



## Original research article

## Rapid recovery of Dungeness crab within spatial fishery closures declared under indigenous law in British Columbia

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## ABSTRACT

Canada's constitution grants indigenous people priority access to marine resources, yet indigenous, commercial and recreational fishers target the same species. Avoiding conflict between different users, therefore, requires evidence-based policies that manage fisheries for conservation while respecting indigenous rights. From 2006 to 2015, Canada's Conservative government demoted the role of science in resource management, stifling research by federal agencies like Fisheries and Oceans Canada. To address ensuing data gaps, during 2014–2015 the Heiltsuk, Kitasoo/Xai'Xais, Nuxalk, and Wuikinuxv First Nations conducted coordinated research on Dungeness crab (*Cancer magister*), a culturally-significant resource. These indigenous groups are experiencing declining catch rates of Dungeness crab and postulate that commercial and recreational fisheries are primary causes of local declines. Accordingly, they applied indigenous laws and declared spatial fishery closures for commercial and recreational fishers at 10 sites (closed) while allowing exploitation by all users to continue at 10 other sites (open). Sampling occurred repeatedly over time and analyses compared temporal trends in population characteristics between closed and open sites. Results were consistent with the hypothesis that fisheries decrease the abundance and size of exploited species, but spatial protection can reverse these effects. The body size and catch-per-unit effort of legal-sized males increased over time at closed sites but declined at open sites. Importantly, fishery status did not affect temporal changes in the relative abundance of unfished classes of crab – sublegal males and females – which is logically consistent with the hypothesis. Our study demonstrates that indigenous governance can create spatial closures for conservation and research when Canada's government fails to do so. Long-term solutions, however, require collaboration in research and management between federal and indigenous governments. Towards that end, Canada's newly elected Liberal government has begun to restore federal science and to address indigenous rights, thereby enhancing the possibility of such collaboration.

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## 1. Introduction

Canada's constitution grants indigenous people priority access to marine resources, yet indigenous, commercial and recreational fishers target the same species. Avoiding conflict between different users, therefore, requires evidence-based policies that manage fisheries for conservation while respecting indigenous rights to fish for food, social and ceremonial

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purposes (DFO, 2007). Between 2006 and 2015, however, Canada's Conservative Government demoted the role of science in resource management, stifling research by federal agencies like Fisheries and Oceans Canada (DFO), hampering evidence-based policies for fishery management (Hutchings and Post, 2013; Turner, 2013), and effectively leaving indigenous people to collect their own data on conservation issues that affect them.

Dungeness crab (*Cancer magister*), an important traditional food for indigenous people of coastal British Columbia, are a case in point. The species lives from southern California to Alaska, yet is well-studied only in northern and southern parts of its distribution. Oceanographic conditions that affect life-history and ecology vary strongly along this 3900-km-long latitudinal range. Therefore, lessons learned from well-studied populations do not necessarily apply to data poor regions (Rasmuson, 2013), such as British Columbia's Central Coast. In that region, indigenous people are experiencing declining catch rates of Dungeness crab and postulate that commercial and recreational fisheries are causing local declines. Federal research programs have yet to address this issue.

Accordingly, during 2014 and 2015 the four Central Coast First Nations – Heiltsuk, Kitasoo/Xai'Xais, Nuxalk, and Wuikinuxv – conducted coordinated research on Dungeness crab. They applied indigenous laws and declared spatial fishery closures for commercial and recreational fishers at 10 sites (closed) while allowing exploitation by all users to continue at 10 other sites (open). DFO chose to not recognize and legislate these closures. Given that indigenous laws arise from collective, long-term observational knowledge and focus on the principles and stewardship practices that have allowed sustainable use of natural resources over many centuries (Trosper, 2003; Housty et al., 2014), Central Coast First Nations considered DFO's decision a lost opportunity for collaboration between different levels of government. Accordingly, each First Nation engaged in public communications asking for compliance from commercial and recreational fishers, and conducted patrols in which they requested non-compliant fishers to remove their traps from closed sites. Sites were sampled repeatedly over time, and the closures were designed to compare temporal trends in population characteristics between closed and exploited sites (Taggart et al., 2004; Wahle et al., 2008). Indigenous fisheries for food, social and ceremonial purposes (FSC) continued at some closed sites, and therefore results provide insight into the effects of non-indigenous fisheries rather than the effects of complete harvest refugia.

By federal law, fishers can retain only male Dungeness crab with notch-to-notch carapace widths of 154 mm or greater. Accordingly, we tested the predictions that declines over time in the relative abundance and size structure of legal-size males would occur at closed but not at open sites, and that closures would have no effect on the abundance of classes not targeted by fishers: smaller males (width < 154 mm) and females. These predictions derive from the well-supported hypothesis that fisheries decrease the abundance and size of exploited species, but spatial protection can reverse these effects (Pauly et al., 2002; Edgar et al., 2014). Although responses to exploitation and protection are best known in fishes (e.g. Claudet et al., 2010 and Shackell et al., 2010), crab appear to respond similarly (Taggart et al., 2004; Wahle et al., 2008).

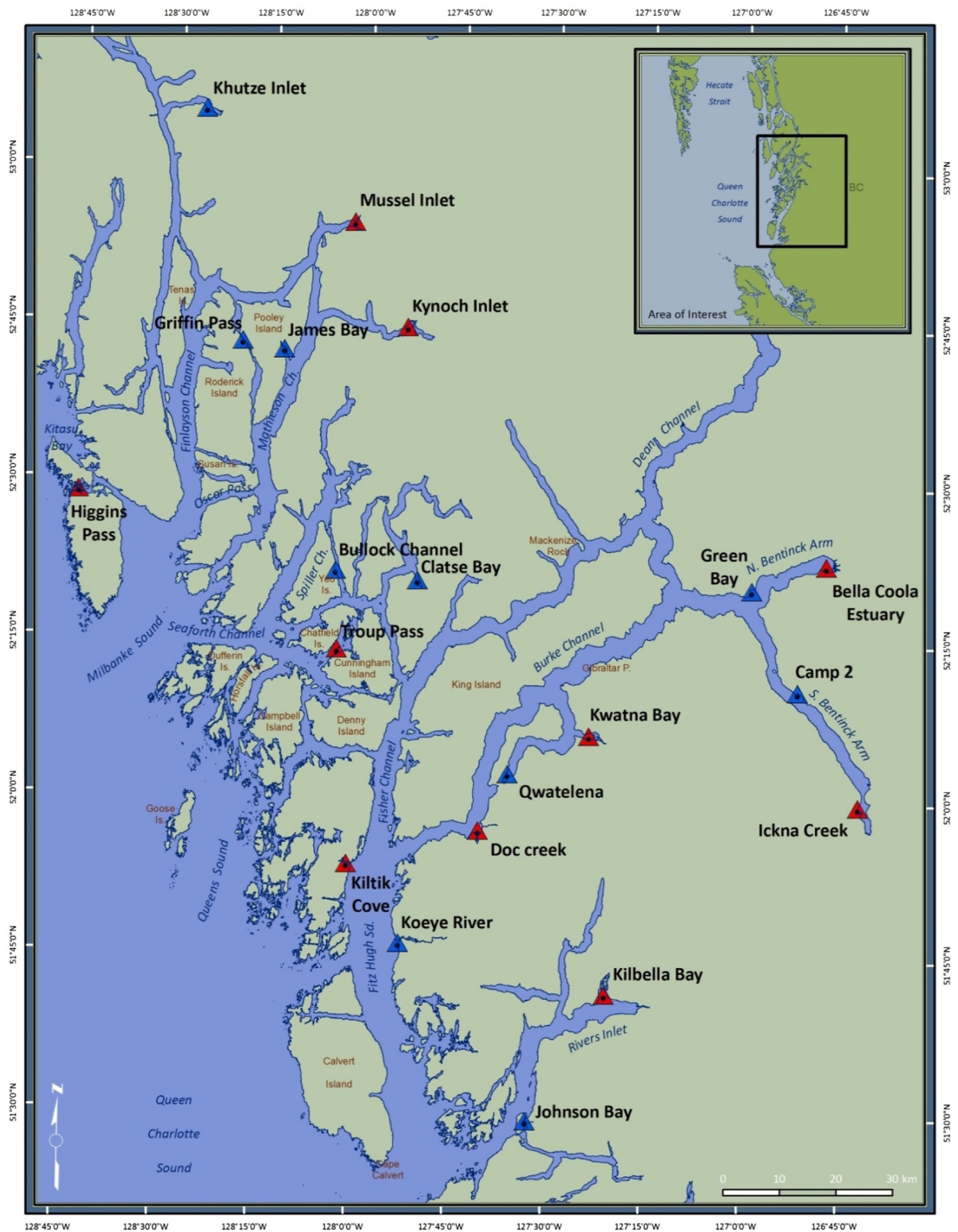
Our results provided evidence that fishery closures declared under indigenous law – effectively social agreements between First Nations and the public without the benefit of federal legislation – could solve a marine conservation problem, albeit temporarily. More importantly, our study is an example of how First Nations can contribute to applied science, thereby setting the stage for long-term conservation via future collaborations between indigenous and federal governments.

## 2. Methods

Starting in the spring of 2014, Dungeness crabs were studied at 20 sites distributed throughout the Central Coast (Fig. 1). Sites were sampled approximately every two months over periods ranging from four to 10 months (Table 1). The exceptions were two sites where sampling occurred daily for three weeks in May 2014 and semi-daily for one week in November of 2014 to accommodate a mark-recapture study reported elsewhere (Frid and Boulanger, 2014).

Three types of fisheries – indigenous FSC, commercial and recreational – occurred at all sites prior to the study. At the onset of research, however, indigenous governments declared fishery closures for commercial and recreational fishers at 10 sites (closed sites) while allowing exploitation by all users to continue at remaining sites (open sites) (Fig. 1; Table 1). Traditional knowledge from each indigenous community was used to select closed and open sites across a similar number of inlet, bay and channel locations, and to ensure that all sites contained good habitat for Dungeness crab. The location of closed sites was determined from community input into marine spatial planning processes (MaPP, 2015), which identified these locations as particularly important to indigenous FSC fisheries.

Sampling methods were based on protocols developed by DFO (Dunham et al., 2011). Traps were stainless steel, inlet-type, circular with 91.4-cm diameter and closed escape ports. Bait was Pacific herring (*Clupea pallasii*) placed inside 500-ml vented jars made of plastic and suspended from the centre of the trap's lid. Bait amount was two large or three smaller herring. For each sampling session, 9–10 traps were deployed per site and stratified along three depth contours: <20 m, 25–50 m, and 51–75 m (i.e., 3–4 traps per contour). Exceptions occurred when sites lacked deep habitats (i.e. all 9–10 traps were set shallow: Table 1) and, occasionally, when fewer than 9 traps were available. Depth and location were recorded for each trap. Minimum trap spacing was 100 m, except in small bays where it was reduced to 50–75 m to fit multiple traps. Soak times averaged approximately 24 h (range 16–26 h), except twice during November 2014 at Johnson Bay in which soak times were 2–3 days. For each individual crab, we recorded sex class, notch-to-notch carapace width and shell hardness and other variables not reported here (Dunham et al., 2011).



**Fig. 1.** Distribution of research sites open (blue) and closed (red) to commercial and recreational fisheries along British Columbia's Central Coast. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

**Table 1**

Fishery status and sampling schedule for research sites. Refer to Fig. 1 for site locations. For brevity, sampling depths are shown as broad categories but depth was collected and analysed as a continuous variable.

First Nation conducting sampling	Site	Fishery status	2014							2015		Depth contour (m)		
			April	May	June	Aug	Sept	Oct	Nov	Jan	Feb	<20	25–50	51–75
Heiltsuk	Bullock Channel	Open		×	×			×		×	×	×	×	×
	Clatse Bay	Open	×		×			×		×	×	×	×	×
	Doc Creek	Closed		×	×							×	×	
	Kiltik Cove	Closed		×	×							×	×	×
	Koeye River	Open		×	×							×	×	×
	Troup Pass	Closed	×		×			×			×	×	×	×
Kitasoo/Xai'Xais	Griffin Pass	Open	×		×		×		×	×		×		
	Higgins Pass	Closed	×		×		×		×	×		×		
	James Bay	Open	×		×		×		×	×		×	×	×
	Khutze Inlet	Open	×		×		×			×		×	×	×
	Kynoch Inlet	Closed	×		×		×		×	×		×	×	×
	Mussel Inlet	Closed	×		×		×		×	×		×	×	×
Nuxalk	Bella Coola Estuary	Closed			×	×		×				×	×	×
	Camp 2	Open			×	×			×			×	×	×
	Green Bay	Open			×	×			×			×	×	×
	Ickna Creek	Closed			×	×		×				×	×	×
	Kwatna Bay	Closed				×		×				×	×	×
	Qwatelena	Open			×	×		×				×	×	×
Wuikinuxv	Kilbella Bay (session 1)	Closed		×	<sup>a</sup>							×	×	×
	Kilbella Bay (session 2)	Closed							×	<sup>c</sup>		×	×	
	Johnson Bay (session 1)	Open		×	<sup>b</sup>							×	×	×
	Johnson Bay (session 2)	Open							×	<sup>d</sup>		×	×	

<sup>a</sup> Sampled daily April 30–May 21, 2014.

<sup>b</sup> Sampled daily April 30–May 17, 2014.

<sup>c</sup> Sampled daily November 9–November 11, 2014.

<sup>d</sup> Sampled November 7 and daily from November 9 to November 12, 2014.

## 2.1. Analysis

Dungeness crabs were divided into three classes: (a) legal males with notch-to-notch carapace width  $\geq 154$  mm (i.e., legal fishery size, or point-to-point width  $\geq 165$  mm: Dunham et al., 2011); (b) sublegal males with notch-to-notch carapace width  $< 154$  mm; and (c) females of all sizes and reproductive stages.

We used Linear Mixed Models (LMM) (Zuur et al., 2009) to examine two types of response variables: (1) catch per unit effort (CPUE), estimated as the number of crabs caught per trap and analysed separately for each crab class, and (2) the size (notch-to-notch carapace width) of legal males. The predictors included in the model were fishery status (open vs. closed sites), date, depth, and two-way interactions between fishery status and date and between depth and date. The interaction between fishery status and date tested our prediction that declines over time in the CPUE and size of legal males would occur at open but not closed sites. The depth by date interaction tested for seasonal effects of depth (Stone and O'Clair, 2002). Depth of each trap and date were treated as continuous variables, with depth being analysed as the average of 3–4 traps within a given contour and sampling session. To account for spatial autocorrelation in the model describing legal male size (which included multiple size measurements per trap deployment), individual traps were treated as sublocations nested within sites in the random component of model. Specifically, the model describing legal male size had the form:

$$y_{ijm} = \beta_0 + \sum_{k=1}^K \beta_k x_{ijkm} + b_i + b_{ij} + \varepsilon_{ijm}$$

where  $y_{ijm}$  is the  $m$ th observation at site  $i$  and sublocation  $j$ ,  $x_{ijkm}$  is the  $m$ th value of the  $k$ th independent variable at site  $i$  and sublocation  $j$ .  $\beta_k$  is the coefficient for the  $k$ th fixed effect,  $K$  is the total number of fixed effects in the model,  $b_i \sim N(0, \sigma_1^2)$  is the random effect of site  $i$ ,  $b_{ij} \sim N(0, \sigma_2^2)$  is the random effect of sublocation  $j$  within location  $i$ , and  $\varepsilon_{ijk} \sim N(0, \sigma^2)$  is the error term (Pinheiro and Bates, 2000). CPUE models had the same form except that the response variable was transformed as  $\log(y_{im} + 1)$  and, given that each trap yielded a single CPUE value, a term for sublocation  $j$  was not required.

Visual inspection of standard model validation graphs were used to verify model assumptions: residuals versus fitted values were used to verify homogeneity; a histogram or Quantile–Quantile (q–q) plot of the residuals for normality; and residuals versus each explanatory variable to check independence. Predictor variables lacking explanatory power were eliminated via AIC model selection (Burnham and Anderson, 2002). Optimal model structures were obtained first for random effects and next for fixed effects. During model selection of random effects, we considered models with random intercept, random slope and no random effect. During model selection of fixed effects, the simplest model considered excluded all interactions but included the independent effects all three predictors (date, depth, fishery status). When competing

**Table 2**

Best linear mixed models describing variation in the CPUE of different classes of crab and in the body size (notch-to-notch-width) of legal males. In addition to fixed effects described below, CPUE models included a random intercept term for site. The legal male size model included a random intercept term for sublocation (i.e. trap) nested within site. Terms including fishery status represent values at open sites relative to closed sites.

Response variable	Predictor	Coefficient	Std error	DF	t-value	p-value
Legal male log(CPUE + 1)	Intercept	−15.063	7.066	1003	−2.13	0.033
	Fishery status	18.62	9.43	18	1.98	0.064
	Date	0.0010	0.00043	1003	2.30	0.022
	Depth	−0.0071	0.0012	1003	−5.87	<0.0001
	Fishery status × date	−0.0012	0.00058	1003	−2.032	0.046
Legal male body size	Intercept	−96.95	77.16	2337	−1.26	0.21
	Fishery status	404.97	83.14	17	4.87	0.0001
	Date	0.016	0.0047	2337	3.47	0.0005
	Depth	3.99	1.89	2337	2.11	0.035
	Fishery status × date	−0.025	0.0051	2337	−4.93	<0.0001
	Depth × date	−0.0002	0.00012	2337	−2.082	0.038
Female log(CPUE + 1)	Intercept	20.00	5.10	1003	3.92	0.0001
	Fishery status	−0.31	0.17	18	−1.83	0.084
	Date	−0.00070	0.00020	1003	−3.45	0.0006
	Depth	−0.0011	0.00031	1003	−3.77	0.0002
	Depth × date	0.000018	0.000009	1003	2.015	0.044
Sublegal male log(CPUE + 1)	Intercept	−34.055	3.86	1003	−8.83	<0.0001
	Fishery status	−0.079	0.21	18	−0.37	0.70
	Depth	−0.0061	0.00099	1003	−6.16	<0.0001
	Date	0.0021	0.00024	1003	9.061	<0.0001

models were not deemed to be different (i.e.  $\Delta AIC < 2$ ), the most parsimonious model was selected (i.e., the one without interactions and/or fewer terms). In all cases, the best model included a random intercept in which variation around that intercept depended on site. For visual displays of estimated responses, confidence intervals (95%) were derived from standard errors around the model's predictions (i.e. from the variance–covariance matrix of the model's predictions), rather than around individual parameters (Pinheiro and Bates, 2000). For CPUE of sublegal males, analyses were conducted with and without a valid but extreme value (52 sublegal males in one trap at Mussel Inlet on 14 January, 2015), which yielded similar estimates. The outlier is excluded from results presented in the main text (Table 2) but included in Table S1 (see Electronic Supplementary Material). Statistical analyses were performed using package 'nlme' (Pinheiro et al., 2014) in R version 3.1.0 (R Core Team, 2014) for Mac OS X. For all tests, significance was determined at  $p < 0.05$ .

### 3. Results

The CPUE of legal males declined slightly over time at sites open to commercial and recreational fisheries while it increased at closed sites (Fig. 2; Table 2; Table S2 in Electronic Supplementary Material). The linear mixed model estimated that, at the onset of fieldwork in late April, 2014, average CPUE differed little between closed and open sites (respectively: 1.6 vs. 1.3 legal males/trap at 15 m depth), whereas by the end of sampling in late February, 2015, closed sites averaged one more legal male per trap than open sites (respectively: 2.5 vs. 1.2 legal males/trap at 15 m depth) (Fig. 2).

Similarly, the body size of legal males declined over time at open sites but increased at closed sites (Fig. 3; Table 2, Table S2). Specifically, the linear mixed model estimated that, in late April, 2014, average notch-to-notch width was similar at closed and open sites (respectively: 170.1 mm vs. 168.0 mm at a depth of 15 m) whereas by late February, 2015, legal males were, on average, 1.3 cm larger at closed than at open sites (respectively: 174.1 mm vs. 163.8 mm at 15 m depth) (Fig. 3).

In contrast, fishery status had no effect on whether the CPUE of sublegal males and females changed over time (Table 2, Table S2). At both open and closed sites, CPUE increased over time for sublegal males (Fig. 2) but decreased very slightly (effectively changed little) for females (Table 2).

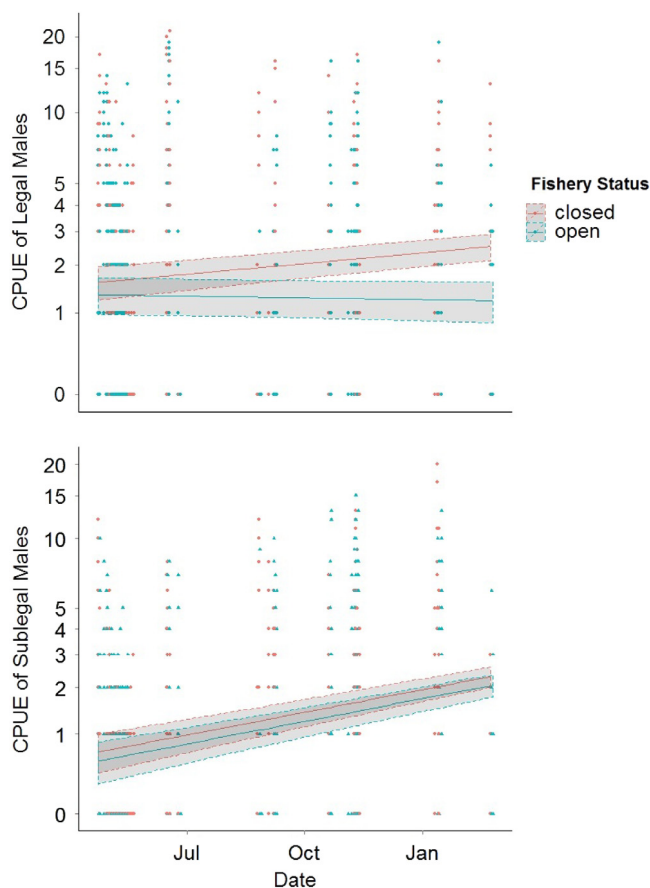
For all classes of crabs, CPUE declined with depth (Fig. 4; Table 2, Table S2). The average size of legal males, however, increased with depth during spring, summer and fall (early and mid sampling periods), but was independent of depth during winter (late sampling period) (Fig. 5; Table 2; Table S2).

### 4. Discussion

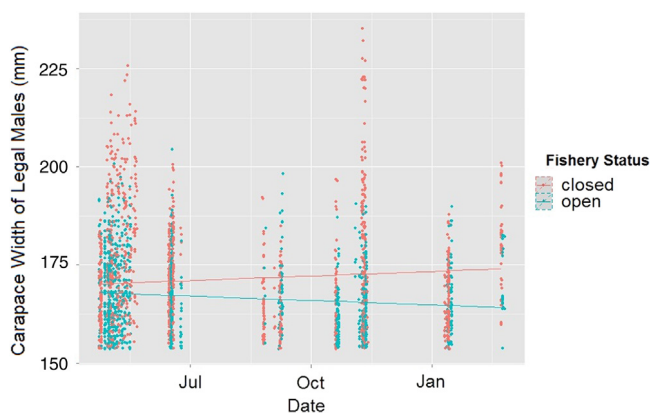
Our results are consistent with the hypothesis that fisheries decrease the abundance and size of exploited species, but spatial protection can reverse these effects (Pauly et al., 2002; Edgar et al., 2014). The body size and relative abundance (CPUE) of legal males increased over time at sites closed to commercial and recreational fisheries, but declined at sites open to all fisheries. Importantly, fishery status did not affect temporal changes in the relative abundance of unfished classes – sublegal males and females – which is logically consistent with the hypothesis.

What mechanisms might have contributed to the abundance and body size of legal males increasing at closed but not at open sites? One possibility involves in situ growth, which can occur at rates fast enough to fit the time frame of our study.



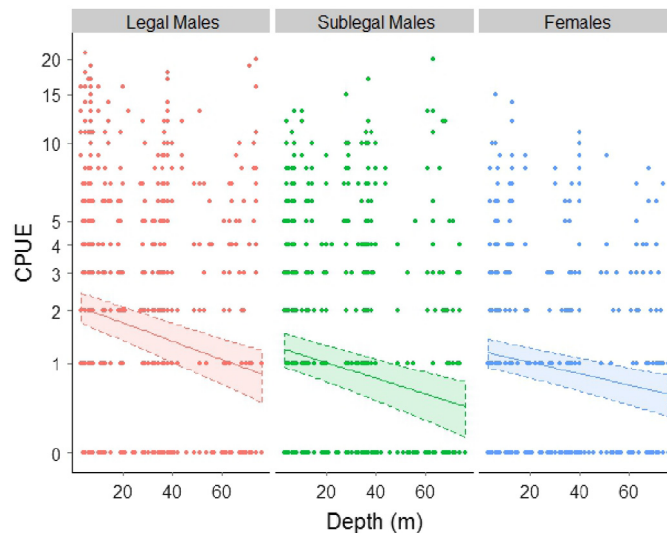


**Fig. 2.** CPUE of legal males (upper panel) and sublegal males (lower panel) in response to date and fishery status. Lines are responses estimated by LMM models (Table 2) superimposed on raw data (with many overlapping points). Y-axes depict the number of crabs caught per trap in a log scale. Bands are 95% confidence intervals.

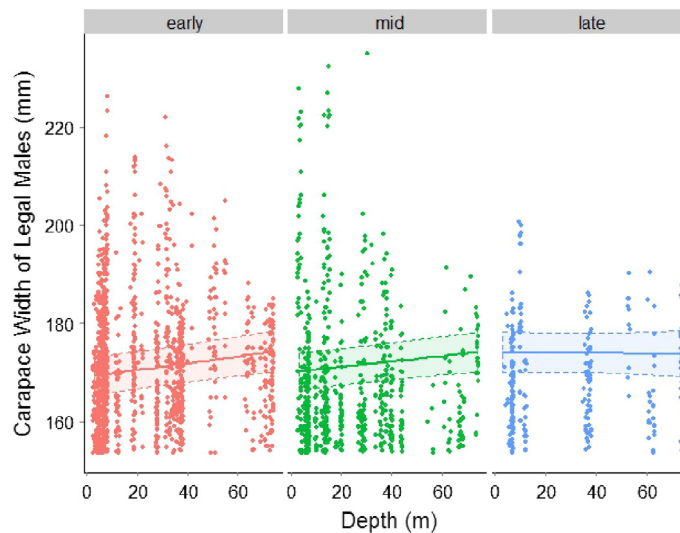


**Fig. 3.** Notch-to-notch carapace width of legal males in response to date and fishery status. Lines are responses estimated by the LMM model (Table 2) superimposed on raw data (with slight random jitter). Bands are 95% confidence intervals.

Research in southern British Columbia found that males with notch-to-notch carapace widths of only 104 mm – that is, 50 mm below minimum legal size – molted twice and grew to legal size in only 18 months. Further, 130-mm-wide sublegal males grew to become 157-mm-wide legal males after a single molt (Smith and Jamieson, 1989). Although growth rates vary with temperature (Kondzela and Shirley, 1993), and therefore oceanographic conditions, it is likely that some individuals that were sublegal males earlier in our study grew to legal size later in the study. Due to fishery mortality at open sites, however, a net increase in the abundance of legal males may have occurred only at closed sites. Similarly, in situ growth of legal males may have led to net increases in average size only under the lower fishery mortality of closed sites. Consistent



**Fig. 4.** CPUE of all classes of Dungeness crab in response to depth. Lines are responses estimated by LMM models (Table 2) superimposed on raw data (with many overlapping points). The y-axis depicts the number of crabs caught per trap in a log scale. Bands are 95% confidence intervals. The effect of depth on CPUE of females increased over time (Table 2) and the LMM estimate is for the midpoint of the study (July 21, 2014).

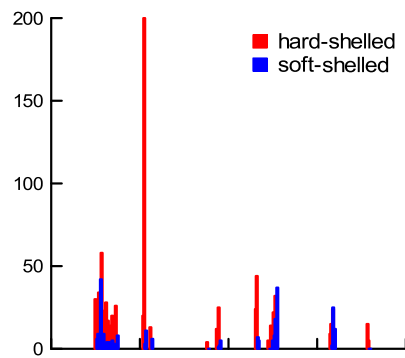


**Fig. 5.** Notch-to-notch carapace width of legal males in response to depth. The scatterplot displays raw data (with slight random jitter) divided in three sampling periods: 23 April to 3 August, 2014 (early), 4 August to 13 November, 2014 (mid), and 14 November 2014 to February 25, 2015 (late). Lines represent responses estimated by the LMM model (Table 2) during 23 April, 2014 (early), 17 June, 2014 (mid) and 25 February, 2015 (late). Bands are 95% confidence intervals.

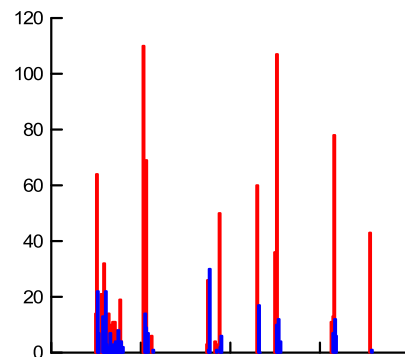
with this possibility, our data on shell hardness suggests that some males did undergo growth periods (Fig. 6). Specifically, soft-shelled males (hardness scores of 2–4), which likely grew and moulted within 3 months prior to being sampled (see Table 1 of Dunham et al., 2011), were recorded throughout the study (Fig. 6).

Other mechanisms that may have influenced our results include seasonal variation in activity levels and depth distribution (Stone and O'Clair, 2002), which in turn affect catchability and therefore CPUE. Also, long distance movements (i.e. >5 km) leading to migration and emigration are known to occur in relatively shallow areas (Smith and Jamieson, 1991); whether such movements occur in the very large range of depths encompassed by our study region remains unknown. In any case, currently we lack a rationale to expect long distance movements and seasonal shifts in behaviour to differ between closed and open sites. Fishery elevated mortality, therefore, remains a leading hypothesis for the observed differences between closed and open sites. This interpretation is consistent with research on the effects of spatial fishery closures on Dungeness crab in Glacier Bay, Alaska, which reached similar conclusions (Taggart et al., 2004).

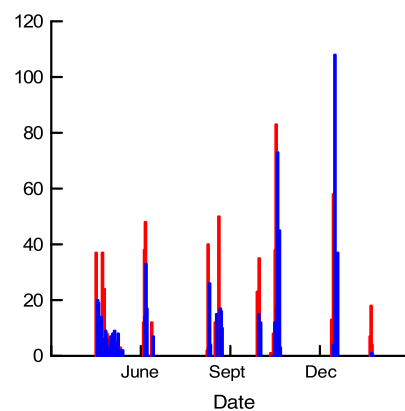
Independent of fishery status, our data suggest that Dungeness crabs were less abundant in deeper habitats, but the average size of legal males increased with depth during spring through fall (but not winter). Use of depth by Dungeness crab



a) Legal males, open sites.



b) Legal males, closed sites.



c) Sublegal males, all sites.

**Fig. 6.** Shell hardness of males over time. Soft-shelled individuals correspond, respectively, to hardness scores of 2–4, implying that they had moulted within the previous three months. Hard-shelled individuals correspond to hardness scores of 1 or 6–8, implying they had moulted more than three months (up to >2 years) prior to sampling (see Table 1 in [Dunham et al., 2011](#)).

([Stone and O'Clair, 2002](#); [Rasmuson, 2013](#)) had not been studied previously in the Central Coast. Future research should continue to investigate depth effects, using drop video camera to pre-screen sites and avoid sampling rocky habitats not-preferred by Dungeness crab. Pre-screening is important because, during our study, bycatch of species that prefer rocky habitats, such as tanner crabs and urchins, suggested that some deeper contours contained rocky areas of lower quality for Dungeness crab, possibly under-representing use of deeper habitats in our data.

All sites had a long history of recreational and commercial fisheries and our sampling spanned 10 months only. Further, as stated earlier, indigenous FSC fisheries continued at some closed sites, and therefore results provide insight only into the



effects of excluding non-indigenous fisheries. Given these caveats, the fact that our statistical modelling detected positive effects of closures on the abundance and sizes of legal males is a strong endorsement for the benefits of spatial protection. We expect longer-term research on permanent closures to detect even greater benefits (Edgar et al., 2014).

Our study demonstrates that indigenous governance can create spatial closures for conservation and research when Canada's government fails to do so. Long-term conservation solutions, however, require collaboration in research and management between federal and indigenous governments (Gutierrez et al., 2011). Towards that end, Canada's newly elected Liberal government has begun to restore federal science (Jones, 2015) and to address indigenous rights, thereby enhancing the possibility of such collaboration.

More generally, indigenous laws have much to contribute to fisheries co-management and other forms of applied science (Housty et al., 2014). For example, in coastal British Columbia hereditary chiefs are responsible for implementing indigenous laws and for the stewardship and inter-generational knowledge of specific areas. Their long-term perspective on the state of a resource transcends the shifting baseline syndrome that mires many short-term fishery data sets, and is an important tool for recognizing whether spatial or temporal fishery closures – like those applied during our study – are required for conservation (Trosper, 2003). Though not grounded in the same cultural principles as the hereditary chief system, “territorial user rights for fisheries” (TURFs) used to manage artisanal fisheries in Chile are another example in which local resource users receive exclusive rights and can formally create fishery closures (Gelcich et al., 2012). Unlike the hereditary chief system in British Columbia, TURFs are integrated with fisheries legislation in Chile, perhaps providing a legislative model for how to use small-scale spatial management in ways that integrate indigenous laws into fisheries co-management. Such integration of legal systems would be relevant to any part of the world where indigenous knowledge remains vibrant (Johannes et al., 2000).

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## Appendix A. Supplementary material

Supplementary material related to this article can be found online at <http://dx.doi.org/10.1016/j.gecco.2016.01.002>.

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