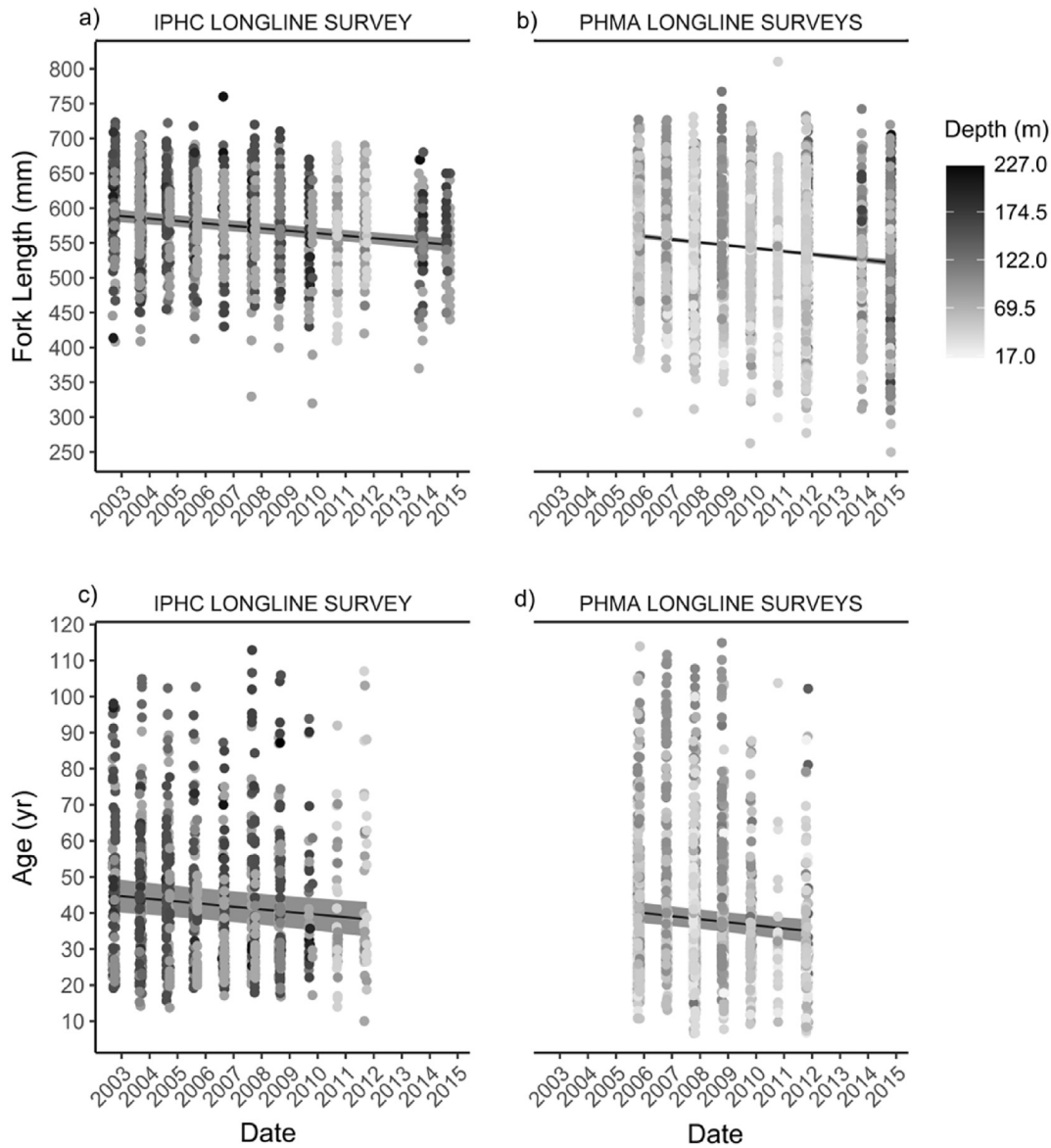


Fig. 2. Trends over time for the fork length and age of Yelloweye Rockfish in the Central Coast of British Columbia and vicinity, by survey type. Lines are responses estimated by the linear mixed models (Table 1) superimposed on raw data. Bands are 95% confidence intervals. Model estimates are fixed for the median depth at which specimens were collected (see text).

The age of Yelloweye Rockfish declined over time in both data sets. Additionally, it increased with depth but did so significantly only in the PHMA data (Table 1), possibly because IPHC surveys tended to be deeper (Fig. S1). In the IPHC data, age of Yelloweye Rockfish declined at an average rate of $-0.73 \text{ yrs yr}^{-1}$, dropping from 44.87 yrs in 2003 to 38.28 yrs in 2012 at the median depth of sampling (122 m) (Fig. 2c). In the PHMA data ($N = 2081$) it declined at an average rate of $-0.86 \text{ yrs yr}^{-1}$, dropping from 40.17 yrs in 2006 to 34.99 yrs in 2012 at median depth (58 m) (Fig. 2d). Within a given year, specimens from the IPHC survey tended to be older than those from the PHMA survey (Fig. 2c and d).

The fork length of Quillback Rockfish in the PHMA data ($N = 5010$) declined over time and increased with depth. It declined at an average rate of -4.57 mm yr^{-1} ; dropping from 393.32 mm in 2006 to 352.18 mm in 2015 at the median depth of sampling (48 m) (Table 1, Fig. 3). (Other data types were insufficient for analysis of this species: Table S2).

4. Discussion

The results corroborate ongoing declines in the lengths of Quillback Rockfish and Yelloweye Rockfish observed by First Nations (Eckert et al., 2017). They also provide evidence for a recent decline in the age of Yelloweye Rockfish which could potentially reflect longevity overfishing (Beamish et al., 2006). Although we lacked the data to analyze age trends for Quillback Rockfish, an age decline associated with the observed length decline would not be unexpected for this species.

Within a given year, Yelloweye Rockfish specimens from the IPHC survey tended to be larger and older than those from the PHMA survey. This was the case possibly because IPHC survey sampled deeper depths (Fig. S1), where larger and older individuals are expected (Frid et al., 2016b and references within), and used larger hooks (see Table S1), which might catch larger specimens. Regardless of which survey type better represents absolute

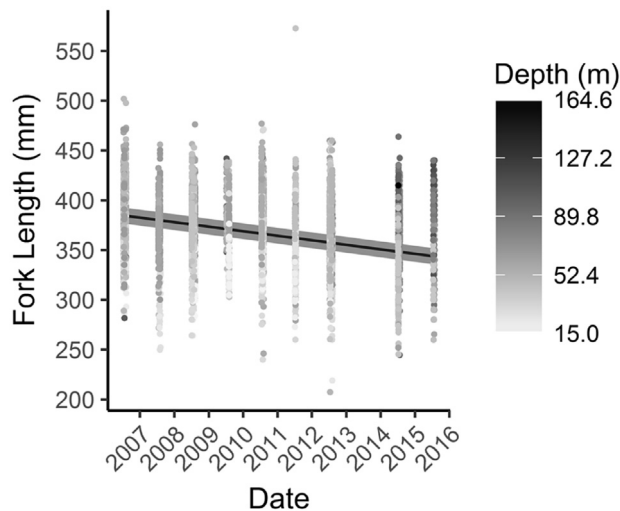


Fig. 3. Trends over time for the fork length of Quillback Rockfish in the Central Coast of British Columbia and vicinity, according to PHMA data. The line is the response estimated by the linear mixed model (Table 1) and is superimposed on raw data. The band is the 95% confidence interval. The estimate is fixed for the median depth at which specimens were collected (48 m).

population changes, both data sets show similar rates of decline.

Length and age truncation of rockfishes is not unique to BC. For example, several rockfish species along the California coast have been declining in size due to fishery pressure (Mason, 1998; Bellquist and Semmens, 2016), which in turn has reduced their population productivity (O'Farrell and Botsford, 2006).

Our analyses inferred temporal trends at the scale of a very large geographic area. However, fishery impacts can vary at small spatial scales. For instance, our earlier work (Frid et al., 2016b) found that the total lengths of Yelloweye and Quillback Rockfish increased with distance from recreational fishery lodges and other ports, suggesting that some fisheries concentrate their footprint at sites that require shorter travel and lower fuel costs. Also, Yelloweye Rockfish were 21% larger inside than outside spatial fishery closures, and environmental factors at small spatial scales were significantly related to the size or age of some rockfish species (Frid et al., 2016b). Other studies have documented similar types of fine-scale spatial variability in rockfish population characteristics (e.g. Starr et al., 2015; Bellquist and Semmens, 2016).

Large-scale fishery exploitation from commercial and recreational sectors is only one plausible explanation for the observed

length and age declines. Environmental change could provide additional, non-mutually exclusive hypotheses. For instance, reduced ocean productivity during strong El Niño years is thought to have increased natural mortality of adult rockfishes (Mason, 1998). Under climate change, the combined effects of ocean warming and lower oxygen concentrations are predicted to reduce metabolic rates, thereby limiting maximum size for marine fish in general (Cheung et al., 2013). Also, year class strength varies with environmental conditions, and strong year classes may increase the proportion of younger and smaller individuals in a population for some years after recruitment (Mason, 1998). The combined effects of fisheries and environmental change are likely to act synergistically. Accordingly, more conservative fishery management is warranted as climate change impacts continue to escalate (Cheung et al., 2013; Planque et al., 2010).

Concerns for reductions in size structure extend beyond single species management. Upper-level predators affect the distribution, foraging rates and abundance of herbivores and mesopredators, thereby influencing species diversity and other ecosystem properties (Madin et al., 2016; Terborgh, 2015). For marine fish and other gape-limited consumers, the strength of predator effects depends on body size. Larger predators can consume larger prey (Beaudreau and Essington, 2007) and also elicit stronger antipredator behaviours, including habitat and diet shifts by prey (Rizzari et al., 2014; Heithaus et al., 2008). Both consumptive and behavioural effects may cascade down to lower trophic levels (Heithaus et al., 2008). Yelloweye Rockfish are generalist predators on rocky reefs. Their maximum known length (L_{\max}) is 91 cm (Love et al., 2002), which is greater than for most other demersal fishes with which they overlap spatially. Further, their trophic level (TL = 4.4) is similar to that of the largest demersal fishes that occupy the same habitats (e.g. *Ophiodon elongatus* L_{\max} = 152 cm and TL = 4.3; *S. borealis* L_{\max} = 120 cm and TL = 4.3). (Froese and Pauly, 2017; Love et al., 2002). Yelloweye Rockfish, therefore have the potential to be ecologically important predators. The size declines documented by our study, however, suggest a weakening of their predator effects and the flattening of trophic pyramids (Strong and Frank, 2010).

Our study has important management implications. Although rockfish management in BC has become more conservative since the early 2000s (Yamanaka and Logan, 2010), the abundances of Yelloweye and Quillback Rockfish remain at historical low levels (DFO, 2012, 2015). Our results, along with the large body of work that precedes them, suggest that loss of reproductive potential associated with size and age truncation could be hampering recovery (Hixon et al., 2014; Dick et al., 2017; Berkeley et al., 2004; Beamish et al., 2006). Current management criteria by Fisheries

Table 1
Linear Mixed Models describing variation in length and age. For all models, depth (m) and date (number of days since Jan 1st, 1990) were the fixed effects and oceanographic subregion (Aristazabal Banks Upwelling Region, Mainland Fjords, and Eastern Queen Charlotte Sound) was the random effect.

Response variable	Data source	Predictor	Coefficient	Std Error	DF	t-value	p-value
Fork length of Yelloweye Rockfish	IPHC	Intercept	686.830	19.194	1776	35.7821	<0.001
		Depth	0.172	0.0349	1776	4.92	<0.001
		Date	−0.0096	0.0012	1776	−7.808	<0.001
	PHMA	Intercept	685.317	16.124	4174	42.504	<0.001
		Depth	0.495	0.035	4174	14.307	<0.001
		Date	−0.012	0.001	4174	−10.213	<0.001
Age of Yelloweye Rockfish	IPHC	Intercept	64.517	9.100	1217	7.0897	<0.001
		Depth	0.020	0.013	1217	1.485	0.1378
		Date	−0.002	0.0006	1217	−3.273	0.0011
	PHMA	Intercept	56.254	9.477	2076	5.936	<0.001
		Depth	0.205	0.0163	2076	12.485	<0.001
		Date	−0.002	0.0007	2076	−3.580	<0.01
Fork length of Quillback Rockfish	PHMA	Intercept	515.104	8.121	5005	63.426	<0.001
		Depth	0.713	0.023	5005	30.469	<0.001
		Date	−0.012	0.0005	5005	−25.041	<0.001

and Oceans Canada (DFO), however, are biomass-based (DFO, 2012, 2015) and might fail to address this problem. Incorporating old age and large size structures into management objectives could enhance rockfish recovery and help maintain the cultural integrity of Indigenous people who rely on these species.

Specifically, recent studies corroborate that “the assumption of proportionality between mature female biomass and total egg production is inappropriate for most *Sebastes* stock assessments” (Dick et al., 2017), and found that the level of stock depletion (i.e., how much biomass has dropped below the “overfished limit”) could be underestimated by as much as 20% if the size-fecundity relationship is strong but not incorporated into assessment models (He et al., 2015). DFO, however, estimates the stock status of BC rockfishes with surplus production models in which total egg production is assumed to be proportional to spawning biomass (DFO, 2012, 2015). If average size or age of spawners declines—as our study documents—then these surplus production models would not account for reductions in population productivity beyond those driven by environmental effects on recruitment. In contrast, a growing number of stock assessments in the United States are age-structured and explicitly model size-dependent fecundity (He et al., 2015). Given that precedent, we argue that size or age dependent fecundity can, and should be, routinely incorporated into rockfish stock assessments (He et al., 2015) in Canada and elsewhere.

We also argue that management objectives for rockfish and other groundfishes should include the restoration and maintenance of the large size and old age structures that preceded large scale exploitation. Meeting this objective—to the extent that changing ocean conditions allow (Cheung et al., 2013)—would enhance fishery sustainability and help maintain ecological interactions between exploited and non-target species (Tolimieri et al., 2013) that potentially affect biodiversity (Heithaus et al., 2008; Madin et al., 2016).

Finally, we emphasize that Central Coast First Nations had observed size declines of culturally-significant rockfishes long before we conducted our analyses (Eckert et al., 2017). Their on-the-water awareness of ecological change derives from historical baselines that span many generations, which highlights the importance of integrating Indigenous and scientific knowledge into the joint management of marine resources (i.e., collaboratively between Indigenous and federal governments). For instance, in our study area hereditary chiefs are responsible for interpreting and implementing Indigenous laws and for the stewardship of specific areas. Their perspective on the state of a stock extends many decades into the past, beyond the short time line of most fishery-independent scientific surveys, and is an important tool for recognizing when conservation requires spatial or temporal fishery closures (Frid et al., 2016a). The responsibility to include Indigenous people in joint fishery management applies anywhere in the world where Indigenous knowledge, rights and traditional stewardship practices remain current (Crook et al., 2016).

Acknowledgements

We are indebted to traditional knowledge holders and stewardship staff from the Heiltsuk, Kitasoo/Xai'xais, Nuxalk, and Wuikinuxv First Nations for their assistance, support, and insight. We thank Lynne Yamanaka (DFO science) for technical advice, Kate Rutherford (DFO science) for access to data, and Julie Beaumont for Fig. 1. Comments from Dan Okamoto and two anonymous reviewers improved the manuscript. The work of the authors is financially supported by the Gordon and Betty Moore Foundation (grant number 1406.03, 2016/17), the Aboriginal Aquatic Resource and Oceans Management Program (grant number ARM2015-MLT-

7006-3, 2016/17), the Marine Planning Partnership (via Tides Canada grant number CCS P098-06143, 2016/17), and the Tula Foundation.

Appendix A. Supplementary data

Supplementary data related to this article can be found at <http://dx.doi.org/10.1016/j.oceco.2017.07.011>.

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