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ARTICLE

Lack of recreational fishing compliance may compromise effectiveness of Rockfish Conservation Areas in British Columbia

Dana R. Haggarty, Steve J.D. Martell, and Jonathan B. Shurin

Abstract: Compliance with spatial fishing regulations (e.g., marine protected areas, fishing closures) is one of the most important, yet rarely measured, determinants of ecological recovery. We used aerial observations of recreational fishing events from creel surveys before, during, and after 77 Rockfish Conservation Areas (RCAs) were established in British Columbia, Canada. There was no evidence of a change in fishing effort in 83% of the RCAs, and effort in five RCAs increased after establishment. Fishing effort in open areas adjacent to the RCAs declined with time and was higher than effort in the RCAs in all 3 years. Next, we used compliance data for 105 RCAs around Vancouver Island to model the drivers of compliance. Compliance was related to the level of fishing effort around the RCA, the size and perimeter-to-area ratio of RCAs, proximity to fishing lodges, and the level of enforcement. Noncompliance in RCAs may be hampering their effectiveness and impeding rockfish recovery. Education and enforcement efforts to reduce fishing effort inside protected areas are critical to the recovery of depleted fish stocks.

Résumé : Bien qu'elle soit rarement mesurée, la conformité à la réglementation spatiale visant la pêche (p. ex., aires marines protégées, zones fermées à la pêche) est un des plus importants déterminants du rétablissement écologique. Nous avons utilisé des observations aériennes d'activités de pêche récréative tirées d'enquêtes par interrogation des pêcheurs avant, durant et après l'établissement de 77 aires de conservation des sébastes (ACS) en Colombie-Britannique (Canada). Aucune indication d'un changement de l'effort de pêche n'a été observée dans 83 % des ACS, alors que cet effort a augmenté dans cinq ACS après leur établissement. L'effort de pêche dans des aires ouvertes attenantes aux ACS a diminué au fil du temps et était plus élevé que l'effort de pêche dans les ACS durant les 3 années. Nous avons ensuite utilisé des données sur la conformité pour 105 ACS autour de l'île de Vancouver pour modéliser les facteurs de conformité. Le degré de conformité était associé au niveau d'effort de pêche autour de l'ACS, à la taille et au rapport du périmètre et de la superficie de l'ACS, à la proximité de camps de pêche et au degré de mise en application des restrictions. Le non-respect des ACS pourrait en limiter l'efficacité et nuire au rétablissement des sébastes. La sensibilisation et les efforts d'application de la réglementation à l'intérieur des aires protégées sont essentiels au rétablissement des stocks de poissons décimés. [Traduit par la Rédaction]

Introduction

Jurisdictions around the world are increasingly using spatial management (e.g., marine reserves, fishing closures) to conserve and restore overfished populations (Hamilton et al. 2010; Parker et al. 2000; Yamanaka and Logan 2010; Yoklavich 1998). The effectiveness of marine reserves and marine protected areas (MPAs) depends on reducing or eliminating fishing pressure within their boundaries (Ainsworth et al. 2012; Gaines et al. 2010; Kritzer 2004; Sethi and Hilborn 2008). Reserves with high rates of noncompliance show limited recovery of fish communities (Ainsworth et al. 2012; Campbell et al. 2012; Kritzer 2004; McClanahan et al. 2009), and compliance information can predict the recovery of fish biomass without incorporating any reserve design factors (Bergseth et al. 2015). Furthermore, a global study of marine reserves identified enforcement as one of five key features that influenced effectiveness (Edgar et al. 2014). Similarly, compliance levels reported by resource users and population density were the best predictors of reserve effectiveness in a study of 56 tropical marine reserves (Pollnac et al. 2010). However, despite their importance for recovery, compliance rates are rarely quantified (Sethi and Hilborn 2008; Smallwood and Beckley 2012), and when compliance is measured, most data are qualitative (anecdotal or expert opinion) and direct empirical observations are rare (Bergseth et al. 2015).

Noncompliance is prevalent where it has been studied. For example, Smallwood and Beckley (2012) found that 8%–12% of recreational boats were fishing in closed zones in Australian MPAs. Ten percent of recreational fishers involved in a questionnaire using the random response technique in Australia admitted to fishing in closed areas (Arias and Sutton 2013). Williamson et al. (2014) used the density of derelict fishing line as a proxy of recreational compliance in no-take zones in the Great Barrier Reef Marine Park and found that no-take areas had 30% of the fishing effort of surrounding open areas (Williamson et al. 2014). Compliance can also change over time. For instance in Mexico, travel to marine reserves by fishermen declined shortly after a reserve was implemented, but compliance declined within 4 years as fishermen learned that there was no enforcement (Fujitani et al. 2012).

The environmental and social drivers that influence compliance in marine reserves are a critical research frontier for the implementation of more effective MPAs (Bergseth et al. 2015). Reserve design features such as size and shape may influence compliance (Gaines et al. 2010; Kritzer 2004; Read et al. 2011). Fishing is often concentrated around the edge of a reserve; therefore, larger

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MPAs with lower perimeter-to-area ratios should have lower fishing rates due to lower straying rates along their perimeters (Read et al. 2011). The location of reserves may also influence compliance as fishing often decreases with the distance to port and is greater with closer proximity to towns, fishing piers, and boat ramps (Read et al. 2011; Stelzenmüller et al. 2008). Involving stakeholders in the planning process of conservation areas may also affect compliance and enhance MPA effectiveness (Pollnac et al. 2010). However, few studies have actually tested these assumptions with empirical measurements of compliance (Bergseth et al. 2015; Pollnac et al. 2010).

Here, we examine recreational fishing compliance in Rockfish Conservation Areas (RCAs), in British Columbia (BC), Canada. In response to conservation concerns associated with a sharp decline in inshore rockfish catches throughout the 1990s in the Northeast Pacific, Fisheries and Oceans Canada (DFO) implemented a system of 164 RCAs. RCAs were established between 2004 and 2007 and prohibit commercial and recreational hook and line fisheries and bottom trawl fisheries; however, aboriginal fishing for food, social, and ceremonial purposes, as well as fisheries with minimal impact on rockfishes, are permitted (see Yamanaka and Logan 2010). The BC commercial fishery exhibits good compliance with the RCAs as a result of onboard and electronic fishery monitoring by global positioning system (GPS) technology and observers (unpublished data, N. Olson, Groundfish Data Unit, DFO, Nanaimo, BC, 2015). Compliance by the recreational fishery has yet to be assessed, although anecdotal observations indicate that fishing in closed areas persists and that recreational compliance might be low (Marliave and Challenger 2009). The purpose of our study was to assess and identify drivers of recreational compliance with RCAs. We aimed to answer two questions: (1) Has the spatial pattern of recreational fishing effort changed in the RCAs since they were established? and (2) What geographic factors affect variation in compliance among RCAs?

Materials and methods

Study area context

RCAs were implemented in BC as part of a larger Rockfish Conservation Strategy. Inshore rockfishes include six species of the genus *Sebastes* (*S. caurinus*, *S. maliger*, *S. melanops*, *S. nebulosus*, *S. nigrocinctus*, and *S. ruberrimus*) that are found on shallow (<200 m) rocky reefs. Although RCAs are not considered MPAs because they are fishery closures rather than permanently legislated protected areas (Robb et al. 2011), they do prohibit commercial and recreational fisheries that target or lead to a significant bycatch of rockfishes (Yamanaka and Logan 2010). Recreational (e.g., through the Sport Fish Advisory Board) and commercial fishers as well as conservationists, First Nations, and the public were consulted in the designation of the RCAs (Yamanaka and Logan 2010). Although the protection targets were ambitious — 30% of rockfish habitat in "inside" waters east of Vancouver Island, and 20% of outer coast habitats — attempts were made to minimize socio-economic impacts on recreational and salmon troll fisheries. Other considerations in the designation of the RCAs included rockfish habitat, the ease of monitoring, and enforcement (Yamanaka and Logan 2010).

Rockfishes are targeted by recreational fishers and caught as bycatch while angling for salmon or bottom fish such as halibut and lingcod (Zetterberg et al. 2012*b*). The contribution of recreational fisheries to rockfish mortality varies by region. In 2011, recreational fishers caught 90% of the estimated 35 000 inshore rockfishes caught in the Strait of Georgia, compared with 35% of 60 000 fish and 8% of 93 000 on the western coast and northeastern coast of Vancouver Island, respectively (recreational data from D. O'Brien, DFO; commercial data from N. Olsen, DFO). In addition to designating RCAs, DFO reduced recreational daily bag limits from ten to five rockfishes in outside waters and from five to one rockfish on the inside as part of the rockfish conservation strategy (Yamanaka and Logan 2010).

We focused our analysis on Vancouver Island and the Strait of Georgia. Vancouver Island is separated from the mainland coast by the inland waters of the Strait of Georgia, Johnstone Strait, and Queen Charlotte Strait, locally called "inside" waters. BC's two largest population centers, Vancouver and Victoria, as well as numerous smaller towns border the Strait of Georgia. The northeastern and western coasts of Vancouver Island are much more sparsely populated but have numerous recreational fishing lodges. Of the 164 RCAs, 144 are found in southern BC and 129 of these are in inside waters (Fig. 1).

Data collection and preparation

DFO monitors the marine recreational fishery in BC using creel surveys (English et al. 2002). The creel survey has two components: (1) dockside interviews, in which fishers are asked where they fished, what they caught, kept, and released, and how long they fished; and (2) effort counts via aerial surveys along predefined flight paths timed to cover major periods of fishing activity. Planes fly at an altitude of 150–300 m a.s.l. to allow for a broad range of vision and easy identification of vessel type and activity. Between six and ten flights per month are completed during the peak fishing season (Zetterberg et al. 2012*a*). An observer counts all boats and uses binoculars to determine whether they are actively fishing (lines in the water) or not (traveling or engaged in other activities such as trap fishing). The observer marks the estimated geographic location of the boats on maps of the study area. The number of boats are summed by management area and used in conjunction with dockside interviews to estimate the total sport-fish effort and the number of salmon and groundfish caught in the sport fishery (i.e., Zetterberg et al. 2012*a*). However, the data have not previously been digitized or geo-referenced with the RCA network to assess compliance.

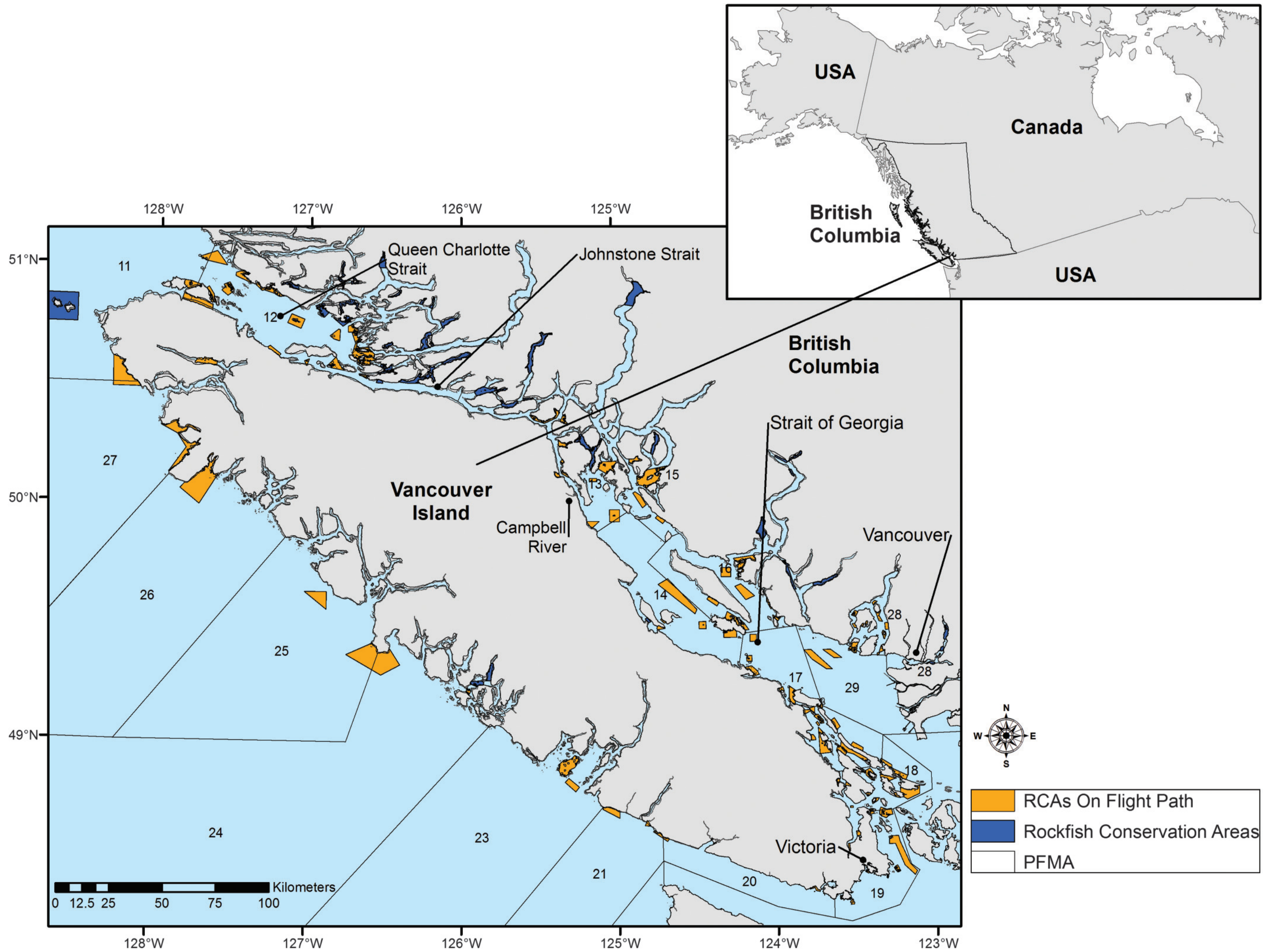
We used the spatial information from the creel survey overflights to assess recreational compliance in the RCAs. We digitized and geo-referenced creel survey maps for the northern and southern Strait of Georgia, Queen Charlotte Sound, and the northwestern coast of Vancouver Island using major coastal features and management area boundaries in ArcGIS 10.1 (ESRI 1999–2012). We recorded the root mean squared (RMS) error (ESRI 2008), a measure of the difference between known locations and points that have been interpolated or digitized, for each image. The fishing observations were then manually digitized for each survey date between May and September, when 85% of the sport-fish effort in BC occurs (Zetterberg et al. 2012*b*). To avoid bias, RCAs were not displayed in the GIS project while we digitized fishing observations. We digitized data for the Strait of Georgia for 2003, 2007, and 2011, while data for the northeastern and western coasts of Vancouver Island were only available for 2011. Only RCAs that fall within view of the survey route were used in our analyses (Fig. 1). Because the flight pattern near one RCA, Desolation Sound, changed between 2007 and 2011, it was dropped from the temporal analysis.

Temporal analysis

We used data from 2003 to represent fishing effort prior to establishment because the RCAs were designated between 2004 and 2006. The creel survey estimates of effort for 2003, 156 670 boat trips, was the median value from 1999–2003 (Zetterberg et al. 2012*b*). The first year all RCAs were in place was 2007 and 2011 is at least 5 years after RCA establishment. The temporal analysis is limited to the Strait of Georgia.

We compared the effort in 77 RCAs in the Strait of Georgia between 2003, 2007, and 2011. Recreational fishing effort is higher on weekends than on weekdays so the creel survey is stratified by type of day (English et al. 2002). Following the methods used by English et al. (2002), we normalized effort in and around RCAs by the type of

Fig. 1. Study area of southern British Columbia showing the Rockfish Conservation Areas (RCAs) on and off of the aerial survey flight path and Pacific Fishery Management Areas (PFMAs) (11–29, excluding 22, which has no RCAs). Basemap is unpublished data provided by Canadian Hydrographic Service. [Colour online.]



day (weekday versus weekend) as well as the number of flights per month to compare effort between years (eq. 1). The number of flights per month varied among years. To normalize the sampling effort for each RCA in each year, the total boat observations by day were multiplied by the total number of each day of that type in each month (i.e., 19, 20, or 21 weekdays and 9, 10, or 11 weekend days) to yield the number of boat-days. We calculated the mean monthly boat observations for each day type by dividing by the number of surveys taken on that day type and then added the mean of the weekday and weekend together for an estimate of the monthly boat observations (per RCA, per year). We then summed the observations for all months (May–September) to get an estimate of fishing effort in boats·year^{-1} during the periods of observation (eq. 1).

$$(1) \qquad \bar{B}_M^R = \sum_t^2 \left[\frac{\left(\sum B_{Mt}^R \cdot D_{Mt}\right)}{F_{Mt}} \right]$$

where B is boats (effort), M is month, t is day type (1 = weekday, 2 = weekend), D is days per month, R is RCA, and F is flights (surveys).

To control for overall changes in fishing effort in the vicinity of the RCAs, we also calculated the effort in a 1 km wide buffer strip around each RCA. In GIS, we intersected the fishing observations with the RCAs and a 1 km wide buffer strip around each RCA. To compare effort among RCAs and between RCAs and buffers, we calculated an effort density by dividing the effort by the area (km^2) of the RCA and the buffer.

To analyse the relationship between fishing effort and protection status among years, we used a linear mixed effects model with a Gaussian distribution in the program R (R Development Core Team 2008) and the package nlme (Pinheiro et al. 2012). Because our data were highly skewed, we used a log(x + 1) data transformation to normalize variance (Zar 1996). Year (2003, 2007, and 2011), treatment (RCA versus Buffer), and the interaction of year and treatment were entered as fixed effects and RCA was a random factor. Visual inspection of the residual plots did not reveal any obvious deviations from homoscedasticity or normality after transformation. The model was estimated using the log-likelihood method so that models could be compared using Aikake's information criterion (AIC) (Zurr et al. 2009). The full model was compared with reduced models with only Year, Treatment, and Year + Treatment without the interaction. An interaction between year and treatment indicates that the fishing effort differential between protected and unprotected areas varied over time. A contrast between 2003 versus 2007 and 2011 indicates an effect of fisheries closure on effort. The final model was fit using restricted maximum likelihood estimation (REML) (Zurr et al. 2009).

Next, we identified which RCAs had experienced a change in fishing effort over time. We used analysis of variance (ANOVA) on the monthly log(x + 1) effort density (May–September) for each RCA with year (2003, 2007, 2011) as the independent variable. We adjusted the critical P value for multiple comparisons with the Bonferroni correction. When significant differences among years were found, we used a pairwise Tukey's honestly significant difference (HSD) test to determine which years differed.

To examine changes in effort on a finer spatial scale than the RCA, we plotted spatial fishing effort using the Kernel Density tool in ArcGIS 10.1 (ESRI 1999–2012) with a grid cell size of 100 m × 100 m and a 1 km search radius. The Kernel Density tool calculates a magnitude effort per unit area from point features using a quadratic function to fit a smoothly tapered surface to each point (ESRI 2012). To turn these kernel density plots into a probability density, we divided effort in each cell in the kernel density plot in each year by the total number of observations used to calculate the plot using the Raster Calculator tool (Abbott and Haynie 2012). Once the density plots have been normalized using this method, the volume under the entire density plot equals 1 and the value in each grid cell is the probability of fishing effort. Abbott and Haynie (2012) used this method to compare fishing effort from trawling in and around two fishing closures in Alaska. We compared the density probabilities among time periods using the raster calculator to subtract the effort between years and mapped the results.

We also calculated the standardized effort for each Pacific Fisheries Management Area (PFMA, Fig. 1) using eq. 1. We compared the proportion of the summed effort in all RCAs in a PFMA to the total effort in each area and compared this proportion among years with a chi-square contingency table analysis.

Factors affecting RCA compliance

We explored the geographic factors that affect recreational compliance with a Generalized Additive Model (GAM) using the package mgcv (Wood 2011) in R (R Development Core Team 2008). We used a Gaussian distribution and Identity link function to predict fishing effort in 2011 in 105 RCAs around Vancouver Island that could be observed from the over-flights. We omitted one extremely small RCA (Hardy Bay) (0.1 km^2). We calculated the fishing effort probability using the normalized kernel density method described above. We made separate probability plots for each region surveyed in 2011. Because we did not compare among years in this analysis, we did not need to standardize the data using eq. 1. We summed the fishing probability over the entire RCA as well as a 2 km wide buffer area around each RCA. The dependent variable in the GAM model was the total probability of effort in each RCA divided by the area of the RCA.

Explanatory variables included the distance from each RCA to the closest city (population >5000) and to the closest fishing lodge; the total probability of fishing effort in the buffer divided by the area of the buffer; the estimated rockfish catch in each PFMA; the human population within a 25 km radius of each RCA; RCA size and the perimeter-to-area ratio; the number of hours patrolled by conservation officers by geographic region; and geographic region as a factor (Supplementary Table S1[1]). We did not include the distance to other coastal features such as the closest community or boat ramps because of the low variability among RCAs in these features. The mean distance between RCAs and the closest community and boat ramp was 7.1 km (SD 6.7 km) and 6.8 km (SD 6.7 km), respectively. We used a rank transformation on the dependent variable and many of the independent variables (effort outside, enforcement, population, and RCA area) because they had highly skewed distributions (Supplementary Table S1[1]). To identify the explanatory variables that have a significant influence on the fishing effort density, we used the package MuMIn (Barton 2013) in R (R Development Core Team 2008) to compare all submodels of the full model and to rank the submodels using the AIC corrected for small sample size (AIC_c). The model with the lowest AIC_c value is the best model and the explanatory variables retained in this model can be assumed to have a significant influence on the fishing-effort density in the RCAs (Stelzenmüller et al. 2008). Finally, we tested the effort density in RCAs among regions and among park type (i.e., RCAs that are in a national park, provincial park, provincial ecological reserve, or not a park) using a Kruskal–Wallis test.

Rockfish catch in RCAs

It is not possible to directly measure the rockfish catch taken from RCAs from the spatial data because creel interviews are conducted over regions at broader spatial resolution. To estimate the fisheries take from the RCAs, we calculated the total recreational effort for each PFMA (Fig. 1) using eq. 1. We then calculated the fraction of fishing effort in each PFMA that occurred in RCAs and applied this proportion to the creel survey estimates of total rockfish caught per PFMA derived from the overflight data and dockside interviews (data from D. O'Brien, South Coast Management, DFO). We assumed that rockfish could be caught anywhere in the PFMA, regardless of habitat features such as depth or bottom cover, and that catch rates are equivalent between RCAs and unprotected areas. This is a conservative estimate of take from the RCAs because it is likely that a greater proportion of the rockfish catch would be caught in suitable rockfish habitat, and therefore in the RCAs.

Results

Data compilation

The number of images geo-referenced by region and year, along with the positional accuracy (RMS error) is shown in Table 1. The positional accuracy (15.9– 30.1 m error) was small in comparison with the size of an RCA (Table 1). The fishing events from the southwestern coast of Vancouver Island in 2011 were supplied digitally by DFO without an estimate of positional accuracy. The data set contains over 65 000 recreational fishing observations.

Temporal analysis

Effort in both the 77 RCAs and the 1 km wide buffers declined with time between 2003, 2007, and 2011 (Fig. 2). This corresponds with the declining trend that is seen for the fishing effort in the whole Strait of Georgia (Supplementary Fig. S1[1]). The linear mixed-effect model with the lowest AIC value was the full model with fixed effects for year, protection status, and the interaction of year and protection status (Table 2). The treatment effect is the strongest, with greater effort outside of the RCAs than inside in all time periods, including 2003 before the RCAs were established. The interaction between year and treatment indicates that the difference between effort in and outside of the RCAs declined with time (Fig. 2).

We also compared the proportion of effort in the RCAs with the total effort in each management area (PFMA) by year (Fig. 3). PFMA 15 is not shown due to a change in the flight pattern over one large RCA. A χ^2 test showed no evidence of change in the proportional effort in the RCAs by year (Fig. 3).

We used estimates of monthly effort per year for each RCA (Table 3; Supplementary Fig. S2[1]; Supplementary Table S2[1]) and the kernel density effort maps (Fig. 4) to examine effort in individual RCAs. There was no evidence of a change in effort in most

[1]Supplementary data are available with the article through the journal Web site at http://nrcresearchpress.com/doi/suppl/10.1139/cjfas-2015-0205.

Table 1. Number of images per region and year, positional accuracy (root mean squared (RMS) error), and number of fishing events observed.

Region and year	No. of images	Mean RMS error (m)	No. of fishing events
Strait of Georgia 2003	575	20.2	18 778
Strait of Georgia 2007	581	15.9	11 734
Strait of Georgia 2011	727	30.1	14 551
Northern Vancouver Island 2011	55	16.9	4 660
Southwestern. Vancouver Island 2011	NA	NA	15 499
Total	1 938		65 222

Note: NA, not applicable.

Fig. 2. Boxplot of standardized log + 1 fishing effort density inside and outside of RCAs in 2003, 2007, and 2011. Two extreme outliers are not shown.

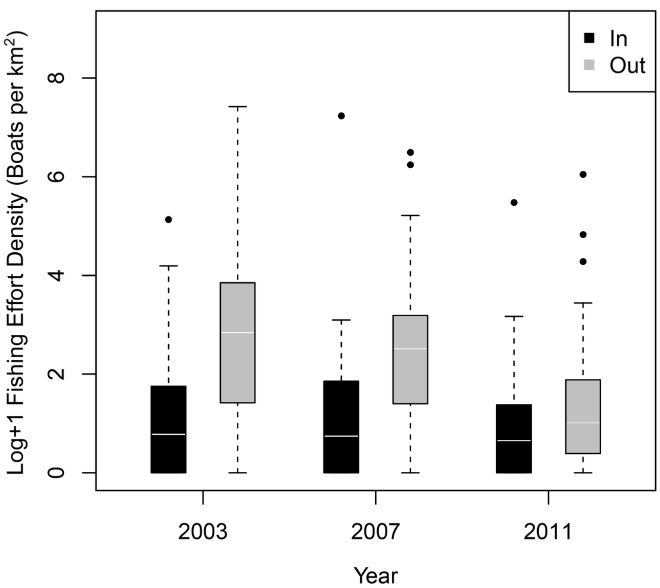


Table 2. Results of the preferred linear mixed effects model (Aikake's information criterion (AIC) = 1379) using 462 observations and 77 groups (Rockfish Conservation Area (RCAs)).

Fixed effects	Value	SE	df	*t*	*p*	2.5% CI	97.5% CI
Intercept	356.6	35.7	382.3	10.0	<0.001*	286.6	1.3
Year	–0.2	0.02	382.3	–9.9	<0.001*	–0.2	–0.1
Treatment	–280.8	50.6	382.3	–5.5	<0.001*	–379.8	–181.9
Year × Treatment	0.1	0.03	382.3	5.5	<0.001*	0.1	0.2

Note: Degrees of freedom calculated with Satterthwaite approximations.
*Significant result at $\alpha = 0.05$.

Fig. 3. Proportion of recreational effort in RCAs in the Strait of Georgia by Pacific Fishery Management Area (PFMA) by year. PFMA 15 is not shown due to a change in the flight pattern over one large RCA. Basemap is unpublished data provided by Canadian Hydrographic Service.

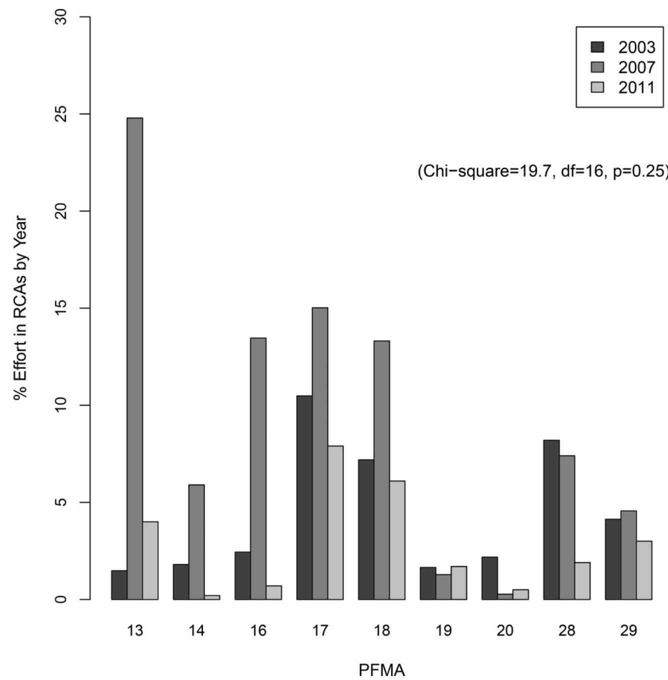


Table 3. Summary of changes in monthly recreational effort with time by Rockfish Conservation Area (RCA).

Change in effort	No. of RCAs	%
No change, effort in all years	30	39.0
No change, no effort	14	18.2
No change, low effort†	20	26.0
Increase in 2007*	2	2.6
Increase in 2011*	3	3.9
Decrease in 2007*	2	2.6
Decrease in 2011*	1	1.3
Decrease in 2007 and 2011*	5	6.5
Total	77	100.0

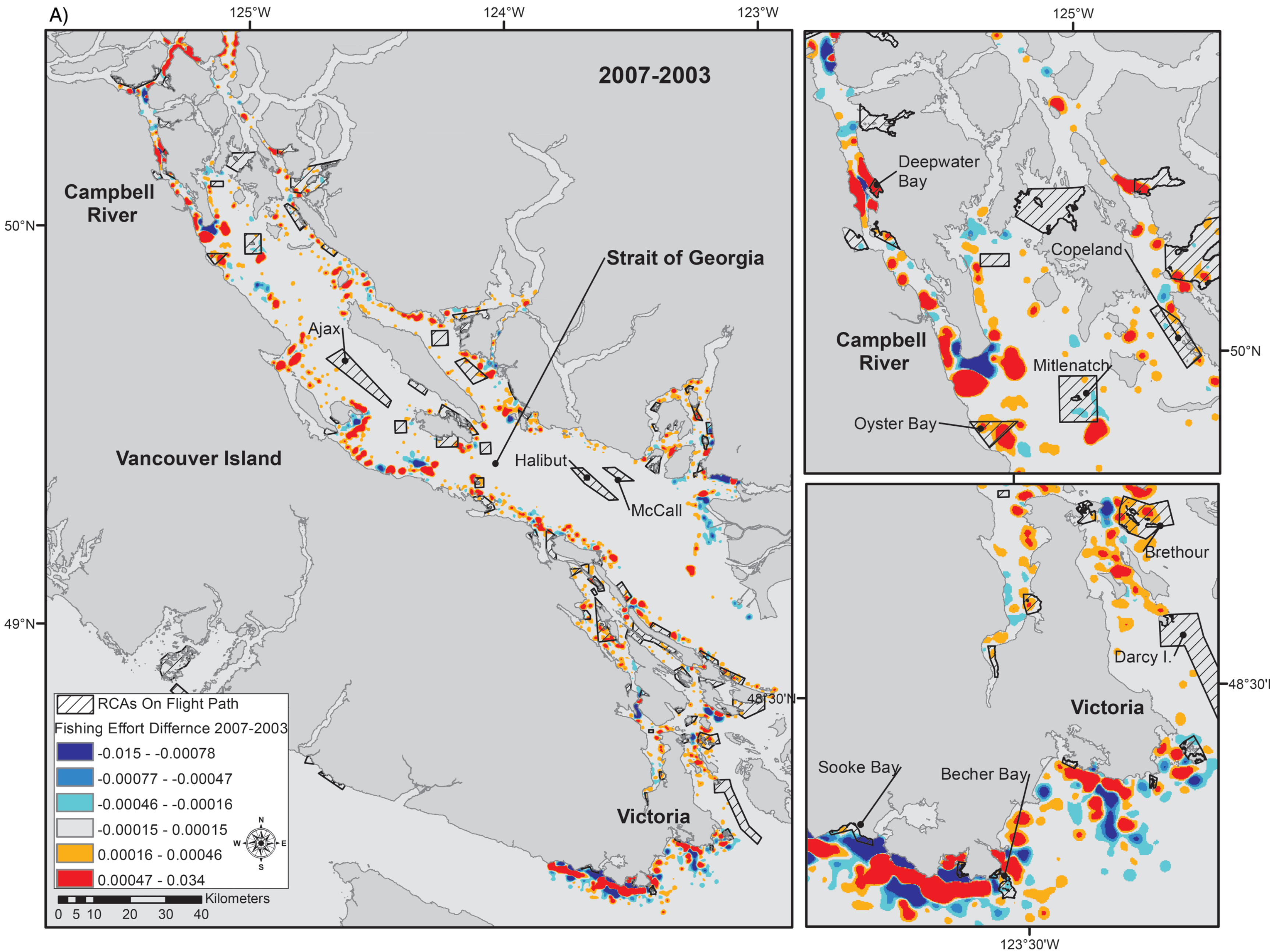
*Monthly effort in some RCAs increased or decreased ($p < 0.05$).
†We characterized RCAs with 0.01–0.5 boats per km² as having low effort.

RCAs (83%) amongst the 3 years. Thirty RCAs had effort greater than 0.5 boats per km² in all years. Effort in two RCAs increased between 2003 and 2007 and effort increased in three different RCAs between 2007 and 2011. Deepwater Bay and Oyster Bay had greater effort 2007 than 2003 and Copeland and Darcy Island had greater effort in 2011 than in 2007. Effort in Deepwater Bay declined in 2011 as compared with 2007 (Fig. 4). Effort declined significantly in five RCAs in both time periods and in three other RCAs in 2007 or 2011 (Table 3). Fishing effort in four RCAs south of Victoria declined in one or both years (Fig. 4). Not all RCAs are fished. Fourteen RCAs had no effort in any year and 20 others had only very low effort in all 3 years. Offshore RCAs, Ajax, Halibut, and McCall banks, had no effort in any year (Fig. 4).

Factors affecting RCA compliance

The best fit GAM model to predict effort in the RCAs retained the fishing effort density in the buffer, the distance to fishing lodges, the amount of enforcement effort (patrol hours), the area of the RCA, and the perimeter-to-area ratio. Distance to cities, population within 25 km, and the level of rockfish catch in the PFMA were not included in the best model (Table 4; Fig. 6). Effort in the RCA generally increased with the amount of fishing effort in the buffer. Fishing effort also increased in proximity to fishing lodges. Fishing effort declined with distance to a lodge up to around 15–20 km, beyond which the relationship was flat. Many RCAs, particularly in the Southern Strait of Georgia, are not near any fishing lodge (Fig. 5). Larger RCAs also experienced greater fishing effort per unit area than smaller RCAs. Effort also increased with the ratio of perimeter-to-area, although the relationship reaches a maximum and flattens out. The influence of enforcement is complex and nonlinear, perhaps because the patrol hours spent in a geographic region is a coarse estimate that may not realistically represent the actual amount of time an RCA in a region was enforced. Region was not a significant factor and

Fig. 4. The density effort in 2007 minus 2003 (A) and 2011 minus 2007 (B). Blue colours indicate lower effort in the later year while warmer colours indicate higher effort. Most RCAs are shown in grey indicating no change in effort. Basemap is unpublished data provided by Canadian Hydrographic Service.



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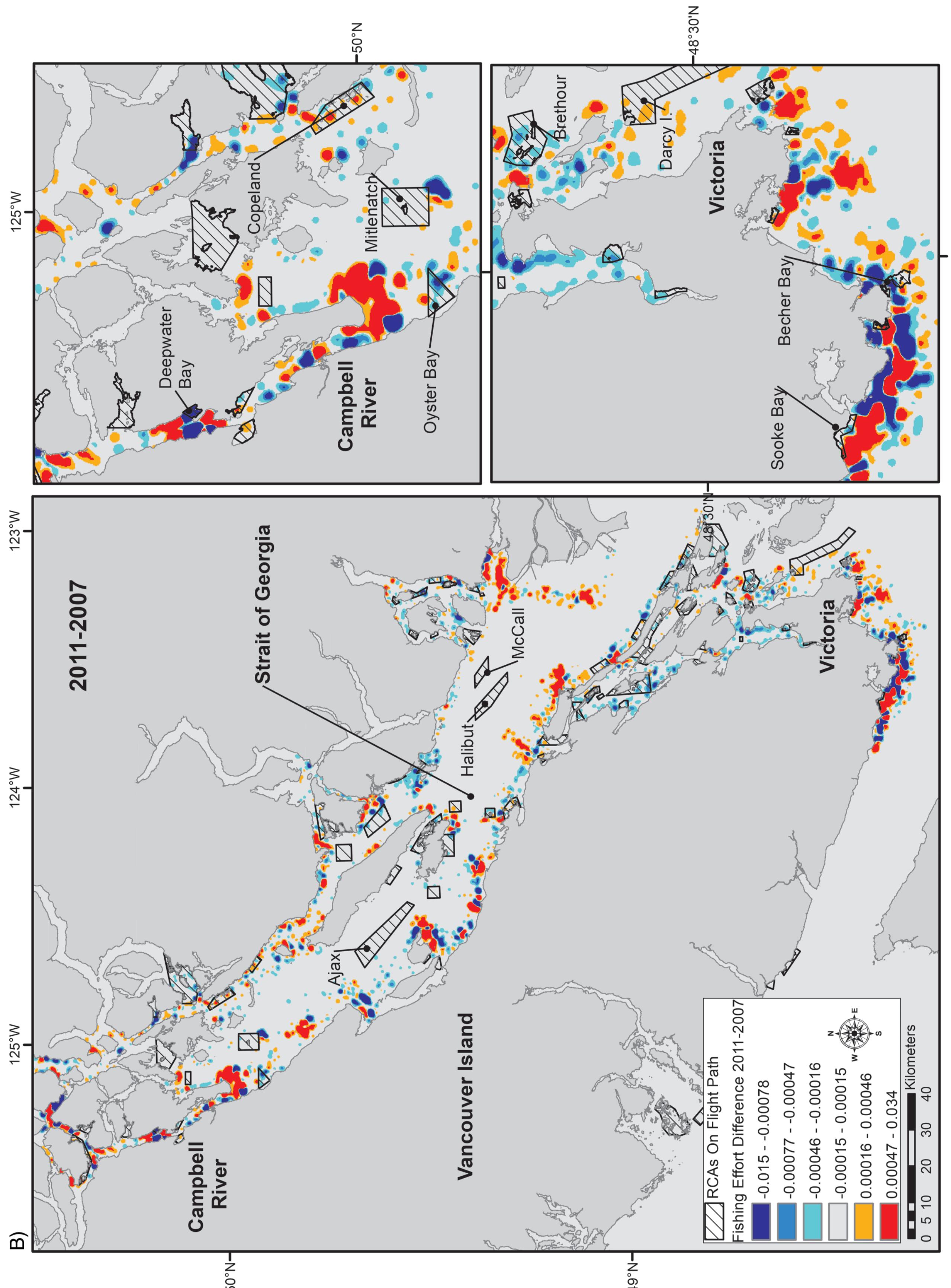


Fig. 4 (concluded).

Table 4. Explanatory variables that were retained and rejected in the best model (deviation explained 75.7%, adjusted R^2 of 0.67, n = 105).

Model variable	Retained in model	F	p
Fishing effort density in 2 km buffer	Yes	8.0	<0.0001
Size (km²)	Yes	31.6	<0.0001
Enforcement (patrol hours by PFMA)	Yes	6.1	<0.0001
Distance to fishing lodge (km)	Yes	3.6	0.001
Perimeter-to-area ratio	Yes	4.0	0.006
Distance to city (km)	No		
Rockfish catch (by PFMA)	No		
Population within 25 km radius	No		
Region (factor)	No		

was not retained in the model despite a significant difference between in effort between Mid-Strait of Georgia (MSOG), where many RCAs are not fished, and the Campbell River (CR) and Queen Charlotte Strait regions (Fig. 6). We found no difference in effort density among park types with a Kruskal–Wallis test (K = 1.4, df = 3, p = 0.7).

Rockfish catch in RCAs

The fishing effort in the RCAs is quite low compared to the effort in each management area (PFMA) (<5% in most PFMAs, Supplementary Fig. S3[1]). However, one large RCA on northwestern Vancouver Island (PFMA 27), Topknot, experiences 10% of the fishing effort in the region (Supplementary Fig. S3[1]). We estimate 175 rockfishes were fished from the Topknot RCA in PFMA 27 in 2011 (Supplementary Fig. S3[1]). Rockfish Conservation Areas near Nanaimo (PFMA 17) and in the southern Gulf Islands (PFMA 18) experienced 8% and 6% of the effort, respectively. We estimate that RCAs in PFMA 17 and PFMA 18 contributed almost 720 and 370 rockfish, respectively, to the fishery in 2011, although this catch was spread over numerous RCAs.

Discussion

Compliance with recreational fishing regulations in the RCAs in BC is low. Of the 77 RCAs studied in the Strait of Georgia, 79% still showed some level of fishing effort after the establishment of the RCAs and effort in five RCAs even increased (Supplementary Table S2[1]). Compliance was influenced by the amount of fishing effort adjacent to the RCA, the proximity to fishing lodges, the size and perimeter-to-area ratio, and enforcement. A lack of compliance in MPAs may inhibit population recovery and impair reserve effectiveness (Bergseth et al. 2015; Edgar et al. 2014; Fujitani et al. 2012); however, the effectiveness of the RCA network remains unknown. Our results indicate that the effectiveness of the RCA network at promoting population recovery may be compromised by lack of compliance.

Only eight of 77 RCAs decreased in one or both years relative to 2003, although effort adjacent to the RCAs declined with time. Recreational fishing effort in the Strait of Georgia is driven by Chinook and Coho Salmon catches and has steadily declined since the 1980s when over 500 000 boat trips per summer were estimated by the creel survey. Recreational effort in the whole Strait of Georgia declined between 2003 and 2011 as a result of declining salmon stocks (Zetterberg et al. 2012*b*). A decline in recreational effort cannot be attributed to the creation of the RCAs. If the recreational fishery increases with improvements in salmon stocks, RCAs may experience greater levels of fishing if compliance is not improved.

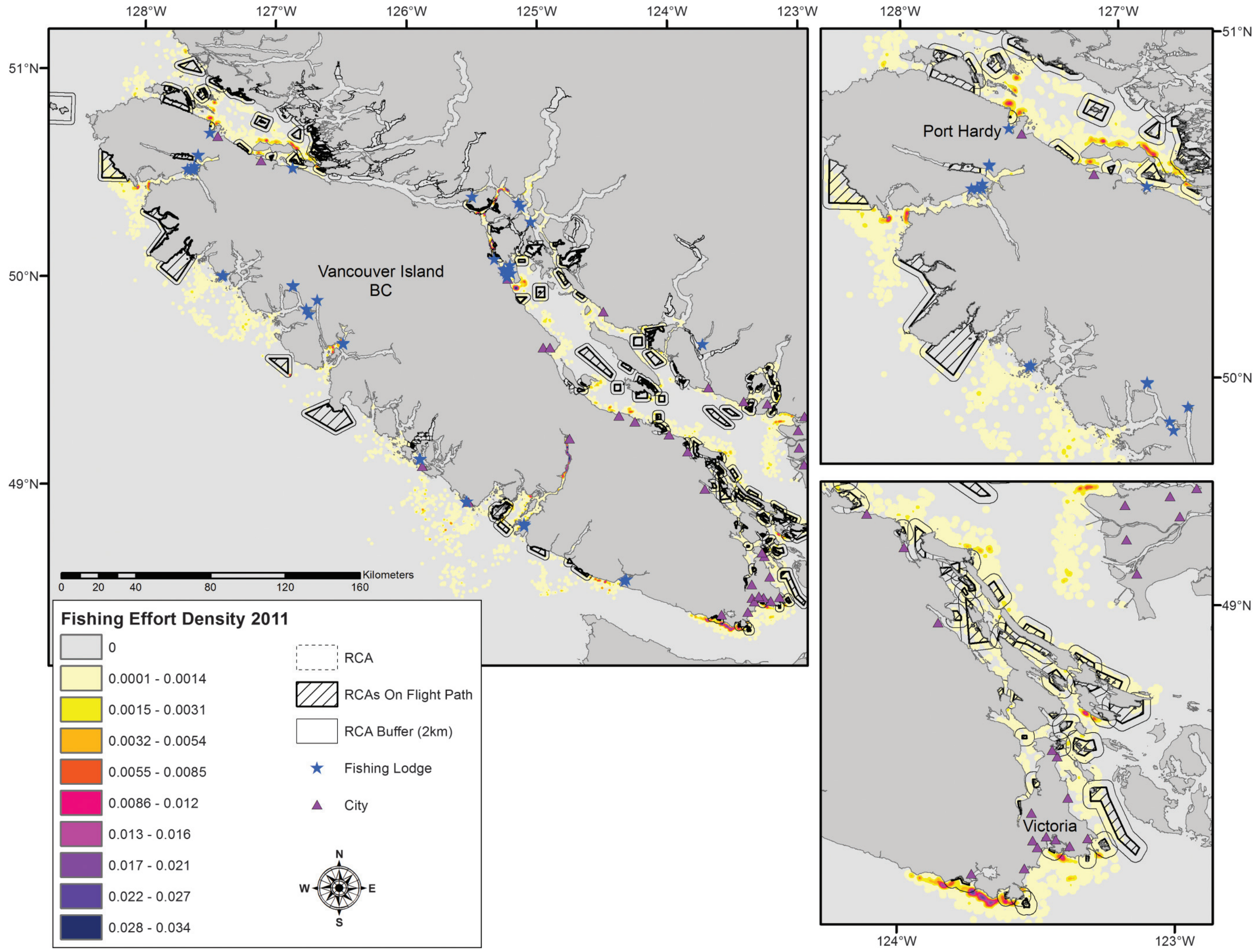
Fishing effort was lower in the RCAs than in unprotected reference buffer areas; however, effort in the area of the RCAs was also lower before they were established. Some RCAs were not fished recreationally in any year and a lack of effort in those RCAs is not evidence of a change in fishing behaviour as a result of spatial management. The RCAs were designated in consultation with the sport fishing community and the boundaries of the RCAs were designed to minimize effects on the sport fishery by leaving popular salmon fishing locations open (Granek et al. 2008; Yamanaka and Logan 2010). Involving the resource users in the implementation of management actions is thought to enhance conservation success and fishery management (Granek et al. 2008). Consultation with recreational fishers may not have been effective in this case as awareness about the RCAs appears to be low. If the most popular fishing spots are also the prime rockfish habitat, then the RCAs may not include the most important areas for promoting population recovery.

The greatest factor influencing compliance among the RCAs is the amount of fishing adjacent to the RCA, followed by the size of the RCA, with larger RCAs having greater effort per unit area than smaller RCAs. This contrasts with results of Kritzer (2004) who found greater compliance in large rather than small MPAs. Kritzer's data highlighted the importance of the perimeter-to-area ratio as people tend to fish near the boundaries of MPAs (Kritzer 2004). RCAs with greater perimeter-to-area ratios are more at risk to fishing; however, this relationship levels off at intermediate perimeter-to-area ratios. RCAs in close proximity to fishing lodges (within 15–20 km) have lower compliance. Although fishing effort is often higher closer to towns (Read et al. 2011; Stelzenmüller et al. 2008), the proximity to cities and the population within 25 km of the RCA were not significant factors. Our model indicates that noncompliance is more likely if there is greater effort in the region, and if the RCAs are a large "target" with a long boundary. Fishers are likely incidentally fishing in RCAs rather than actively targeting them, particularly because the rockfish catch did not influence compliance rates. Recreational fishing patterns in BC are not driven by rockfish because the primary target of most recreational fishers in BC is salmon and the most sought-after groundfish are halibut and lingcod (Fisheries and Oceans Canada 2012). Fishers may not, therefore, be aware of the regulations or locations of RCA, despite the fact that rockfishes are caught incidentally in these other fisheries that are prohibited in RCAs.

The number of patrol hours by region was also a significant predictor in the model, although the patterns are complex and nonlinear. RCAs near Victoria are relatively well patrolled and have good compliance, despite high fishing effort adjacent to the RCAs. Conversely, one of the most heavily fished RCAs, Topknot, on the remote northwestern coast of Vancouver Island, is close to fishing lodges and is rarely patrolled. These patterns might reflect the dense population near Victoria versus the sparsely populated northwestern coast of Vancouver Island, although population within 25 km of an RCA did not influence compliance. Pollnac et al. (2010) found that reserves close to dense populations were more effective than those near lower populations, perhaps due to greater vigilance by reserve neighbours. Their findings did, however, suggest that compliance is related to a range of conditions such as education, formal consultation, monitoring by community, and clearly defined boundaries rather than to just the level of enforcement per se (Pollnac et al. 2010). Additional enforcement would likely increase compliance in RCAs as fishers are able to adjust to levels of enforcement (Fujitani et al. 2012). For example, effort in one RCA increased between 2003 and 2007, but declined between 2007 and 2011, perhaps as a result of targeted outreach and enforcement by Fishery Officers in Campbell River (personal communication, Joe Knight, Conservation and Protection, DFO).

Other factors that were not included in the model, such as local stewardship, may also affect compliance. A local newspaper has printed information about the Lion's Bay RCA and residents with waterfront properties bordering the RCA actively promote it. The Lion's Bay RCA is the only RCA in Howe Sound that had lower effort in 2007 and 2011 than in 2003. In another case, a resident with waterfront property adjacent to the Mayne Island North RCA

Fig. 5. Fishing effort probability around Vancouver Island along RCAs on the flight path and 2 km wide buffers, as well as the location of fishing lodges and cities (population >5000). Insets show RCAs in the southern and northern extents of Vancouver Island. Basemap is unpublished data provided by Canadian Hydrographic Service.



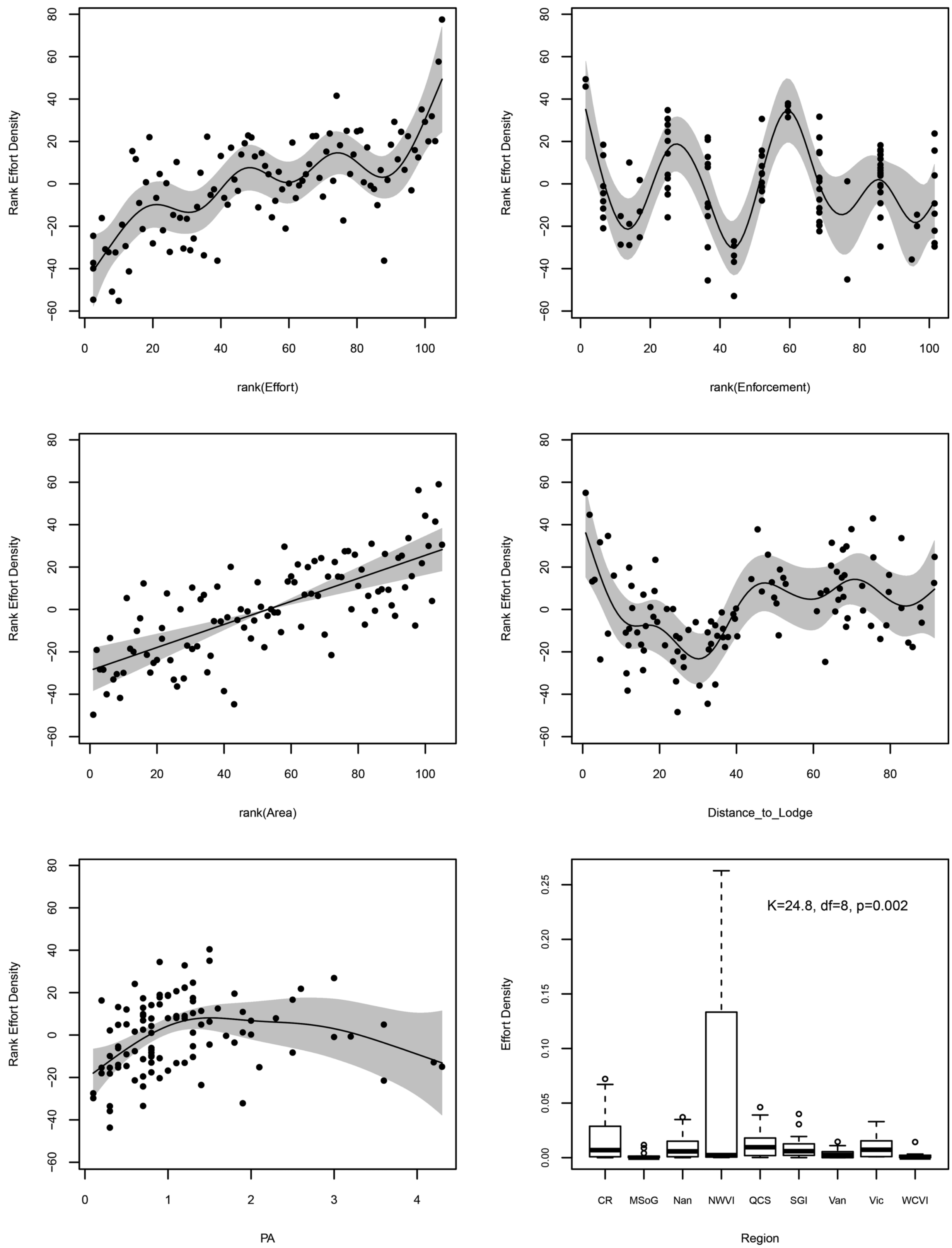
reportedly uses a bullhorn to inform people fishing in that RCA of the fishing regulations and reports observations to DFO. This RCA had less effort in 2011, while a nearby RCA, the Bell Chain Islets, saw an increase in effort. Park type did not, however, affect compliance. There was no difference in fishing effort among RCAs in national or provincial parks, or provincial ecological reserves and those with no additional protection. Education and enforcement by park staff could improve compliance in the RCA within parks.

Lack of awareness about the location and regulations in the RCAs likely contributes to noncompliance. No physical markers demark the boundaries of the RCAs. After an initial outreach campaign associated with the Rockfish Conservation Strategy, DFO promoted the RCAs with references in the Sport Fishing Guide (e.g., DFO 2016.), information on its website, and signs at some boat ramps. The hard copy of a booklet published about the RCAs is not widely available and fishers are often directed to the internet to download an electronic copy (Fisheries and Oceans Canada 2008). The location of the RCAs are not readily available in any electronic form or on mapping software used by sport fishers, so it is difficult for a fisher to determine when they are in one. This is particularly a problem in inside waters where there are numerous RCAs. Awareness of the RCAs could be ameliorated by including the RCAs on nautical charts and the use of new technologies such as GPS and smart phones and the development of tools (apps) that help fishers to locate RCAs as well as educate them about rockfishes and regulations. No-take reserves are more effective than reserves that allow some fishing (Edgar et al. 2014). Therefore, increasing the level of protection to no-take reserves might also simplify the regulations, increase compliance, and increase effectiveness.

Positional accuracy of boat observations represent the greatest source of error in identifying whether boats are fishing in RCAs, especially near their boundaries. Although the error associated with the geo-referencing process was low (RMS error of 16–30 m), the positional accuracy of the placement of the boat observations by the aerial survey observer cannot be assessed in this study. Bias was avoided for most of the study because the boundaries of the RCA were not included on the maps used in the aerial survey or during digitizing, with the exception of the west coast of Vancouver Island (WCVI) where the observer had the locations of the RCAs. This region had lower instances of boats fishing in RCAs than most other regions. The difference was not significant, so observer bias likely had little effect on our analysis.

Although aerial surveys can cover much larger areas, boat-based surveys might have greater positional accuracy. Smallwood and Beckley (2012) measured compliance in an Australian MPA using aerial and boat-based surveys. They found that aerial and coastal surveys yielded similar results; however, they identified

Fig. 6. Five significant variables were retained in the RCA Compliance Generalized Additive Model. Plots show the smooths of the significant variables. Shaded regions are two standard error confidence bands for smooths and the points are partial residuals. Region (lower right) was not retained in the model despite an overall significant difference among regions; however, a multiple comparison test showed that Effort Density in RCAs was only lower in the Mid-Strait of Georgia (MSOG) than in the Campbell River (CR) and Queen Charlotte Strait (QCS) regions. PA, Perimeter-to-area ratio; Nan, Nanaimo; NWVI, northwestern coast of Vancouver Island; SGI, Southern Gulf Islands; Van, Vancouver; Vic, Victoria; WCVI, western coast of Vancouver Island.



more boats as being engaged in fishing during the boat-based survey because the activity the boat operators were engaged in could not conclusively be determined for 30% of their aerial observations. The aerial survey found that 8% of recreational boats were fishing in closed zones while coastal surveys found a slightly higher proportion, 12%, were fishing in closed zones. Our estimates of fishing effort might, therefore, be conservative if some of the boats observed as "not fishing" were actually fishing.

The results of this study could be used to target outreach and enforcement activities. For instance, outreach with fishing lodges could decrease effort in RCAs. Fishers who stay at lodges are often not local and may be less aware of the regulations. Education and outreach activities have been shown to reach a broader population than enforcement and, therefore, have greater effects on compliance (Alder 1996; Leisher et al. 2012). An Australian study found that education and outreach activities such as newspaper articles and flyers, TV and radio ads, displays at boat and outdoor shows, signage at boat ramps, and education courses for tourism operators and school children, had a wider impact than enforcement. The per-capita cost of education was also lower than enforcement, although total education costs were greater because education reaches a wider audience (Alder 1996). A study in Indonesia also found that education and outreach activities resulted in greater knowledge of conservation issues and a more positive attitude towards MPAs, particularly among people who were initially undecided about their attitudes towards MPAs. Education and outreach did not change the attitudes of people who started with negative attitudes about MPAs; therefore, a combination of education and enforcement are required to change compliance levels (Leisher et al. 2012).

Despite the lack of compliance in many RCAs, the proportional effort in RCAs in most management areas is quite low. However, some of the more heavily fished RCAs in the southern Strait of Georgia may be impacted and the Topknot RCA on the northwestern coast of Vancouver Island experiences at least 10% of effort in that region. Continued fishing may affect the performance of such RCAs. In an age-structured model of Black Rockfish, Sethi and Hilborn (2008) found that high rates of poaching negated the biological and fishery benefits of implementing reserves. High rates of noncompliance in reserves have been found to limit recovery of fish communities empirically as well (Campbell et al. 2012; Edgar et al. 2014; McClanahan et al. 2009; McCook et al. 2010; Pollnac et al. 2010). In an Indonesian marine reserve, Campbell et al. (2012) found that low compliance with no-take zones resulted in decreases in fish biomass in all reserve zones despite an observed recovery in coral cover. In the Great Barrier Reef, McCook et al. (2010) found that no-entry zones had a higher abundance of coral trout than no-take and fishing zones. They concluded that this implied some noncompliance in the less strictly enforced no-take zones. In reserves in the Indian Ocean, McClanahan et al. (2009) found that zones with high enforcement showed significant trends in fish size and age, whereas zones with less enforcement and implied weaker compliance showed lower responses. In the Mediterranean, no-take zones that were accessible by car had a lower abundance of harvested sea urchins than inaccessible no-take zones (Ceccherelli et al. 2011). The impacts of noncompliance may be much greater for long-lived species with low recruitment rates such as rockfishes (Bergseth et al. 2015). Noncompliance in the RCAs may, therefore, affect the performance of RCAs and may be one reason why most RCAs have not shown reserve effects in an accompanying study of fish density measured with remotely operated vehicle surveys inside and outside of RCAs (Haggarty 2015).

Compliance is critical to spatial fisheries management to promote recovery of over-exploited populations (Bergseth et al. 2015; Edgar et al. 2014; Pollnac et al. 2010). Recreational fishing compliance in the RCAs needs to be improved for the RCAs to conserve rockfish populations. Several approaches should be taken including greater enforcement, developing a communication and outreach plan (Grorud-Colvert et al. 2010), and developing tools to assist with locating the RCAs. DFO should continue to use the fine-scale spatial information in the creel survey over-flight data to monitor compliance in the RCAs and other spatial management actions. In addition to assessing management actions, the model results can be used to inform policy and to target enforcement and education to enhance compliance. The results indicate that efforts to improve compliance with RCAs are urgently needed if they are to meet their goal of contributing to recovery of rockfish populations.

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