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1 **Drivers and trends in catch of benthic resources in Chilean TURFs and surrounding Open**
2 **Access Areas.**

3

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18

19 **Abstract**

20 Beginning in the 1990's, Chile implemented an extensive Territorial User Rights for Fisheries
21 (TURFs) network that now comprises nearly 1,000 TURFs. This network provides a rare
22 opportunity to examine spatial and temporal trends in TURF use and impacts on surrounding open
23 access areas (OAAs). In this analysis, landings of keyhole limpet (*Fissurella* spp.), kelp (*Lessonia*

24 spp.) and red sea urchin (*Loxechinus albus*) were used to estimate catch-per-unit effort (CPUEs)
25 and catch-per-unit area (CPUAs) indices inside and outside TURFs by fishing cove. For these
26 species, CPUEs and CPUAs in 2015 were significantly higher inside TURFs. However, temporal
27 trends analyzed with a linear mixed effects model indicate that CPUAs inside TURFs have been
28 significantly decreasing since 2000 for keyhole limpet, red sea urchin and for loco (*Concholepas*
29 *concholepas*), while in OAAs this measure only decreased for limpet. An elastic net regression
30 was used to better explain catches in OAAs during 2015, including a variety of variables related
31 to the characteristics and activity of proximal TURFs. Results indicate that exogenous factors
32 unrelated to TURF management were the primary drivers of catches in OAAs during 2015 but that
33 factors related to proximal TURFs appear to have a slight negative impact that grows over time.
34 Collectively, these results indicate that while TURFs are associated with higher catch rates than
35 surrounding OAAs, catch rates appear to be decreasing over time and, though limited, the impact
36 of TURFs on surrounding OAAs may be negative. These findings suggest a need for a more
37 nuanced and dynamic approach to spatial management on benthic resources in Chile.

38

39 **Abbreviations**

40 CPUA: Catch per unit of area

41 CPUE: Catch per unit of effort

42 OAA: Open access area

43 TURF: Territorial user right for fisheries

44

45 **1. Introduction**

46 Spatial property rights can eliminate many common pool externalities that plague fisheries,
47 thereby better incentivizing sustainable and profitable resource use (Beddington et al. 2007,
48 Cancino 2007, Costello et al. 2008). Specifically, Territorial User Rights for Fisheries (TURFs) is
49 a management tool that grants individuals or groups exclusive access to harvest resources within
50 an area (Christy 1982). TURFs have been associated with biological, ecological and economic
51 benefits in several small-scale fisheries (Castilla and Fernández 1998, Gelcich et al. 2008a, 2012,
52 Defeo et al. 2016). During the last decade, TURFs have been promoted as a general approach to
53 tackling the negative impacts of open access fishing (Wilén et al. 2012, Kratz and Block 2013,
54 FAO 2014, Nguyen Thi Quinh et al. 2017), particularly for unassessed fisheries in developing
55 countries that often suffer from overexploitation (Costello et al. 2012). However, the full impacts
56 of TURFs on fisheries sustainability, including long-term trends in catch rates and impacts beyond
57 TURFs boundaries, are not yet fully understood (Orensanz et al. 2005, Aburto and Stotz 2013,
58 Aburto et al. 2014, Gelcich et al. 2019). As the implementation of individual quotas and marine
59 protected areas has been found to have unintended impacts on unregulated subpopulations and
60 habitats (referred to here as “management spillover”; Hilborn et al. 2004, Murawski et al. 2005,
61 Asche et al. 2007, Branch 2009, Abbott and Haynie 2012), similar effects might be expected from
62 other area- or rights-based management and conservation instruments, including TURFs. To our
63 knowledge, the influence of the implementation of TURFs on surrounding areas has not yet been
64 assessed (Nguyen Thi Quinh et al. 2017) despite the fact that the spatial dynamics of most fisheries
65 exceed the scale of an individual TURF. This study looked at the long-term changes in catch and
66 catch rates (i.e., catch per unit effort, CPUEs, and catch per unit area, CPUAs) inside and outside
67 TURF managed areas and also evaluated the possibility of management spillover.

68 In Chile, the implementation of TURFs was a reaction to the collapse of the economically
69 important artisanal fishery for the muricid snail *Concholepas concholepas* in the 1980s (known in
70 Chile as *loco*, elsewhere as the false abalone) (Bernal et al. 1999). The fast recovery of the high
71 valued *loco* stocks in initial TURFs increased demand for further TURF development along the
72 entire Chilean coast throughout the 2000s. In 2017, there were 957 officially designated Chilean
73 TURFs implemented as part of a national TURF policy (Fishery and Aquaculture Law n° 18,
74 1991). According to the Chilean Fisheries Authorities, the primary objectives of Chilean TURFs
75 are to “ensure the sustainability of artisanal fishing through the assignment of natural banks”, and
76 to “maintain and increase the biological productivity of benthic resources” (SUBPESCA, 2003).
77 This TURF network constitutes the dominant form of spatial management of benthic resources in
78 Chile and is the largest worldwide, covering about 1,500 km² (though only about half of these 957
79 TURFs are currently operative). Known in Chile as “Área de Manejo y Explotaciones de Recursos
80 Bentónicos” (Management Areas for the Exploitation of Benthic Resources; AMERB), this system
81 grants exclusive fishing rights to legally constituted fishing organizations for the exploitation of
82 benthic resources in defined portions of the seabed – usually adjacent to a *caleta* or artisanal fishing
83 cove (Aburto et al. 2013). Each TURF has species-specific quotas proposed by the fishing
84 organization and approved by the Undersecretary of Fisheries. Artisanal fisher organizations have
85 to comply with a series of regulations, such as establishing a baseline study, management plan,
86 and regular stock assessments, for which they have to contract technical assistance from
87 specialized environmental and/or fisheries consultants (Gelcich et al. 2008b). TURFs are
88 interspaced with open access areas (OAAs) where seasonal closures and limits on catch size are
89 used, but entry, within-season effort, and total catch are not restricted. The Chilean TURFs system
90 was initially (i.e., from the 1990s to the 2000s) successful and associated with positive ecological

91 and economic benefits, such as the recovery of *loco* stocks, increased species richness inside
92 TURFs, and increased welfare and economic revenues (Castilla and Fernandez 1998, Defeo and
93 Castilla 2005, Gelcich et al. 2008a, 2012). OAAs produced the majority of catch and fishing
94 revenues however. While income from TURFs was largely supplemental, believed to represent
95 7% to 41% of total incomes (Romero et al. 2016), it was thought to play an essential role in
96 securing fishers' livelihoods (Aburto et al. 2013, Van Holt 2012, Gelcich et al. 2017).

97 Though ecological conditions appear to have improved within TURFs (Castilla and
98 Fernández 1998, Gelcich et al. 2012), TURF profitability is thought to have declined over the last
99 decade (Gelcich et al. 2017). The development of abalone aquaculture in Asia has negatively
100 influenced international demand for *loco*, leading to a reduction in exports from Chile to Asia
101 (from 2,400 mt in 1993 to less than 1,000 mt in 2013), and a drop in the price of *loco* (Chávez et
102 al. 2010, Castilla et al. 2016). Furthermore, the cost of TURF maintenance, which includes
103 assessment, enforcement, and surveillance, is thought to have increased (based on perception
104 surveys; Gelcich et al. 2009, 2017). Assessments are typically conducted by private environmental
105 consultants, whose fees have increased in part because of the relatively small number of such
106 companies available in Chile (Gelcich et al. 2009, Davis et al. 2015). Additionally, extensive
107 illegal fishing (González et al. 2006, Andreu-Cazenave et al. 2017, Oyanedel et al. 2017) suggests
108 that local fishing organizations must dedicate significant time and resources to enforcement in
109 TURFs. Though the Chilean government recognizes that there is poaching activity and, in theory,
110 is responsible for apprehending and penalizing poachers, in practice the responsibility of detecting
111 poaching in TURFs often falls on fishing organizations. Many fishers now indicate they do not
112 have enough capacity (i.e. resources and time) for surveillance of their TURFs and consider
113 “government punishment of poachers to be ineffective” (Moreno and Revenga 2014, Davis et al.

114 2015, Biggs et al. 2016). Thus, the combined influence of a lower price for *loco* and presumed
115 increased maintenance costs, with a reduced enforcement capacity, have likely increased
116 variability in financial returns and decreased the profitability of TURFs (Chávez et al. 2010,
117 Gelcich et al. 2010, 2017). In fact, in recent years (roughly 2010-2017), fishers appear to be relying
118 on TURFs less than initially (i.e., 1990s-2000s) and TURF exploitation now represents a smaller
119 fraction of fishers' overall incomes (Gelcich et al. 2017). This has coincided with an observed
120 increase in exploitation of OAAs (de Juan et al. 2017) and substantial illegal fishing of *locos*
121 (Andreu-Cazenave et al. 2017). Reduced incentives for the exploitation of a TURF could either
122 result in its abandonment (San Martín et al. 2010, Gelcich et al. 2017), its maintenance for purposes
123 other than fishing such as market access or social empowerment (Cancino et al. 2007, Zúñiga et
124 al. 2010, Aburto et al. 2013, Rosas et al. 2014, Gelcich et al. 2017), or its maintenance at a lower
125 but still positive level of profitability.

126 Potential positive or negative interactions between maintained TURFs and surrounding
127 OAAs are unknown. The large TURF system of Chile offers opportunities to explore the
128 consequences of spatial management on fisheries in surrounding areas. TURFs are expected to
129 secure fisheries harvests within their boundaries and provide incentives for sustainable use of
130 surrounding fishing grounds (Christy 1982). Recent studies in the Chilean system of TURFs have
131 shown higher potential egg production of two benthic species (the limpet *Fissurella latimarginata*
132 and the red sea urchin *Loxechinus albus*) within TURFs than under an open access scenario (67%
133 and 52% higher, respectively) (Blanco et al. 2017, Fernández et al. 2017), suggesting the potential
134 to enhance fishing opportunities both inside and outside TURFs. Negative impacts of TURFs and
135 other entry-restriction management and conservation tools beyond their limits are less well known.
136 Management spillover consisting of effort displacement from high-regulation TURFs to lower-

137 regulation areas outside TURFs (analogous to the “fisheries squeeze effect” in the context of
138 marine protected areas; Attwood and Bennett 1995, Bohnsack 2000, Halpern et al. 2004) could be
139 expected to occur, potentially deteriorating opportunities in surrounding fishing grounds. Recent
140 reductions in TURF profitability may provide increased incentives for TURF users to increase
141 fishing effort in OAAs, possibly further eroding the sustainability and profitability of Chilean
142 coastal fisheries in these areas.

143 The primary goals of this study were to analyze catch and catch rates within and outside of
144 TURFs to document any trends and interactions that might impact the ability of the TURF system
145 to meet the objectives of ensuring sustainability and increasing biological productivity of benthic
146 fishery resources. Specifically, we first examined and compared CPUE and CPUA indices (catch
147 rates) between TURFs and adjacent OAAs by fishing cove in 2015 for three important target
148 species (keyhole limpet (*Fissurella spp.*), kelp (*Lessonia spp.*) and red sea urchin (*Loxechinus*
149 *albus*)). Second, temporal dynamics in TURF and OAA catch rates were investigated by looking
150 at time series of CPUAs calculated for each management area by fishing cove and year. Finally,
151 to assess if catch rate differences between TURFs and adjacent OAAs observed in 2015 were
152 related to TURF implementation, a penalized regression model was developed to explain catch in
153 OAAs. The explanatory variables examined in the model were either related to proximal TURFs’
154 characteristics and activity (e.g., TURF age, TURF area fraction, TURF fishing effort), or
155 additional geospatial variables related to the spatial extent and context of OAAs (e.g., coastline
156 length, local productivity, proximity to urban areas).

157

158 **2. Methods**

159 *2.1 Data*

160 National data on catch and effort by fishing cove were obtained from the governmental
161 agency SERNAPESCA (National Fisheries Service). Artisanal fishers are required to report
162 landings by species, weight and origin (i.e., TURF or OAA; Moreno and Revenga 2014). TURF
163 geographical layers were obtained from the governmental agency SUBPESCA (Undersecretary of
164 fisheries). Fishing coves considered for the study (Fig. 1) had at least one designated TURF
165 assigned to a fishers' organization (referred to here as a functioning TURF; i.e., an operative TURF
166 with a use agreement and quota in place or a stand-by TURF for which a quota has been assigned
167 in the last 4 years, but monitoring has not been conducted by the due date, Appendix 1).

168 The artisanal benthic fisheries of Chile target a variety of species, including crustaceans,
169 mollusks, sea urchins, tunicates and several species of seaweed (Gelcich et al. 2010). Catch data
170 were obtained from landings reports, focusing on the most important benthic resources targeted in
171 TURFs. The primary target resource inside TURFs is the *loco*, which has the highest commercial
172 value (beach sale value: 11,647 US\$/mt; landings: 2,255 mt in 2011) (Moreno and Revenga 2014).
173 *Loco* extraction is banned in OAAs, and, therefore, only catches from inside TURFs were analyzed
174 for this species. Kelps (comprising the *Lessonia nigrescens* species complex, *Lessonia*
175 *trabeculata*, *Macrocystis pyrifera* and *Macrocystis integrifolia*) and the red sea urchin (*Loxechinus*
176 *albus*) are the largest landed benthic resources ranked by weight (landings: ~300,000 mt and
177 31,901 mt for kelp and sea urchin, respectively, in 2011). We also considered catches of keyhole
178 limpets (comprising *Fissurella* spp., *Fissurella costata*, *Fissurella cumingi*, *Fissurella*
179 *latimarginata*, *Fissurella picta*, and *Fissurella maxima*), another economically important benthic
180 resource (beach sale value: 2,354 US\$/mt; landings: 1,785 mt in 2011). Individual catch reports
181 from 2000 through 2015 for these four main exploited benthic resources were aggregated by
182 fishing cove and month (an individual harvester could report catch several times in a month), and

183 distinguished by their origin (i.e., inside or outside TURFs). Catches in OAAs (i.e., outside
184 TURFs) included catches gathered from artisanal boats or from the shore.

185 The number of active harvesters in 2016 per fishing cove was also obtained from
186 SERNAPESCA (most recent estimation, note that the number of fishers for 2015 was not
187 available). Individuals who have not operated for the last three successive years were removed
188 from the national registry. Chilean law distinguishes four categories of artisanal harvesters: 1)
189 Divers, who manually extract mollusks, crustaceans or echinoderms, or spearfish for reef fish,
190 usually operating from a boat; 2) Collectors, who harvest or collect seaweeds from the shore; 3)
191 Fishers, who are captains or crew members of an artisanal boat, from which they operate with nets,
192 including trammel nets, long lines, and hand lines; and 4) Ship owners, who are limited to one or
193 two artisanal boats, defined as 18 meters or less in length, and 50 tons or less. The different
194 categories are not mutually exclusive. Effort was estimated in terms of the number of divers (for
195 *loco*, limpet and sea urchin exploitation) or number of collectors (for kelp exploitation) registered
196 in a fishing cove and able to exploit the resource. Fishers' organizations that are granted a TURF
197 can only be comprised of licensed artisanal harvesters. However, not all licensed artisanal
198 harvesters are part of a fishers' organization. Therefore, effort "inside" TURFs only considered
199 licensed harvesters who were also registered in the corresponding fishers' organization, while
200 effort "outside" TURFs considered all licensed harvesters registered in a particular fishing cove.
201 A small number of harvesters (about 10%) were licensed in one fishing cove but associated with
202 fishing organizations in different fishing coves. To avoid overestimating effort per fishing cove,
203 the contribution of an individual harvester to effort in a cove was calculated by equally dividing
204 one unit of effort (i.e., one harvester) among the different fishing coves with which the harvester
205 was associated.

206 Fishing area estimates, for both TURFs and OAAs in each cove, were calculated using
207 different data and proxies. TURF areas were obtained through a Google Earth layer publicly
208 available on the SUBPESCA website for 2016. Total fishing ground polygons (comprising TURFs
209 and OAAs) were created per fishing cove based on sailing time and bathymetry (Appendix 2).
210 Buffer zones of 17 km (alongshore cutoff) around fishing coves were produced in ArcGIS to
211 represent total accessible fishing grounds for each cove. The 17-km cutoff was based on the
212 average distance from the fishing cove center to fishing grounds potentially visited as determined
213 by artisanal fisher survey results (Ruano-Chamorro et al. 2017). These 17-km buffers were then
214 intersected with a bathymetric polygon consisting of the area between 0 and 20 m depth. The
215 offshore width of these polygons was based on a typical maximum harvest depth of 20 m
216 (González et al. 2006). These alongshore and offshore cutoffs are similar to those used by Castilla
217 (1994) and Aburto et al. (2009) which applied an offshore limit of 30 m and an alongshore cutoff
218 of 15 km based on travel distance with one full tank of gas. The 20-m isopleth was only available
219 for central Chile (from 27° to 36°, Fig. 1) whereas a 100-m isopleth was available for the whole
220 Chilean coast (source GEBCO). Estimates for the areas of the 0-20 m fishing ground depth range
221 were derived from the areas of 0-100 m depth range using multiple linear regression (see Appendix
222 2 for details). Finally, estimates of OAA areas were calculated as total area of fishing grounds
223 minus assigned TURFs areas.

224

225 *2.2 Catch rate comparisons between TURFs and OAAs in 2015*

226 Annual catches divided by the number of active months (several species are only landed
227 during part of the year) of keyhole limpet, kelp, and red sea urchin were used to estimate CPUEs
228 and CPUAs per fishing cove for 2015 (most recent complete year for catch data at the time of the

229 study, SERNAPESCA). *Loco*'s estimates were not compared since its extraction is banned in
230 OAAs, and, therefore, only catches from inside TURFs were available. CPUEs and CPUAs were
231 differentiated by their origin, i.e., catches inside TURFs or in OAAs, and then compared to one
232 another to determine differences in fisheries productivity. CPUEs for each fishing cove were
233 calculated as the catches inside or outside TURFs divided by the adjusted number of divers (or
234 collectors) (i.e., after having adjusted this number to account for harvesters associated with
235 multiple fishing coves) inside or outside TURFs, respectively. The number of licensed harvesters
236 in 2016 was the best available effort proxy for estimating CPUEs in 2015 even though this is a
237 crude estimate as it is unknown how many trips each individual took. CPUAs for each fishing cove
238 were calculated as the catches inside or outside TURFs divided by the total assigned TURF area
239 (inside) or the estimated OAA area (outside). For each group of species, differences between
240 CPUEs and CPUAs inside and outside TURFs were tested for statistical significance using a
241 nonparametric Wilcoxon signed-rank test. Reporting rates from TURFs and OAAs could differ
242 given higher enforcement capacity within TURFs (Ruano-Chamorro et al. 2017). We therefore
243 calculated what catch in OAAs would have to be for catch rates in OAAs to equal those in TURFs
244 (assuming full reporting in TURFs), and then deduced the misreporting rate in OAAs it would
245 imply for each species and catch rate metric.

246

247 2. 3 Temporal analyses of CPUAs inside and outside TURFs

248 CPUAs of *loco*, keyhole limpet, kelp, and red sea urchin were analyzed over time to
249 investigate temporal performance of TURFs and OAAs over the last two decades. Fisheries data
250 was only available at the scale of an entire fishing cove, prohibiting differentiation between
251 multiple TURFs associated with a single fishing cove. Estimated OAA areas from 2016 were

252 adjusted over years according to implemented TURFs' area for that year and fishing cove
 253 (implementation year of TURFs were available from the SUBPESCA data). Complementary
 254 temporal analysis of CPUE trends was not feasible as the annual number of fishers was not
 255 available at the fishing cove scale. Changes in CPOA over time may reflect changes in biomass,
 256 changes in fishing effort, or changes in spatial management. If biomass were improving inside
 257 TURFs, CPOAs in these areas might be expected to increase over time. Conversely, if TURFs
 258 displaced fishing effort into OAAs, CPOAs in OAAs might be expected to decrease due to
 259 overfishing (but may increase initially as increased effort fishes down stocks). Additionally, a
 260 fishing cove can have several TURFs (up to 15 managed areas, but on average three). If the initial
 261 TURF implemented in a given fishing cove was located in the best habitat (Wilén et al. 2012), then
 262 fishing coves with multiple TURFs might experience sequential reductions in CPOAs. Finally, as
 263 catch depends on effort, it is also possible that changes in CPOA reflect changes in fishing effort
 264 over time (e.g., CPOA reductions arising due to reduced fishing effort independent of any changes
 265 in fish stocks).

266 A linear mixed effects model (i.e., model 1) was used to estimate the temporal trend and
 267 the effect of the number of TURFs per fishing cove on CPOAs inside and outside TURFs:

$$\ln(CPOA_{s,i,t,a}) = \beta_1 year_t + \beta_2 N_{TURF_{i,t}} + \delta_i + \varepsilon_{s,i,t,a} \quad (1)$$

268 In (1), the dependent variable is the log-transformed CPOA for species s , observed in the fishing
 269 cove i , for year t , in area a (inside or outside TURFs). β_1, β_2 are the unknown coefficients of the
 270 fixed effects variables year (from 2000 to 2015) and N_{TURF} , the number of functioning (i.e.,
 271 operative or stand by) TURFs per fishing cove for each year, respectively. δ_i is a random effect
 272 for fishing cove i , to control for heterogeneity across fishing coves and $\varepsilon_{s,i,t,a}$ is the error term.

273 To further disentangle the effects of time and number of TURFs per fishing cove on
274 CPUAs, an additional linear mixed effects model (i.e., model 2) was developed without the
275 variable N_{TURF} . Model 2 included a subsample of 57 fishing coves (29% of the 196 coves
276 considered in this study) that have had a constant number of TURF(s) for at least 10 years.

277 Statistical estimation of coefficients was performed in R (R Core Team, 2018) with the
278 lme4 package (Bates et al. 2015). Marginal and conditional coefficients of determination, r^2_m and
279 r^2_c , respectively, were estimated with the MuMIn package (Nakagawa and Schielzeth 2013).

280

281 *2. 4 Elastic net regression model*

282 The catches of keyhole limpet, kelp and red sea urchin from OAAs in 2015 were examined
283 to assess the impact of adjacent TURF characteristics and activity. Chile is divided into 15
284 administrative regions; fisheries for each of the species groups considered in this analysis generally
285 occur in only a subset of these regions (Appendix 3). As the great majority of limpet and kelp catch
286 occurred in the northern regions of Chile (specifically regions II, III, IV and V) and the great
287 majority of sea urchin catch occurred in the southern region (specifically, regions VIII, IX, XIV,
288 X and XI), data for species-specific analyses were limited to these northern and southern zones
289 (see Section 3.1 for details regarding the basis for selecting these zones).

290 A regularized linear regression model, the elastic net regression (Zou and Hastie 2005, see
291 Appendix 4 for model development), was developed to explain catch per cove in OAAs, including
292 explanatory variables either related to proximal TURFs' characteristics and activity, or related to
293 geospatial context (e.g., area and coastline length) and number of fishers targeting a given species.
294 This model uses a penalized maximum likelihood method that allows a large number of variables
295 to be included with relatively few observations and prevents over-fitting issues prevalent in more

296 common Ordinary Least Square (OLS) or stepwise regression methods (Friedman et al. 2010,
297 Morozova et al. 2015). The algorithm accomplishes variable selection by constraining the sum of
298 the magnitudes of normalized coefficients. A shrinkage penalty is included in the objective
299 function; it “shrinks” the effect of unimportant variables to select the simplest and most accurate
300 model. Two different values of the regularization parameter controlling the strength of the
301 shrinkage were considered; only results from the less restrictive regularization are shown here (see
302 Appendix 5 for results with the more restrictive regularization, i.e., a larger penalty that leads to
303 models with a smaller number of predictors with non-zero coefficients).

304 The response variables, i.e., catches in OAAs for limpet, kelp, and sea urchin, were log-
305 transformed before centering. We considered catch as the dependent variable instead of CPUEs
306 and CPUAs because we preferred a model including both effort and area as explanatory variables
307 simultaneously.

308 Given that effort displacement and any resulting ecological and social impacts are dynamic
309 processes, TURFs established for longer periods might be expected to have more significant
310 effects on catches outside of TURFs. In order to assess these temporal effects, elastic net models
311 included the variables number of years since the implementation of a TURF (*Age_TURF*) and
312 number of years since the establishment of the associated fishers’ organization
313 (*Age_Organization*) (source SUBPESCA). In theory, a fisher’s organization is established before
314 a TURF is implemented, but in some instances (~30% of our fishing coves), the organization had
315 changed over time or several TURFs had merged or been split leading to the TURF being
316 implemented before the associated fishers’ organization. Since several fishers’ organizations can
317 operate in each cove and a fishing cove can have several TURFs, each associated with one fisher’s
318 organization, the average and maximum values were calculated for both *Age_TURF* and

319 *Age_Organization*. Spatial aspects of TURF use were captured by the variables *N_TURF*,
320 *Area_Fraction* and *Area_OA* which measured the number of functioning TURFs per fishing cove,
321 the fraction of the total estimated fishing ground managed as TURFs and the total area of open
322 access grounds, respectively. The potential effects of fishing effort displacement should be greater
323 in fishing grounds with more TURFs and/or proportionately larger TURFs or smaller OAAs.
324 Fishing effort was included through the variables *Harvesters_All*, *Harvesters_per_OAA* and
325 *Harvesters_per_TURFs*, respectively, the total number of divers (or collectors) in OAAs, the
326 number of divers (or collectors) in OAAs divided by the OAAs area, and the number of divers (or
327 collectors) inside TURFs divided by the TURFs area. The predictions are that catch in OAAs
328 should increase with the total number of divers (or collectors) and decrease with the number of
329 divers (or collectors) per unit of area. Finally, the number of fisher's organizations per fishing
330 cove, *N_ORG*, was used as another proxy for local effort levels and fisheries involvement.

331 Data on additional geospatial variables related to the spatial extent and context of OAAs
332 were also obtained to include in analyses of catch for each species. Coastline length was calculated
333 for fishing grounds adjacent to a fishing cove to capture differences in coastal habitats (e.g.,
334 straight along beach and sinuous along cove leading to short and long coastline lengths,
335 respectively). Fractured coastlines with many small inlets are expected to be more favorable for
336 sea urchin productivity (Lawrence 2006) whereas linear beaches may represent regions of wide
337 continental shelf where unproductive sandy habitat is more common. As proximity to urban areas
338 might impact exploitation rates and other human pressures on benthic resources, a binary variable
339 was included to indicate if a fishing cove was within 50 km of one of the ten biggest cities of Chile
340 (source Instituto Nacional de Estadísticas). We also identified fishing coves close to fishing ports,
341 since increased market access could trigger higher effort and catches. Thus, if a fishing cove was

342 within 50 km of one of the forty major fishing ports of Chile, total landings by weight (comprising
343 algae, fish, mollusk, crustacean, other) from these proximal fishing ports were summed together
344 and associated with this cove; if no fishing ports were within 50 km, this variable was set to zero.
345 Finally, CPUEs for each species group (i.e., *loco*, keyhole limpet, kelp and sea urchin) within
346 TURFs were included as proxies for local abundance conditions. Abbreviations, definitions and
347 units for all variables included in the elastic net regression are given in Table 1.

348 Model parameters were estimated with the glmnet algorithm in R (Friedman et al. 2010, R
349 Development Core Team 2018). A bootstrapping process, randomly sampling the data with
350 replacement, was used to re-estimate the model 10,000 times. Coefficient means ($\bar{\beta}$), standard
351 errors (σ_{β}) and probabilities of inclusion for each regression coefficient were calculated following
352 bootstrap iterations. We considered “highly important” predictors to be those with coefficients
353 retained in at least 80% of the bootstrap iterations; “important” predictors to be coefficients
354 retained in 60 to 80 % of the iterations; and “moderately important” to be coefficients retained in
355 40 to 60% of the iterations. Elastic net log-linear regression coefficients were transformed into
356 percent changes in catch for a given change in the predictor variable using the following formula:
357 $\% \Delta y = 100 \cdot (e^{\beta \cdot \Delta x} - 1)$.

358 OLS models using either the full set of independent variables (OLS_all), using only TURF
359 related variables (OLS_TURF), using only geospatial context variables (OLS_Geo) or using only
360 variables selected by the elastic net model (OLS_elastic) were also run for comparison with the
361 elastic net outputs. P-values for the coefficients of each explanatory factor in the OLS models were
362 adjusted utilizing the Dunn-Šidák correction method for multiple statistical tests (Šidák 1967, Ury
363 1976). We considered the possibility of spatial heterogeneity in catch reporting by examining OLS
364 model residuals using Studentized Breusch-Pagan tests.

365

366 **3. Results**

367 *3.1 Regional description of the system*

368 We analyzed 196 fishing coves with a total of 478 functioning TURFs in this study.
369 Average TURF size was 1.5 km² (ranging from 0.01 km² to 39 km²). Average total TURF area per
370 fishing cove was 4 (± 7.3) km² while average OAA area per fishing cove was 82 (± 29) km². Limpet
371 and kelp catch in the northern regions (i.e., regions II, III, IV, V) accounted for 81.3% and 84.8%
372 of total national catch of each species group, respectively. Contrarily, 95.1% of sea urchin catch
373 and 77.6% of *loco* catch were landed in the southern regions (i.e., regions VIII, IX, XIV, X and
374 XI, Fig. 1, Appendix 3). The contrasting landing patterns were accompanied by differences in
375 TURFs' size. TURF average area per fishing cove was higher and more variable in southern
376 regions (4.9 ± 9.3 km²) than in the northern region (3.2 ± 3.1 km²), and OAA average sizes
377 associated with each fishing cove were larger in southern regions (90.5 ± 29.2 km²) than in northern
378 regions (58.0 ± 103.0 km²) (Table 2). The sizes of OAAs were consistently larger than those of
379 TURFs, however the ratio between OAA and TURF size was similar between the north and the
380 south. In terms of effort, the number of divers (or collectors) that could fish in OAAs was higher
381 than the number that could fish in TURFs, with this difference being larger for fishing coves in the
382 south (Table 2).

383

384 *3.2 Catch rate comparisons between TURFs and OAAs*

385 CPUE and CPUA values for 2015 for each fishing cove were compared by their origin, i.e.
386 inside or outside TURFs (Fig. 2). CPUEs for limpet were observed to be higher inside TURFs
387 ($p=0.01$). However, CPUEs were not significantly different between the two origins for kelp

388 (p=0.36) and sea urchin extraction (p=0.34), though their corresponding medians were higher
389 inside TURFs. For each of the three groups of species, CPUAs were significantly higher inside
390 TURFs (p=2.1 x 10⁻⁵ for limpet, p=5.4 x 10⁻⁶ for kelp, and p=1 x 10⁻³ for sea urchin). Overall,
391 median catch rates were at least 75% higher inside TURFs (Table 3). With regard to catch rate
392 values across species, limpet and red sea urchin were caught at similar rates in terms of metric
393 tonnes per month per unit effort/area, whereas kelp was caught at a much higher rate, and *loco* was
394 caught at an intermediate rate. Assuming perfect reporting within TURFs, equal catch rates
395 between TURFs and OAAs imply 70% to 99% of catch from OAAs would be unreported. Higher
396 catch rates observed in TURFs therefore appear to be robust to catch misreporting

397

398 *3.3 Temporal mixed effects analysis of area catch rates*

399 Linear mixed effects models revealed that CPUAs had decreased significantly over time
400 inside TURFs, with rates of decrease of 7.8%, 4%, and 4.8% per year for *loco*, limpet, and sea
401 urchin, respectively (p < 0.05, Table 4). For all species groups, CPUAs also significantly decreased
402 inside TURFs as the number of TURFs implemented in a fishing cove increased (between 10 and
403 29% decrease in CPUA per additional TURF implemented, p<0.05, Table 4). Effects of the
404 temporal driver *Year* were weaker in OAAs (Table 5). Only CPUAs for limpet significantly
405 decreased in OAAs over years (4.7% decrease in CPUA/year, p<0.05, Table 5). Interestingly,
406 CPUAs for kelp increased significantly outside of TURFs over time (3% increase per year, p=0.02,
407 Table 5) whereas there was no temporal trend inside TURFs. The number of TURFs did not have
408 any effect on CPUAs in OAAs for any of the species groups considered. Predicted values of
409 CPUAs inside TURFs from 2000 and 2015 were consistently higher than predicted values of
410 CPUAs within OAAs (Figure 3). When the models were restricted to just the subset of fishing

411 coves having a constant number of TURFs (i.e., model 2), CPUAs were found to decrease
412 significantly over time inside TURFs for *loco* (8.5% decrease per year), and outside TURFs for
413 limpet (2.5% decrease per year, $p < 0.05$, Tables 4 and 5). Differences between conditional r^2_c and
414 marginal r^2_m show that 40% to 80% of variability is due to spatial heterogeneity across fishing
415 coves (Tables 4 and 5).

416

417 *3.4 Elastic net regression of OAA catch*

418 *3.4.1 OLS and elastic net regressions comparison*

419 Catch of limpet, kelp, and sea urchin in OAAs were examined to resolve the effect of
420 TURFs on adjacent areas in 2015 (*loco* is not included in OLS and elastic net regressions since its
421 extraction is banned in OAAs). OLS models were inconclusive, yielding no significant predictors
422 of catches outside TURFs though a considerable proportion of the variances were explained
423 (adjusted $r^2 = 0.31$ for limpet, 0.55 for kelp, and 0.34 for sea urchin, Table 6). Geospatial variables
424 were found to explain a greater amount of variance than TURF variables in OLS models for all
425 species. Elastic net regression models explained similar proportions of variance as the OLS
426 models, but with fewer variables (adjusted $r^2 = 0.31$ for limpet, 0.55 for kelp, and 0.51 for sea
427 urchin, Table 6).

428

429 *3.4.2 Predictors selected by the elastic net regression of OAA catch*

430 Contrasting results from the elastic net regression model were found for the three groups
431 of species, with different predictors selected by the penalized model in explaining OAA catches
432 (Table 7). All “highly important predictors” retained to explain catch in OAAs for the three species
433 groups were related to the geospatial context. The predictor *Urban_Area* was selected in 83.69%

434 of the 10,000 bootstraps when modeling limpet catches and 99.73% of the bootstraps when
435 modeling kelp extraction, being the strongest identified driver of catch outside of TURFs in both
436 cases. This predictor exhibited a negative relationship with catches outside TURFs for both species
437 groups, with lower catches in the OAAs for limpet (33% decrease for coves within 50 km to urban
438 areas compared to those far from urban areas) and kelp (72% decrease) in fishing coves close to
439 urban areas. Additional predictors for catch of limpet outside TURFs included *Area_OAA*²
440 (selected in 60.35% of cases) and *Area_fraction* (selected in 41.86% of the bootstraps; definitions
441 of predictors in Table 1). There was a 0.08% reduction in limpet catch per 10 km² of additional
442 OAA area and a 1.5% reduction per 1% increase in the fraction of the total area that is TURF.

443 Several variables were found to be important predictors of kelp catches in OAAs. *Loco*
444 CPUEs inside TURF (*Loco_per_diver*) was a highly important, positive predictor of outside
445 catches of kelp and was included in 91.11% of the bootstraps (42% increase of kelp catch in OAAs
446 for every additional 1 mt catch of *loco* per diver within the TURF, with the average *loco* catch
447 being 0.46 mt *loco*/diver). Similarly, higher catch rates of kelp inside TURFs were associated with
448 higher catches of kelp outside (1.4% increase of kelp catch outside a TURF for every additional 1
449 mt catch of kelp per collector within the TURF, with the average kelp catch being 8.6 mt
450 kelp/collector). Counterintuitively, lower catches of kelp outside of TURFs were associated with
451 fishing coves that had larger OAAs (11% decrease in catch for every additional 10 km² of OAA
452 area; *Area_OAA* and *Area_OAA*² were selected in at least 80% of bootstraps). Lower catches of
453 kelp outside of TURFs were associated with fishing coves that had older TURFs (e.g., for every
454 year increase in *Age_TURF_max*, there is a ~8% decrease in catch; *Age_TURF_mean* and
455 *Age_TURF_max* were included in 73.03% and 84.40% of the bootstraps) and fishing coves with a
456 higher fraction of fishing grounds managed as TURFs (0.8% decrease for every 1% increase in the

457 fraction of area designated as TURFs; *Area_fraction* was selected in 47.36% of models). Finally,
458 lower catches of kelp in OAAs were observed in fishing coves with several fishers' organizations
459 (4.4% decrease for every additional organization). The model indicates that OAAs with higher
460 catches of kelp tended to be smaller, outside of urban centers, in areas with productive *loco*
461 fisheries, and have fewer, younger, and proportionately smaller proximate TURFs.

462 Higher catches of sea urchin in OAAs were associated with fishing coves that have longer
463 coastline lengths (13% increase in catch for every additional 10 km of coastline). This predictor
464 was highly important in explaining catch of sea urchin (selected in 98.98% of cases). A decrease
465 of sea urchin catch in OAAs was observed in fishing coves that had older TURFs (3% decrease in
466 catch for every additional year since TURF implementation). The related variables
467 *Age_TURF_max* and *Age_TURF_mean* were included in 47.3% and 47.0% of the bootstraps,
468 respectively.

469

470 **4. Discussion**

471 We evaluated temporal and spatial trends in catch and catch rates for TURFs and OAAs in
472 Chile. This study is the first to consider fishing coves all along the Chilean coast to understand the
473 TURF system in its entirety (TURFs and their surrounding areas) over two decades. Though
474 increased CPUEs inside of TURFs compared to OAAs has been demonstrated in previous
475 literature (Castilla and Fernández 1998, Gelcich et al. 2012, Defeo et al. 2016), most studies have
476 focused on small-scale projects in specific regions of the country. The most spatially extensive
477 study was based on a systematic literature review of the effects of TURFs on ecosystem services
478 in Chile considering 268 study sites all along the Chilean coast (Gelcich et al. 2019). It showed
479 that TURFs sustain biodiversity and all typologies of ecosystem services (i.e., supporting,

480 provisioning, regulating and cultural services), but stressed a lack of studies addressing potential
481 negative or unpredicted consequences of TURFs and a need to better understand changes over time
482 (Gelcich et al. 2019). Our study expands the scale of previous analyses, focusing on the comparison
483 between TURFs and OAAs, and shows that median catch rates (CPUAs and CPUEs) of benthic
484 resources were at least 75% higher inside TURFs than in surrounding areas. To the extent that
485 these catch rates are indicators of biomass, this result points out that Chilean TURFs appear to
486 align with their main objectives in 2015, i.e. “ensure the sustainability of artisanal fishing through
487 the assignment of natural banks” and “maintain and increase the biological productivity of benthic
488 resources”. However, our study also indicates that catch rates have been steadily declining within
489 TURFs and that TURFs may impact catch levels in surrounding OAAs, both of which are potential
490 risks to system sustainability.

491 Three possible mechanisms could produce higher CPUASs and CPUEs in TURFs: 1)
492 recovered biomass could have built up and improved catch rates within TURFs over time, 2)
493 TURFs could have been implemented in areas of better habitat and higher quality grounds, and/or
494 3) effort displacement following the implementation of TURFs could have degraded OAAs over
495 time. CPUAs and CPUEs of *loco*, keyhole limpet, kelp, and red sea urchin in TURFs and OAAs
496 were analyzed to investigate differences between areas and over time. Additionally, catch of
497 keyhole limpet, kelp, and red sea urchin in OAAs was investigated to resolve any impacts of
498 proximal TURFs. Our findings indicate that CPUAs and CPUEs are consistently larger inside
499 TURFs but that CPUAs have been decreasing in TURFs over time and also with the number of
500 TURFs implemented by fishing cove. Further, a weak negative impact of proximal TURFs on
501 catches in OAAs was also found. This evidence appears to provide the strongest support for the
502 hypothesis that TURFs were selectively implemented in the best fishing grounds since catch rates

503 are higher inside TURFs throughout our data, yet declining over time and with the addition of new
504 TURFs. Additionally, the small negative effect of proximal TURFs of OAA catches could result
505 from effort displacement and suggests management spillover. Declining catch rates over time
506 within TURFs does not appear to support the hypothesis that catch rates are improved in TURFs
507 due to a recovery of biomass. As we were only able to calculate CPUAs over time, this finding
508 could result from consistent reductions in effort. Nationally, however, the number of registered
509 divers has been constant while the number of collectors has increased over the last decade
510 (Appendix 6, Sernapesca 2015). It is not clear how average fishing effort by registered harvesters
511 (e.g., number of trips/harvester) may have changed over this period, and TURFs may now be used
512 less intensively. Interestingly, for some species, CPUAs were found to have been decreasing in
513 fishing coves that have had a constant number of TURF(s) for at least 10 years, indicating that the
514 observed temporal change in CPUA is not only due to selective implementation of TURFs, but
515 possibly due to changes in the local environment or the intensity of fishing effort.

516 Exogenous geospatial factors (e.g., coastline, OAA areas, urban areas) were the main
517 drivers explaining variability of catches in OAAs across fishing coves for 2015 (based on selection
518 in elastic net regressions and the greater amount of variance explained in the OLS analyses
519 including just these variables, Table 5). Geospatial predictors always had a higher percentage of
520 inclusion when compared to TURF management-related predictors (Table 6). The negative
521 relationship between catches of limpet and kelp in OAAs and proximity to urban centers could be
522 due to higher historical fishing pressure and deteriorated environments in more populated urban
523 areas. Additionally, catch of kelp, a lower value product, in OAAs could also be higher in rural
524 areas where there are fewer economic opportunities and thus lower opportunity costs for fishers.
525 Fishing coves with longer coastline lengths seem to support higher catches of sea urchin,

526 suggesting environmental factors related to coastline complexity may be the principal drivers for
527 sea urchin abundance and availability. The effect of TURFs on catches in OAAs was especially
528 weak for limpet and sea urchin (TURF-related predictors selected for 40 to 50% of bootstraps).
529 However, when predictors related to TURFs' characteristics and activity (i.e., time since TURF
530 registration or fisher organization implementation, and fraction of TURF area) were retained in
531 the models, they consistently displayed a negative relationship with OAA catches.

532 Several aspects of the Chilean TURF system and available data are worth mentioning to
533 provide additional context and inform interpretation of results. First, this study only considered
534 fishing coves with at least one functioning TURF (operative or stand by) in 2016. Gelcich et al.
535 (2017) revealed that about 40% of TURFs are inactive or currently abandoned in Chile. TURFs
536 that have been abandoned would have increased OAAs, inferring that C_{PUA} values could be lower
537 in OAAs than actually observed (but possibly higher within TURFs). Second, it is possible that
538 temporal dynamics and interactions between TURFs and OAAs may have changed over time. Our
539 analysis began in 2000, however TURF management commenced in the early 1990s and
540 approximately 18% of the TURFs considered here were initiated prior to 2000. Further analysis
541 and investigation are needed to determine temporal changes and management interactions during
542 the first decade of TURF management. Finally, TURFs are a management tool typically used to
543 achieve sustainable fisheries and resource extraction within their boundaries (Christy 1982,
544 Aceves-Bueno and Halpern 2018), though it is possible that some TURFs in Chile are maintained
545 today for non-extractive purposes. For example, Chilean TURFs have been argued to build
546 leadership and social cohesion among fishers (Rosas et al. 2014, Gelcich et al. 2019) and may offer
547 benefits for conservation or restoration of benthic habitats (Gelcich et al. 2008a, Blanco et al. 2017,

548 Fernández et al. 2017). Non-extractive social or ecological benefits arising from maintained
549 TURFs in Chile are not considered here but are important areas for future research.

550 While this analysis was able to discern broad temporal and spatial trends by evaluating
551 catch and catch rates across 196 fishing coves over two decades, the available data was generally
552 coarse and requires consideration for potential biases. Recent studies have shown that misreporting
553 can be a problem in officially reported catches (Oyanedel et al. 2017, Ruano-Chamorro et al.
554 2017), particularly with respect to *locos* (official catch is thought to only account for 14-30% of
555 total *loco* extraction in Chile). As this research was primarily focused on relative trends and
556 comparisons among catch and catch rates in OAAs and TURFs, misreporting was considered to
557 only be problematic if it were non-uniform over space or time or differing between TURFs and
558 OAAs. We examined the possibility of spatial heterogeneity in catch reporting by examining OLS
559 model residuals using Studentized Breusch-Pagan tests and found no evidence of heterogeneous
560 error variances across observations ($p > 0.05$, Appendix 7). Additionally, higher catch rates
561 observed in TURFs appeared to be robust to catch misreporting. Estimation of OAAs and fishing
562 effort were based on a number of assumptions regarding fishing behavior. The negative
563 relationship found between catches of kelp and limpet and OAA size appears counterintuitive:
564 higher catches outside of TURFs were observed in fishing coves with smaller OAAs. It is possible
565 that total fishing ground boundaries based on average travel distance (Ruano-Chamorro et al.
566 2017) and bathymetry were too liberal and thus OAA areas were over-estimated in some instances
567 (e.g., coastline complexity and wave exposure might limit sailing of small boats and the effective
568 fishing area). Future research could incorporate fishers' mobility among proximal fishing coves in
569 fishing effort estimates, though it would require extensive field studies to determine the
570 appropriate spatial range of effort. Finally, though CPUE values were found to be lower in OAAs,

571 this metric relies on a crude estimate of effort as information on the number of trips or dive
572 durations was not available. Nevertheless, consistency between CPUE and CPUA measures
573 (metrics were found to be positively correlated in all areas) suggests that our CPUE values were a
574 reasonable reflection of catch rates around fishing coves.

575 Various factors related to local governance could further explain low CPUAs and CPUEs
576 observed in OAAs as well as the decrease of CPUAs observed over time. Such variables could
577 include leadership, organizations' degree of cooperation, government support and governance
578 network structure. A social-ecological-system framework (Ostrom 2007) was found to be useful
579 for examining these variables and associated institutional regimes in Mexico and Costa Rica
580 (Basurto et al. 2013, García Lozano and Heinen 2016). This type of analysis would require
581 extensive fieldwork, and, therefore, the spatial scale of such analysis would likely be considerably
582 smaller than that used in this study. Nevertheless, application of such an approach to the Chilean
583 context represents an important avenue for future work that could enhance our understanding of
584 the interaction between institutional factors and successful TURFs-based fisheries management.

585 Many countries are transitioning marine resource management from common property
586 systems towards rights-based approaches (e.g., individual transferable quotas, catch shares, or
587 TURFs), driven by concerns related to sustainability and resource stewardship (Orensanz et al.
588 2005, Nguyen Thi Quinh et al. 2017). Although the influence of MPAs on surrounding areas and
589 fisheries sustainability are now well known, enhancing biomass through larval export and adult
590 spillover (Gell and Roberts 2003, Harrison et al. 2012) or negatively impacting surrounding
591 unprotected waters through “fishery squeeze” and/or “fishing the line” behavior (Kellner et al.
592 2007, Caveen et al. 2014, Abbott and Haynie 2012), the impacts of TURFs on surrounding areas
593 have been poorly documented. This study contributes to a better understanding of management

594 spillover between TURFs and OAAs. Whereas the impacts of TURFs appeared weak in this study,
595 possibly growing over time given the negative relationship with TURF age variables, CPUEs and
596 CPUAs were significantly lower in OAAs. This finding suggests that OAAs, whose total area is
597 more than 50 times larger than grounds currently managed as TURFs, may be substantially
598 degraded and overfished. Several authors have suggested that resources in OAAs might be heavily
599 exploited and even depleted (González et al. 2006, Orensanz and Parma 2010, Andreu-Cazenave
600 et al. 2017, de Juan et al. 2017, Oyanedel et al. 2017, Ruano-Chamorro et al. 2017). Interestingly,
601 our results do not show significant temporal declines in OAA CPUAs, suggesting either shifts in
602 effort over time or that OAAs were depleted prior to 2000. The research presented here suggests
603 that TURFs could place additional burden on already heavily fished OAAs. The current fisheries
604 management regime in Chile includes limited assessment or monitoring of OAAs. It appears
605 important that more attention be focused on OAAs, and on the system as a whole. By knowing
606 that TURFs affect fisheries in OAAs, stocks outside managed areas may be more effectively
607 controlled, provided that existing harvest controls outside of TURFs (i.e., bans, minimum legal
608 size) are better enforced.

609 The Chilean TURF network is the largest worldwide, has been extensively studied and
610 may, therefore, provide useful guidance for countries or regions transitioning toward rights-based
611 approaches. For example, many Latin America countries have similar spatial management policies
612 for small-scale fisheries (Mexico, Brazil, Costa Rica, Ecuador, Galapagos) and also share similar
613 capacities for enforcement, dependence on a few high-value benthic species, extended OAAs, and
614 co-management regimes (da Silva 2004, Beitzl 2011, Defeo et al. 2016, Garcia Lozano and Heinen
615 2016). Determining whether or not unintended impacts of TURFs on OAAs, similar to those found
616 here, exist in these regions is an important area for future research.

617

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630

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838

839 **Tables**

840

841 Table 1. Response variable and predictor abbreviations and definitions for the elastic net model.

Variable	Definition
Y	Log-transformed, centered catches for species <i>s</i> in OAA areas per fishing cove (mt)
Age_TURF_mean	Average time since the different TURFs implementation per fishing cove (yr)
Age_TURF_max	Maximum time since the oldest TURF implemented per fishing cove (yr)
Age_Organization_mean	Average time since the different fishers' organizations implementation per fishing cove (yr)
Age_Organization_max	Maximum time since the oldest fishers' organization implemented per fishing cove (yr)
N_TURF	Number of TURFs per fishing cove
N_ORG	Number of fishers' organizations per fishing cove
Area_OAA	Open access areas per fishing cove (km ²)
Area_OAA ²	Open access areas per fishing cove (km ⁴)
Area_Fraction	TURF areas divided by total fishing ground (TURF areas + OAA areas) (%)
Harvesters_All	Outside effort, or all licensed divers (or collectors) per fishing cove (divers or collectors)
Harvesters_per_OAA	Outside effort divided by the OAA areas per fishing cove (km ⁻²)
Harvesters_per_TURF	Inside effort divided by the TURF areas per fishing cove (km ⁻²)
Limpet_per_diver	Catches of limpet inside TURF divided by inside effort (mt /diver)
Kelp_per_collector	Catches of kelp inside TURF divided by inside effort (mt /diver)
Urchin_per_diver	Catches of sea urchin inside TURF divided by inside effort (mt /diver)
Loco_per_diver	Catches of <i>loco</i> inside TURF divided by inside effort (mt /collector)
Coastline_length	Length of coast adjacent to the fishing cove (km)
Landings_port	Total landings (algae, fish, mollusk, crustacean, other) of fishing port(s) within 50 km, if any (mt)
Urban_area	Fishing cove is within 50km to one of the ten biggest cities ^a (1 0)

^a Antofagasta, Arica, Concepcion, Iquique, Puerto Montt, Punta Arenas, San Antonio, Serena, Valdivia, Valparaiso.

843 Table 2. Average size of TURFs and OAAs with associated average harvesters effort for fishing
 844 coves considered in each region. Standard deviations are indicated in parentheses. Northern
 845 regions consist of regions II, III, IV, V while southern regions include regions VIII, IX, XIV, X
 846 and XI. The number of fishing coves included for each region is given by N.

Region	TURF		OPEN-ACCESS AREA	
	Area (km ²)	Effort (individual)	Area (km ²)	Effort (individual)
Northern <i>N=63</i>	3.2 (±3.1)	25.1 (±25.4)	60.8 (±16.5)	33.1 (±34.5)
Southern <i>N=114</i>	4.9 (±9.3)	37.0 (±57.1)	90.5 (±29.2)	58.0 (±103.0)

847

848

849 Table 3. 2015 median catch rates (i.e., catch per unit of effort and catch per unit of area) from
 850 inside TURFs and OAAs (i.e., outside TURFs) for each of the four species groups. CPUE is
 851 given in mt/month/harvester. CPUA is given in mt/month/km². % Diff. is the percentage
 852 difference between median catch rates from the two areas.

	Loco	Limpet			Kelp			Sea urchin		
	Inside	Inside	Outside	% Diff.	Inside	Outside	% Diff.	Inside	Outside	% Diff.
CPUE	0.13	0.04	0.01	75.00	0.66	0.16	75.75	0.07	0.01	85.71
CPUA	1.09	0.36	0.001	99.72	12.85	0.39	96.96	0.49	0.01	97.96

853

854 Table 4. Results of the linear mixed effect models estimating log-transformed CPUAs for *loco*,
855 limpet, kelp, and sea urchin inside TURFs. Model 2 only considers a subsample of fishing coves
856 that have a constant number of TURF(s) for at least ten years. Significance is denoted by:
857 $p < 0.001 = '***'$, $p < 0.01 = '**'$, $p < 0.05 = '*'$, $p < 0.1 = '.'$. Coefficients were transformed in the text
858 into percent changes in CPUA for a given change in the predictor variable using the following
859 formula: $\% \Delta y = 100 \cdot (e^{\beta \Delta x} - 1)$. Marginal and conditional coefficients of determination are
860 respectively given by r_m^2 and r_c^2 . Number of observations and number of fishing coves included
861 for each model are respectively given by n and N .

Model	Predictor	Loco		Limpet		Kelp		Sea urchin	
		Coeff.	p-value	Coeff.	p-value	Coeff.	p-value	Coeff.	p-value
1	Intercept	1.19	1.23E-19 ***	0.37	0.01 *	3.63	5.32E-18 ***	0.82	0.01 *
	Year	-0.08	3.46E-25 ***	-0.04	2.80E-4 ***	-0.02	0.45	-0.05	0.03 *
	N_{TURF}	-0.11	1.19E-4 ***	-0.29	3.07E-10 ***	-0.34	4.31E-7 ***	-0.22	4.10E-3 **
	r_m^2	0.10		0.22		0.25		0.12	
	r_c^2	0.68		0.64		0.65		0.72	
	n	1,077		473		203		220	
	N	138		78		49		50	
2	Intercept	178.18	2.47E-13 ***	21.22	0.49	138.30	0.16	53.13	0.53
	Year	-0.09	2.71E-13 ***	-0.01	0.49	-0.07	0.17	-0.03	0.53
	r_m^2	0.08		1.38E-3		0.03		2.81E-3	
	r_c^2	0.59		0.63		0.43		0.67	
	n	372		160		52		65	
	N	49		31		13		16	

862

863 Table 5. Results of the linear mixed effect models estimating log-transformed CPUAs for limpet,
864 kelp, and sea urchin outside TURFs (OAAs). There is no result for *loco* as it is not exploited in
865 OAAs. Model 2 only considers a subsample of fishing coves that have a constant number of
866 TURF(s) for at least ten years. Significance is denoted by: $p < 0.001 = '***'$, $p < 0.01 = '**'$,
867 $p < 0.05 = '*'$, $p < 0.1 = '.'$. Coefficients were transformed in the text into percent changes in CPUA
868 for a given change in the predictor variable using the following formula: $\% \Delta y = 100 \cdot$
869 $(e^{\beta \Delta x} - 1)$. Marginal and conditional coefficients of determination are respectively given by r_m^2
870 and r_c^2 . Number of observations and number of fishing coves included for each model are
871 respectively given by n and N .

Model	Predictor	Limpet		Kelp		Sea urchin	
		Coeff.	p-value	Coeff.	p-value	Coeff.	p-value
1	Intercept	-5.87	1.40E-16 ***	-2.63	8.03E-19 ***	-5.23	2.48E-16 ***
	Year	-0.05	4.57E-9 ***	0.03	0.03*	-8.01E-3	0.41
	N _{TURF}	0.02	0.61	-0.03	0.66	6.87E-3	0.85
	r_m^2	0.01		2.21E-3		2.33E-4	
	r_c^2	0.60		0.81		0.75	
	n	1,433		933		1,155	
	N	179		148		161	
2	Intercept	44.93	0.05*	4.49	0.92	-23.49	0.45
	Year	-0.03	0.02*	-3.01E-3	0.89	8.82E-3	0.57
	r_m^2	4.84E-3		2.59E-5		3.29E-4	
	r_c^2	0.55		0.65		0.66	
	n	534		336		394	
	N	54		49		52	

872

873 Table 6. Change in OLS variance explained with specific variables: OLS_all includes all initial
 874 predictors, OLS_TURF includes only TURF related predictors, OLS_Geo includes only
 875 geospatial context predictors and OLS_elastic includes only predictors selected by the elastic net
 876 model.

		OLS_all	OLS_TURF	OLS_Geo	OLS_elastic
Limpet	Adj.r ²	0.31	0.12	0.25	0.31
	r ²	0.54	0.28	0.37	0.36
Kelp	Adj.r ²	0.55	0.26	0.42	0.55
	r ²	0.71	0.40	0.52	0.65
Sea Urchin	Adj.r ²	0.34	0.33	0.40	0.51
	r ²	0.70	0.52	0.55	0.58

877

878 Table 7. Results of the elastic net regression model estimating catches for limpet, sea urchin and
879 kelp outside the TURFs according to λ_{\min} , the value that minimizes the cross-validation MSE
880 which yields the most accurate model. Only predictors that were selected for at least 40% of the
881 10,000 bootstraps are shown in this table and they are ranked according to their importance (i.e.,
882 higher percentage of inclusion in the model). Elastic net mean coefficients were returned on the
883 original scale here but they were transformed in the text into percent changes in catch for a given
884 change in the predictor variable using the following formula: $\% \Delta y = 100 \cdot (e^{\beta \Delta x} - 1)$. OLS
885 normalized coefficients are unitless. Number of observations for each model is given with n.

	Predictor	% inclusion	Sign	Elastic net coefficient	OLS normalized coefficient
Limpet <i>n=54</i>	Divers_All ^a	100	+	0.02	0.99
	Urban_Area	83.69	-	0.40	0.50
	Area_OAA ²	60.35	-	8.15E-5	0.58
	Area_fraction	41.86	-	0.02	0.72
Kelp <i>n=54</i>	Collectors_All ^a	100	+	2.31E-3	0.93
	Urban_Area	99.73	-	1.28	0.63
	Loco_per_diver	91.11	+	0.35	0.47
	Area_OAA	90.48	-	0.01	0.51
	Area_OAA ²	84.77	-	1.03E-4	2.10E-3
	Age_TURF_max	84.40	-	0.08	0.16
	Kelp_per_collector	78	+	0.01	0.29
	Age_TURF	73.03	-	0.05	0.33
	Age_Organization_max	59.74	-	0.07	0.16
	Area_fraction	47.36	-	7.53E-3	0.18
N_ORG	41.80	-	0.05	0.48	
Sea	Divers_All ^a	100	+	0.01	1.37
Urchin	Coastline_length	99.67	+	0.01	1.86

<i>n=36</i>	Limpet_per_diver	62.45	-	4.84 ^b	0.48
	Age_TURF_max	47.34	-	0.04	0.56
	Age_TURF	46.96	-	0.03	0.02

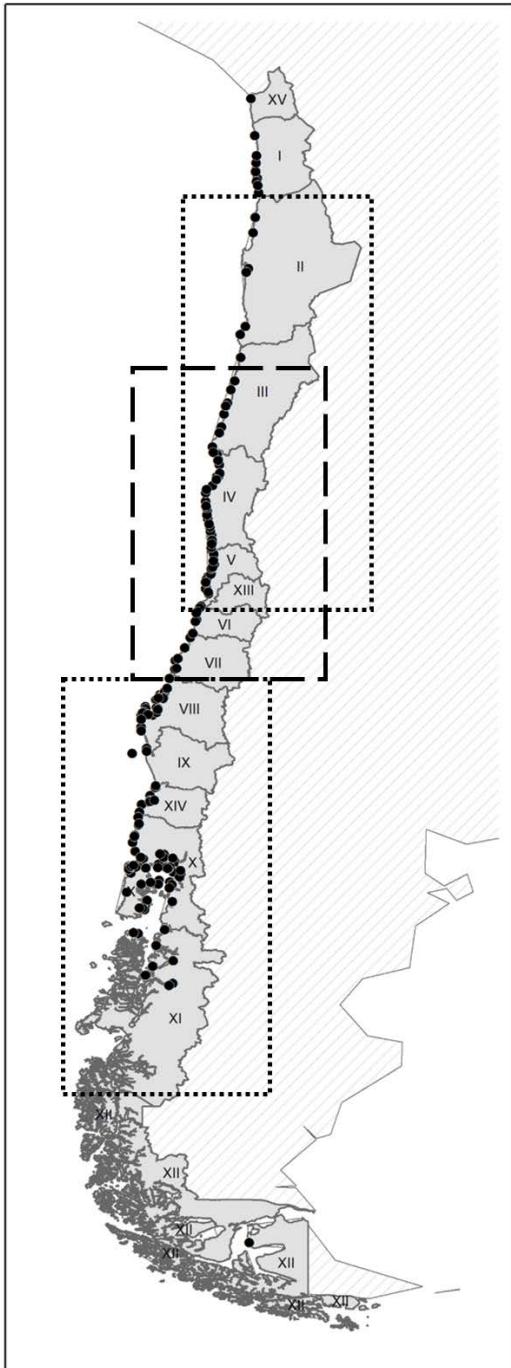
886

887 ^a The shrinkage penalty was set to 0 for the variable Divers_All and Collectors_All (instead of 1
888 for other variables), forcing this variable to be included in the model.

889 ^b This large effect is driven by two outliers. Removing this predictor did not change qualitatively
890 the results.

891

892 **Figures**

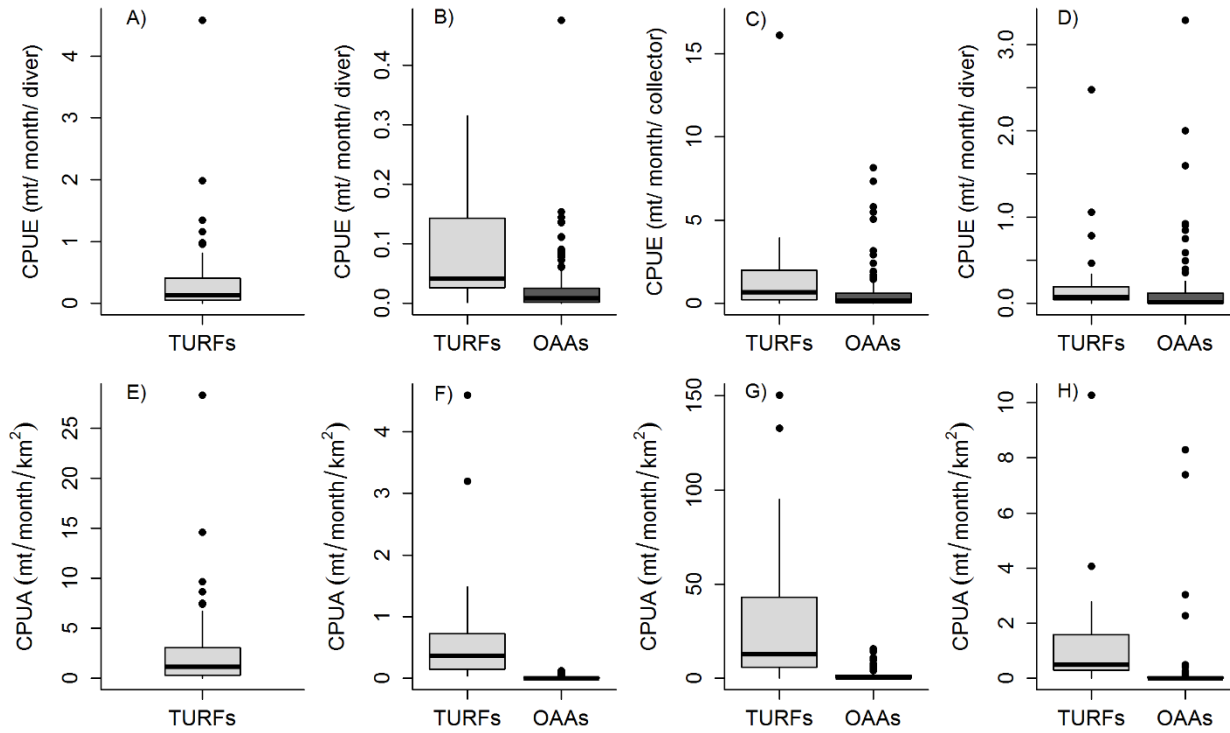


893

894 Figure 1. Administrative regions of Chile. Fishing coves included in the comparison of 2015 catch
 895 rates and mixed effect models are represented with the black dots. The elastic net regressions only
 896 consider fishing coves within the northern regions II, III, IV, V and within the southern regions

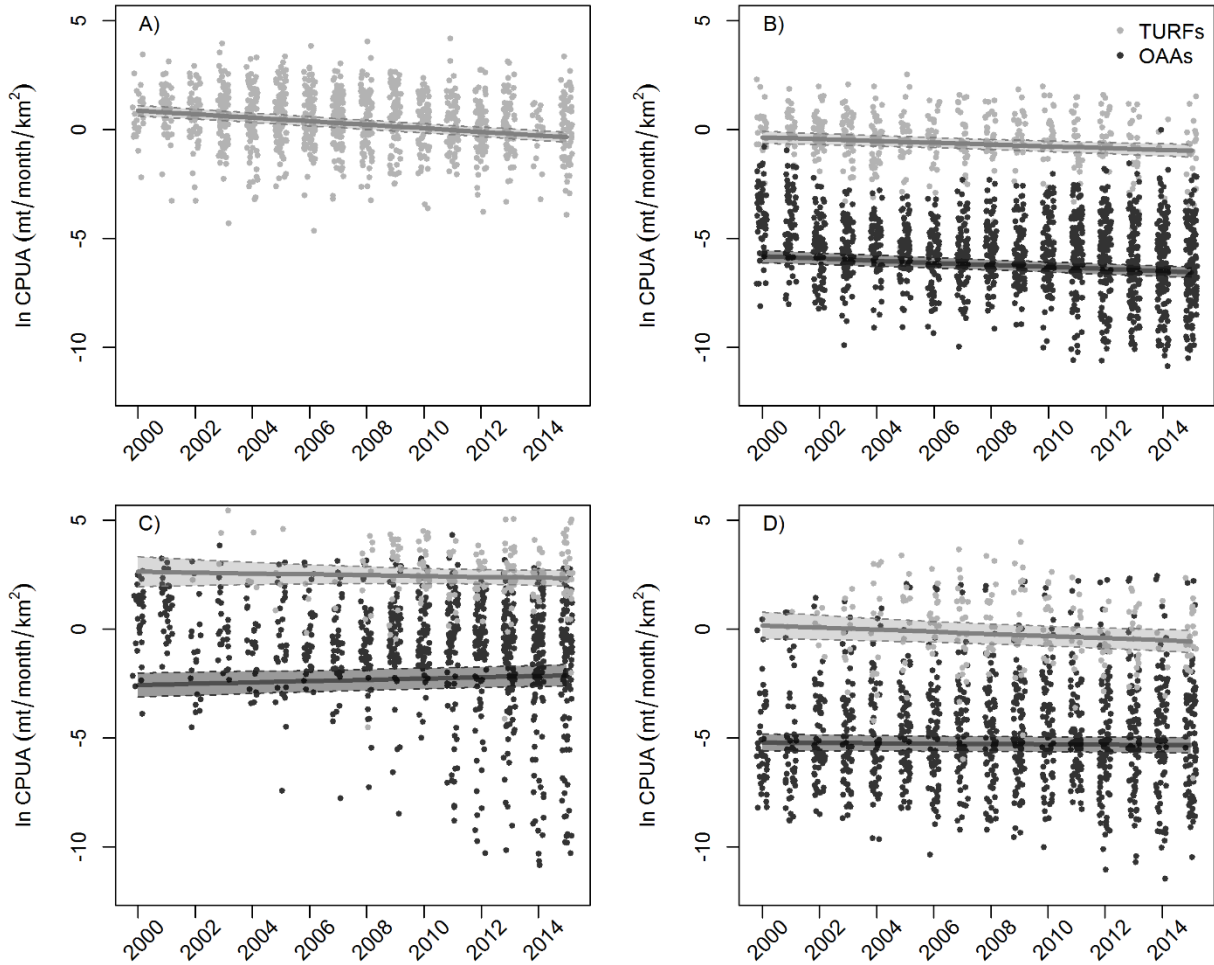
897 VIII, IX, XIV, X and XI (dotted rectangles). The 20 m isobaths layer was only available from
898 central Chile (dashed rectangle from 27° to 36°).

899



901 Figure 2. Boxplots of 2015 CPUEs (A, B, C, D) and CPUAs (E, F, G, H) for the four species *loco*
 902 (A,E) keyhole limpet (B, F), kelp (C, G), and red sea urchin (D, H) by fishing coves, differentiated
 903 by catch origin inside or outside TURFs (i.e. OAA). *Loco*'s extraction is banned in OAAs.

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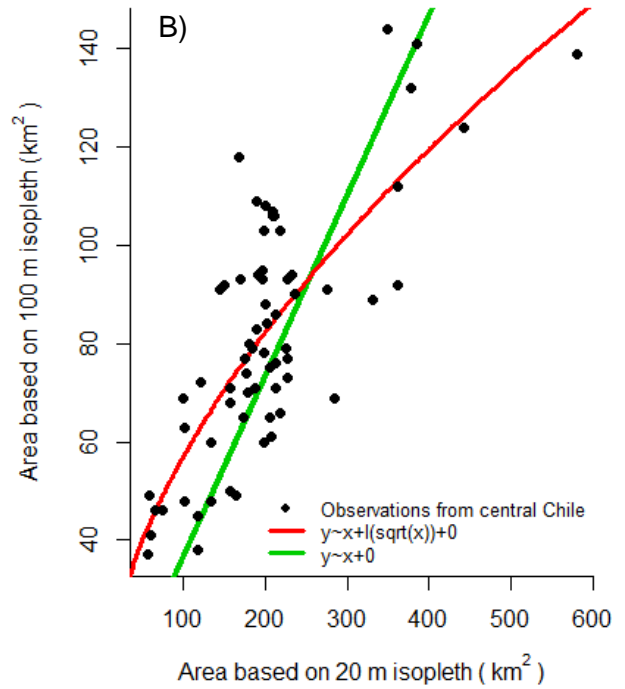
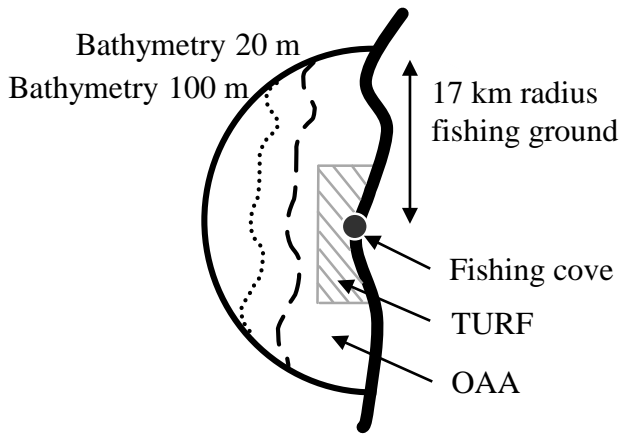
906 Figure 3. Observed catch per unit of area (mt/ month/ km^2) values for the four species *loco* (A),
 907 keyhole limpet (B), kelp (C), and red sea urchin (D) used in the mixed effect models. Light grey
 908 dots are CPUAs from inside TURFs, dark grey dots are CPUAs from OAAs. Predicted value and
 909 standard errors for a given year is given by the straight line and shaded area.

Appendices

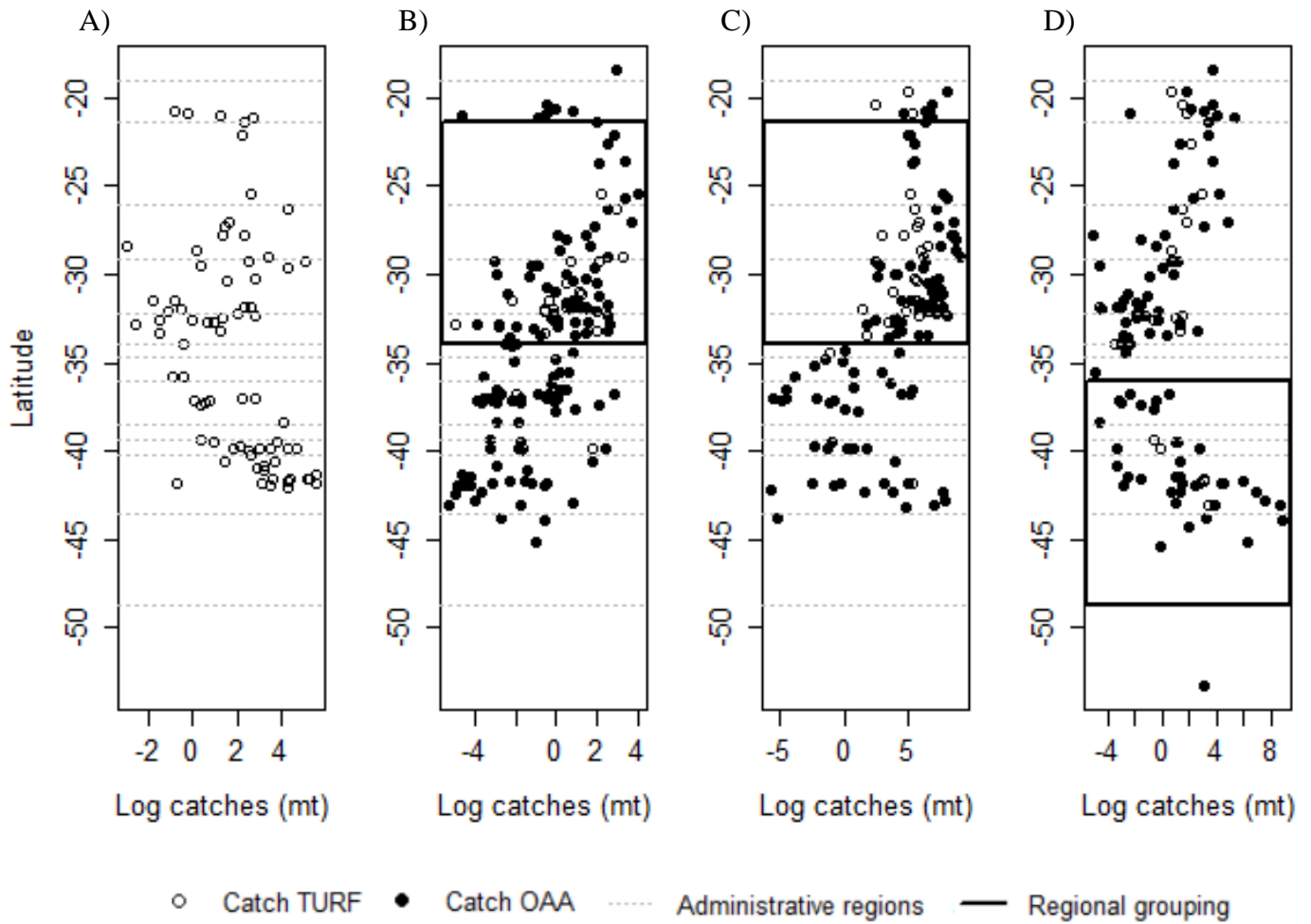
A1. TURFs status in Chile in 2017.

TURF status		Definition	Count
Designated with a public decree in force	Assigned to a fisher organization	Operative and designated TURFs with a baseline study, an approved management plan, a use agreement and a TAC in place.	391
		In stand-by TURF for which monitoring has not been conducted by the due date. However, there was a quota assigned in the last 4 years.	221
	Rejected	TURFs without an assigned fishing association (include a change in organizations and rejected application).	4
	Available for assignment	Designated TURFs that are not assigned to a fishing organization yet or the organization has not complied with necessary initial baseline studies.	164
	Disaffected	TURFs that returned to an open access regime because fishers organizations have not met the requirements (reports, management plans).	1
In evaluation		TURFs without a public decree in force, in process of consultation before the establishment of the availability decree.	297
Rejected		TURFs that have followed the consultation process but have been rejected for various reasons (economic or environmental).	234

A)



A2. A) Total fishing grounds (comprising TURFs and OAAs) were created per fishing cove based on sailing time and bathymetry. The offshore width of these polygons was based on a typical maximum harvest depth of 20 m (dashed line) extrapolated for the whole coast from a 100 m isobaths layer (dotted line, source GEBCO). Estimates of OAA areas were calculated as fishing ground areas minus assigned TURFs areas (grey striped area). B) Fishing ground area based on bathymetry 20 m in function of fishing ground area based on bathymetry 100 m according to the relationship $y = x + \sqrt{x} + 0$ (red line) that fits better than the relationship $y = x + 0$ (green line).



A3. Log catches (mt) per fishing coves as a function of latitude for each group of species: *loco* (A), keyhole limpet (B), kelp (C), and red sea urchin (D) and differentiated by their origin, i.e., catches inside TURFs (white dots) or from the OAA (black dots). Dashed lines represent the delimitations of the 15 administrative regions of Chile. Black boxes represent regional grouping of important regions for each fishery.

A4. Elastic net model development

Given a linear regression model with p predictors, the elastic net solves this regularization problem:

$$\min_{\beta_0, \beta} \left(\frac{1}{2N_s} \sum_{i=1}^{N_s} (y_{i,s} - \beta_{0,s} - x_{i,s}^T \beta_{p,s})^2 + \lambda P_\alpha(\beta_{p,s}) \right), \quad (1)$$

Where

$$P_\alpha(\beta_{p,s}) = \frac{(1-\alpha)}{2} \|\beta_{p,s}\|_2^2 + \alpha \|\beta_{p,s}\|_1 = \sum_{j=1}^p \left(\frac{(1-\alpha)}{2} \beta_j^2 + \alpha |\beta_j| \right). \quad (2)$$

In (1), $y_{i,s}$ is the response, here catches of species s in the open access area at fishing cove i ; N_s is the number of fishing coves with catches from OAAs for species s ; $x_{i,s}$ is explanatory data, a vector of p values for species s at fishing cove i ; $\beta_{p,s}$ is the for species s ; λ is a positive regularization parameter; and α is the elastic net penalty. The coefficient for each p predictor elastic net minimizes the sum of squared differences between observed and predicted values subject to a constraint, $P_\alpha(\beta)$, that penalizes for model complexity as well as for large absolute values of normalized coefficients (Equations 1, 2). The form of the penalty is controlled by the parameter α . With $\alpha=0$, coefficients of correlated predictors shrink towards each other. With $\alpha=1$, the most influential correlated predictor is selected while others are discarded. The elastic net sets α to 0.5, which leads to selection of groups of predictors that independently or jointly explain variance (Equation 2, Zou and Hastie 2005, Friedman et al. 2010). Separate penalty factors can be applied to each coefficient to allow different shrinkage. In our case, the penalty factors were considered equal for all variables except for the variable *Harvesters_all* (representing the total number of harvesters), for which the penalty was set to 0 so that this variable was always included in the model. The optimal value of the regularization parameter λ , which controlled the strength of the penalty, was selected using a 10-fold cross-validation method. Two different values of λ were considered: the value that minimized the cross-validation mean squared error (MSE) (λ_{\min}), and the maximum value within one standard error of the λ_{\min} (λ_{1SE}). The more restrictive regularization with λ_{1SE} (i.e., the larger penalty that leads to models with smaller or fewer parameter values) yields a simpler model while maintaining a level of accuracy found to be close to that obtained when using λ_{\min} (Hastie et al. 2009). The cross-validation process, which randomly selects training data and returns new values for λ_{1SE} and λ_{\min} at each iteration, was repeated 1,000 times and the final model used average values for λ_{1SE} and λ_{\min} .

A5. Elastic net model results with λ_{1SE}

Results of the elastic net regression model estimating catches for limpet, sea urchin and kelp outside the TURFs according to λ_{1SE} , the maximum value within one standard error of the λ_{min} which yields the most restrictive model. Only predictors that were selected for at least 40% of the 10,000 bootstraps are shown in this table and they are ranked according to their importance (i.e., higher percentage of inclusion in the model). Elastic net mean coefficients were returned on the original scale here but were transformed in the text into percent changes in catch for a given change in the predictor variable using the following formula: $\% \Delta = 100 \cdot (\beta_{\Delta} - 1)$. OLS normalized coefficients are unitless.

	Non-null predictor	% inclusion	Sign	Elastic net coefficient	OLS normalized coefficient
Limpet	Divers_All ^a	100	+	0.021	0.661
	Urban_Area	41.43	-	0.100	0.644
Kelp	Collectors_All ^a	100	+	0.002	0.448
	Urban_Area	99.49	-	0.976	0.860
	Area_OAA	86.25	-	0.006	0.435
	Area_OAA ²	85.89	-	7.68E-5	0.025
	Age_TURF_mean	67.20	-	0.031	0.181
	Age_TURF_max	51.78	-	0.025	0.324
Sea	Divers_All ^a	100	+	0.011	1.231
Urchin	Coastline_length	98.98	+	0.006	2.087

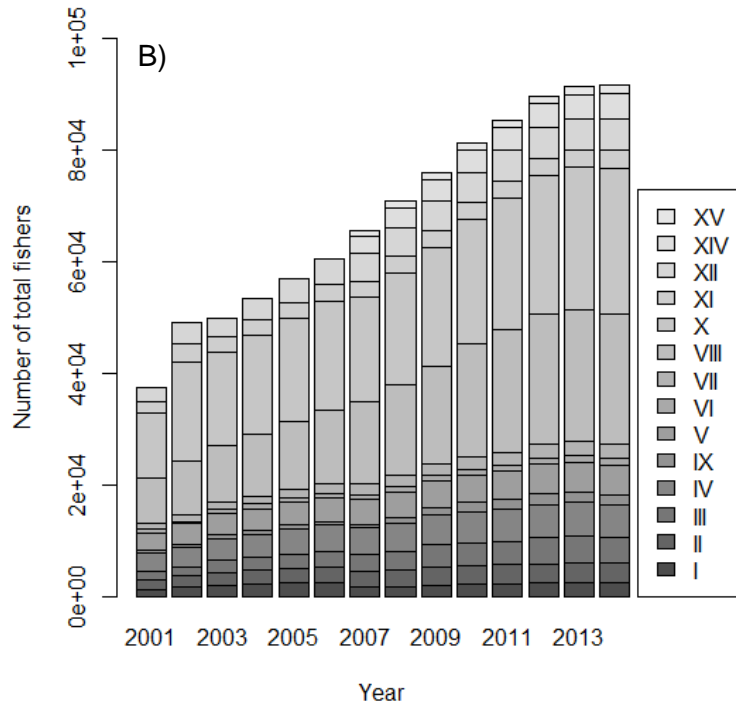
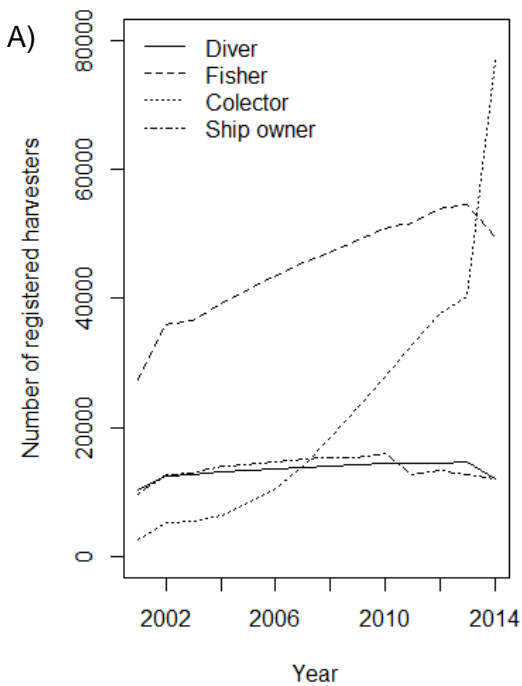
^a The shrinkage penalty was set to 0 for the variable Divers_All and Collectors_All (instead of 1 for other variables), forcing this variable to be included in the model.

A5. Elastic net model results with λ_{1SE}

For the most restrictive models using the regularization parameter λ_{1SE} , most of the predictors retained to explain catch in OAAs were related to the geospatial context. The predictor *Urban_Area* was selected in 41.30% of the 10,000 bootstraps when modeling limpet catches and 99.49% of the bootstraps when modeling kelp extraction, being the strongest identified driver of catch outside of TURFs in both cases. This predictor exhibited a negative relationship with catches outside TURFs for both species groups, with lower catches in OAAs for limpet (10% decrease) and kelp (165% decrease) close to urban areas.

No other predictors were selected for limpet, whereas several predictors related to OAA and time since TURF implementation were selected for kelp. Lower catches of kelp outside of TURFs were counterintuitively associated with fishing coves that had larger OAA areas (6% decrease in catch for every additional 10 km² of OAA area). *Area_OAA* and *Area_OAA*² were selected in at least 80% of bootstraps and were considered to be highly important drivers for kelp catch outside of TURFs. Moderately lower catches of kelp outside of TURFs (3% decrease) were associated with fishing coves that had older TURFs. The related variables *Age_TURF_mean* and *Age_TURF_max* were included in 67.2% and 51.78% of the bootstraps, respectively.

Higher catches of sea urchin in OAAs were associated with fishing coves that have longer coastline lengths (6% increase in catch for every additional 10 km of coastline). This predictor was the only additional factor selected for explaining sea urchin catches in OAAs (selected in 98.98% of cases).



A6. A) Number of active licensed harvesters over time according to the different categories with the solid line representing number of divers for loco, limpet and sea urchin exploitation and the dotted line representing the number of collectors mainly for kelp extraction. The different categories are not mutually exclusive. Licensed harvesters can exploit the open-access area but are not necessarily granted TURF access. B) Total number of licensed harvesters per regions and per year.

A7. Test of heteroscedasticity using the Studentized Breusch-Pagan test from the OLS output considering all initial predictors. P-values < 0.05 indicate heteroscedasticity of the OLS residuals.

Species	All predictors
Limpet	p=0.35
Kelp	p=0.83
Sea urchin	p=0.97
