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Drivers and trends in catch of benthic resources in Chilean TURFs and surrounding open access areas

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2   **Access Areas.**

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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

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1. Introduction

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

In Chile, the implementation of TURFs was a reaction to the collapse of the economically important artisanal fishery for the muricid snail *Concholepas concholepas* in the 1980s (known in Chile as *loco,* elsewhere as the false abalone) (Bernal et al. 1999). The fast recovery of the high valued *loco* stocks in initial TURFs increased demand for further TURF development along the entire Chilean coast throughout the 2000s. In 2017, there were 957 officially designated Chilean TURFs implemented as part of a national TURF policy (Fishery and Aquaculture Law n° 18, 1991). According to the Chilean Fisheries Authorities, the primary objectives of Chilean TURFs are to "ensure the sustainability of artisanal fishing through the assignment of natural banks", and to "maintain and increase the biological productivity of benthic resources" (SUBPESCA, 2003). This TURF network constitutes the dominant form of spatial management of benthic resources in Chile and is the largest worldwide, covering about 1,500 km^2 (though only about half of these 957 TURFs are currently operative). Known in Chile as "Área de Manejo y Explotaciones de Recursos Bentónicos" (Management Areas for the Exploitation of Benthic Resources; AMERB), this system grants exclusive fishing rights to legally constituted fishing organizations for the exploitation of benthic resources in defined portions of the seabed – usually adjacent to a *caleta* or artisanal fishing cove (Aburto et al. 2013). Each TURF has species-specific quotas proposed by the fishing organization and approved by the Undersecretary of Fisheries. Artisanal fisher organizations have to comply with a series of regulations, such as establishing a baseline study, management plan, and regular stock assessments, for which they have to contract technical assistance from specialized environmental and/or fisheries consultants (Gelcich et al. 2008b). TURFs are interspaced with open access areas (OAAs) where seasonal closures and limits on catch size are used, but entry, within-season effort, and total catch are not restricted. The Chilean TURFs system was initially (i.e., from the 1990s to the 2000s) successful and associated with positive ecological

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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

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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 CPUA over time may reflect changes in biomass,

256 changes in fishing effort, or changes in spatial management. If biomass were improving inside

257 TURFs, CPUAs in these areas might be expected to increase over time. Conversely, if TURFs

258 displaced fishing effort into OAAs, CPUAs 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 (Wilen et al. 2012), then

262 fishing coves with multiple TURFs might experience sequential reductions in CPUAs. Finally, as

263 catch depends on effort, it is also possible that changes in CPUA reflect changes in fishing effort

264 over time (e.g., CPUA 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 CPUAs inside and outside TURFs:

$$ln\left(CPUA_{s,i,t,a}\right) = \beta_1 year_t + \ \beta_2 N_{TURF_{i,t}} + \delta_i + \varepsilon_{s,i,t,a} \qquad (1)$$

268 In (1), the dependent variable is the log-transformed CPUA 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

13

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 $\%\Delta y = 100 \cdot \left(e^{\beta \cdot \Delta x} - 1\right).$

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

3. Results

3.1 Regional description of the system

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

3.2 Catch rate comparisons between TURFs and OAAs

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

17

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

18

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 km^2 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 km^2 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 CPUA 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, Beitl 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

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 s 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 *loco* 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, Conception, Iquique, Puerto Montt, Punta Arenas, San Antonio, Serena, Valdivia, Valparaiso.

842

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.

	TURF		OPEN-ACCESS AREA	
Region	Area (km^2)	Effort (individual)	Area (km^2)	Effort (individual)
Northern *N=63*	3.2 (±3.1)	25.1 (±25.4)	60.8 (±16.5)	33.1 (±34.5)
Southern *N=114*	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/km^2. % 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: $\%\Delta y = 100 \cdot \left(e^{\beta \Delta x} - 1\right)$. Marginal and conditional coefficients of determination are

860   respectively given by r^2_m and r^2_c. Number of observations and number of fishing coves included

861   for each model are respectively given by n and N.

Model	Predictor	Loco Coeff.	Loco p-value	Limpet Coeff.	Limpet p-value	Kelp Coeff.	Kelp p-value	Sea urchin Coeff.	Sea urchin 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^2_m	0.10		0.22		0.25		0.12	
	r^2_c	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^2_m	0.08		1.38E-3		0.03		2.81E-3	
	r^2_c	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^2_m

870 and r^2_c. Number of observations and number of fishing coves included for each model are

871 respectively given by n and N.

		Limpet		Kelp		Sea urchin	
Model	Predictor	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^2_m	0.01		2.21E-3		2.33E-4	
	r^2_c	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^2_m	4.84E-3		2.59E-5		3.29E-4	
	r^2_c	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: $\%\Delta y = 100 \cdot \left(e^{\beta \Delta x} - 1\right)$. 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	Divers_All [a]	100	+	0.02	0.99
n=54	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	Collectors_All [a]	100	+	2.31E-3	0.93
n=54	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

|					
n=36	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**

43

893
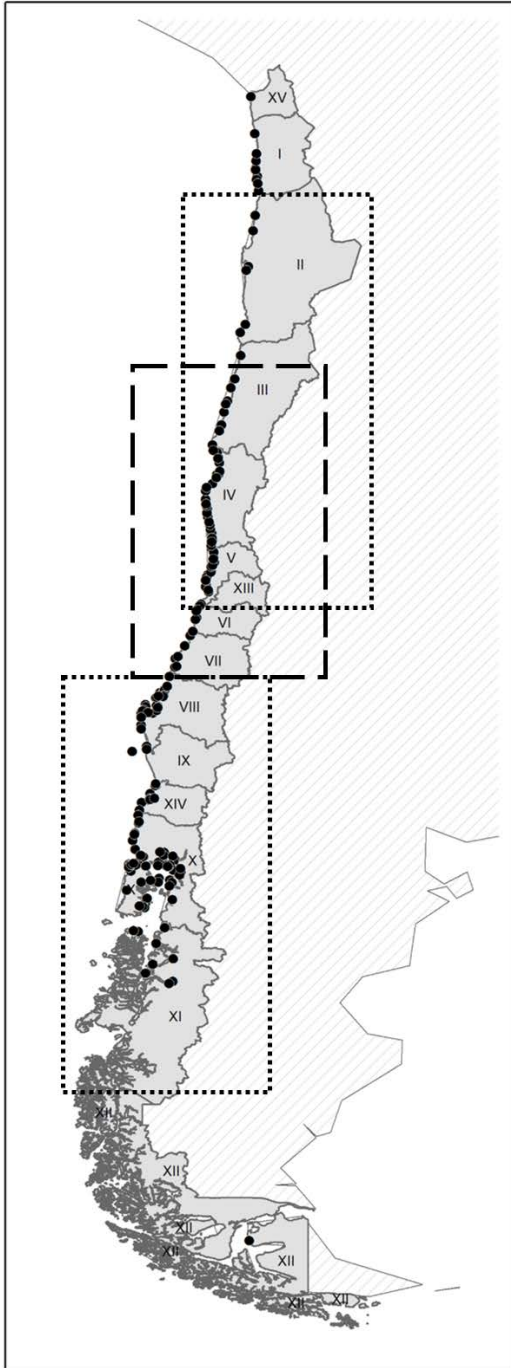
Figure 1. Administrative regions of Chile. Fishing coves included in the comparison of 2015 catch

rates and mixed effect models are represented with the black dots. The elastic net regressions only

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
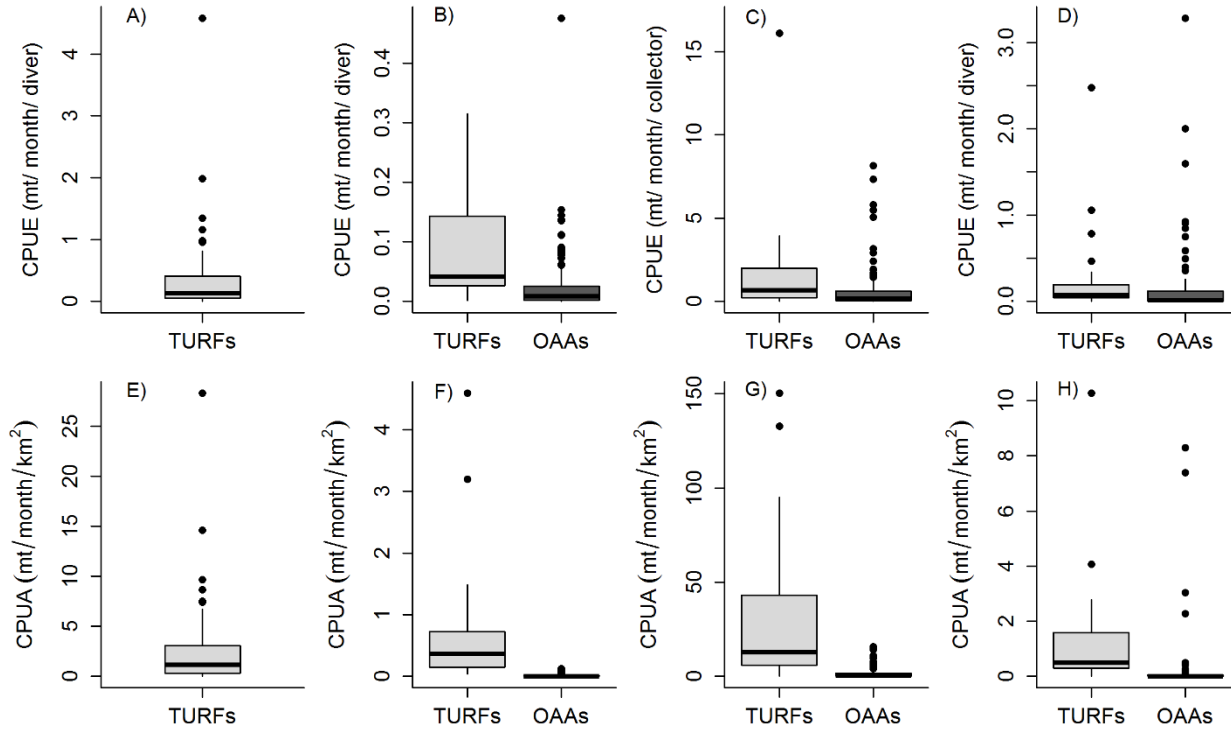
Figure 2. Boxplots of 2015 CPUEs (A, B, C, D) and CPUAs (E, F, G, H) for the four species *loco* (A,E) keyhole limpet (B, F), kelp (C, G), and red sea urchin (D, H) by fishing coves, differentiated by catch origin inside or outside TURFs (i.e. OAA). *Loco*'s extraction is banned in OAAs.
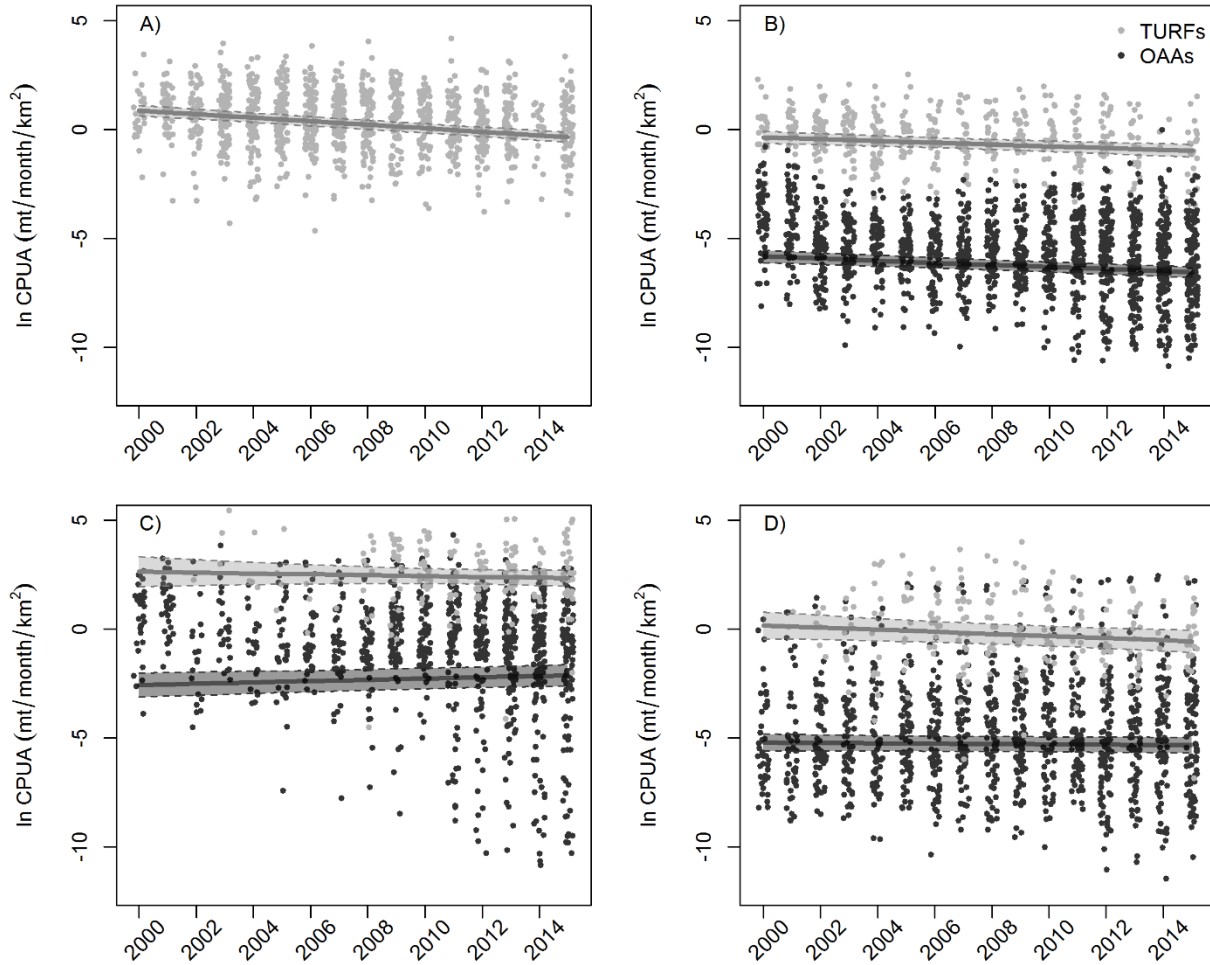
905

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)

B)
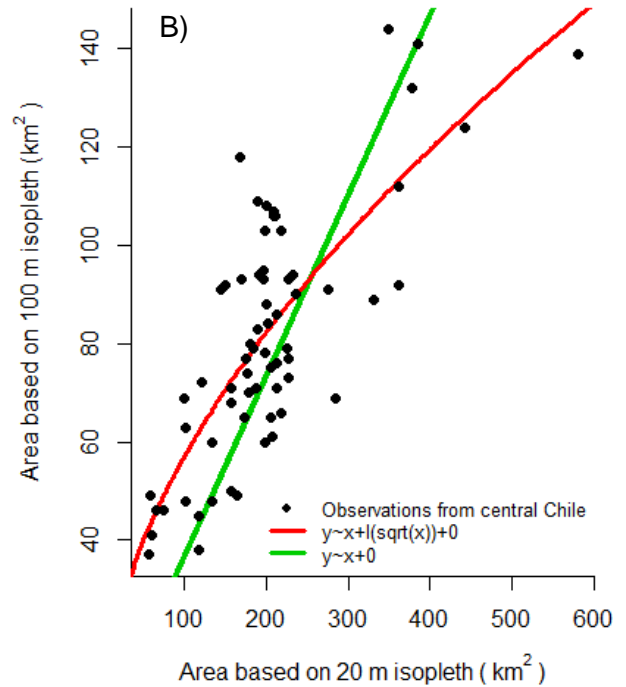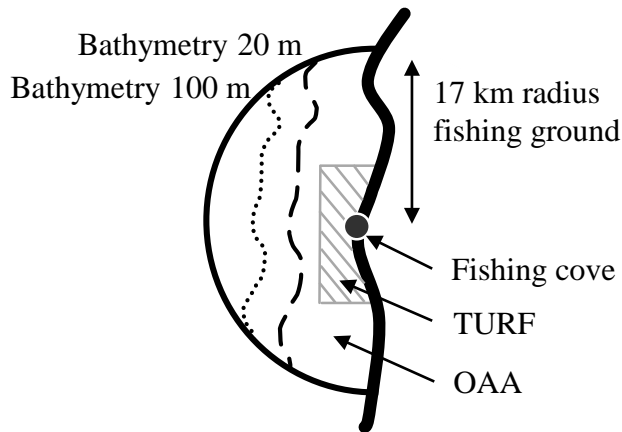
A2. A) Total fishing grounds (comprising TURFs and OAAs) were created per fishing cove based on sailing time and bathymetry. The offshore width of these polygons was based on a typical maximum harvest depth of 20 m (dashed line) extrapolated for the whole coast from a 100 m isobaths layer (dotted line, 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 $y = x +\sqrt{??} + 0$ (red line) that fits better than the relationship $y = x + 0$ (green line).
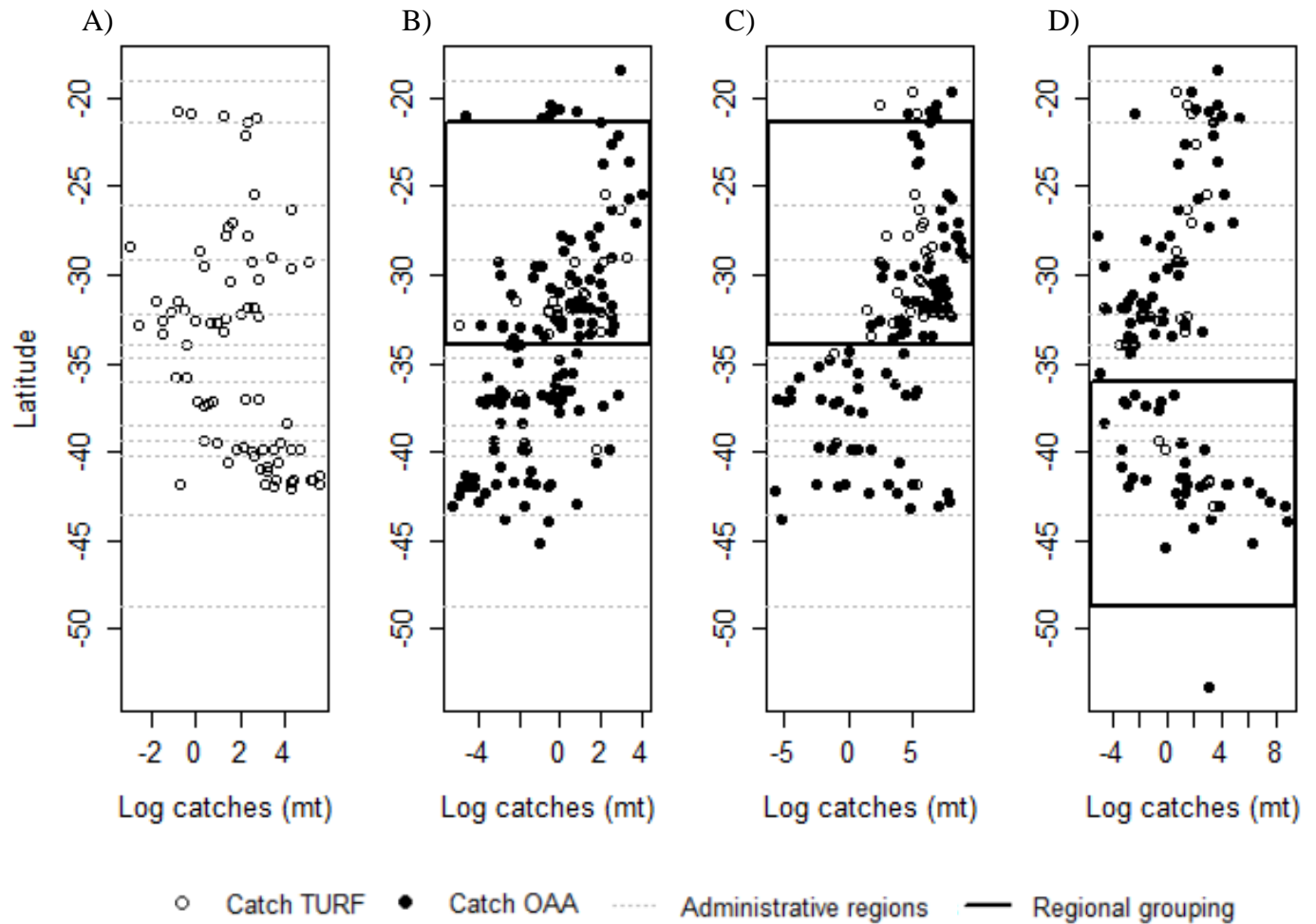
A3. Log catches (mt) per fishing coves as a function of latitude for each group of species: *loco* (A), keyhole limpet (B), kelp (C), and red sea urchin (D) and differentiated by their origin, i.e., catches inside TURFs (white dots) or from the OAA (black dots). Dashed lines represent the delimitations 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:

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

Where

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

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: $\%\Delta?? = 100 \cdot (??^{??\Delta??} - 1)$. 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 Urchin	Divers_All [a]	100	+	0.011	1.231
	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 $\lambda_{1SE,}$ 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_OAA²* 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).
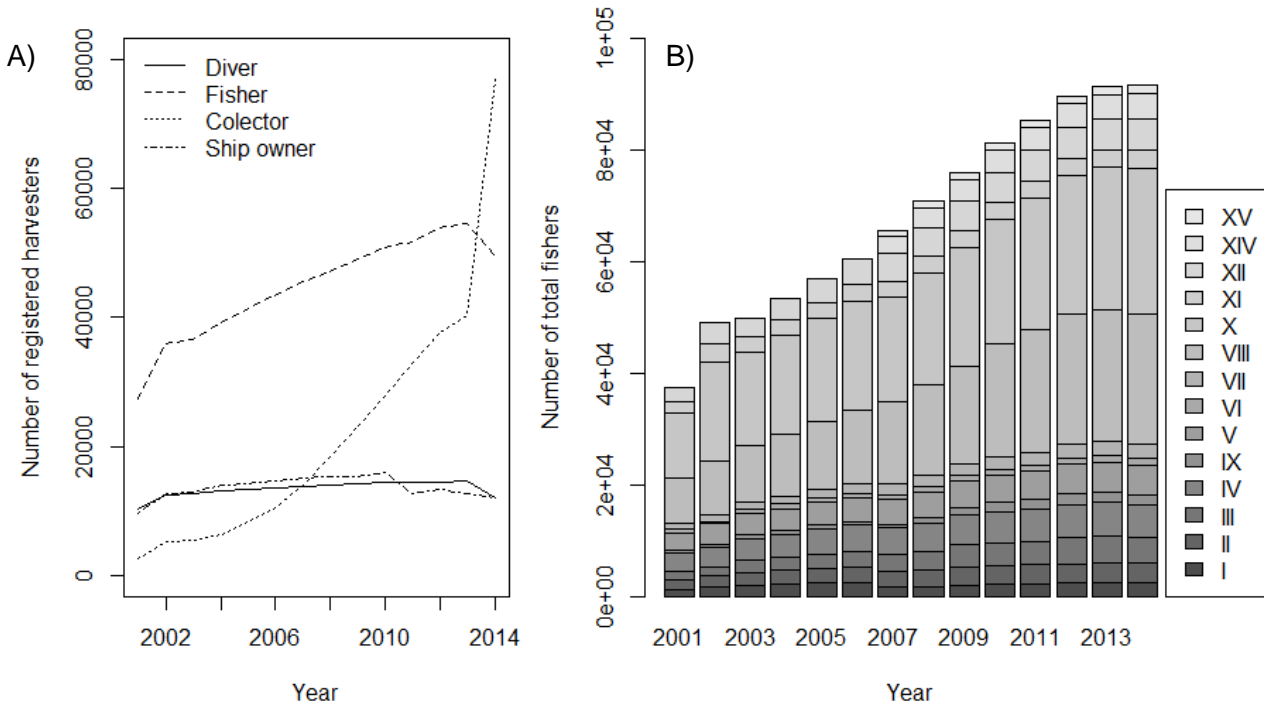
A6. A) Number of active licensed harvesters over time according to the different categories with the solid line representing number of divers for loco, limpet and sea urchin exploitation and the dotted line representing the number of collectors mainly for kelp extraction. The different categories are 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