

1 **Market Demand and Size Selective Fishing**

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24 **Abstract**

25 Market demand can have a great influence on the sustainable use of natural resources. However, little is
26 known about how biological or institutional factors mediate the effects of market demand on social and
27 ecological outcomes. Here, we investigate the role of these factors by examining the Pacific red snapper
28 (*Lutjanus peru*) fishery around La Paz, Mexico, where medium or "plate-sized" fish are sold to
29 restaurants at a premium price. If demand for plate-sized fish increases the relative abundance of the
30 smallest (needed to recruit to the adult population) and largest (most fecund) fish, this may be a market
31 mechanism to increase stocks and fishermen's revenues. We tested this hypothesis by estimating the
32 effect of prices on the distribution of catch across size classes using daily records of prices and catch. We
33 linked the predictions from this economic choice model to a staged-based model of the fishery to
34 estimate the effects on the stock and harvest revenues. We found that the supply of plate-sized fish
35 increased by 6% while the supply of large fish decreased by 4% as a result of a 13% price premium for
36 plate-sized fish. This market-driven size selection may increase revenues (14%) but may decrease total
37 fish biomass (-3%). However, when market-driven size selection is combined with limited institutional
38 constraints, both fish biomass (28%) and fishermen's revenue (22%) may increase. These results show
39 the important effects of both biological attributes and institutions in mediating the effects of market
40 demand on biological populations and human behavior.

41

42 **Introduction**

43 Demand for fisheries products, tourism opportunities, and other ecosystem services have contributed
44 substantially to ecosystem change in coastal and marine systems (e.g., (1-3)). Nonetheless,
45 investigations of human impacts in marine systems, and even of fisheries-related impacts specifically,
46 often ignore market demand entirely or simply consider it to be an exogenous factor leading directly
47 and uniformly to greater pressure on fisheries (as reviewed in (4)). However, evidence from a variety of
48 systems suggests that ecological, economic, and institutional processes can dictate the strength of the
49 relationship between market demand and ecosystem health, and even whether growing demand
50 reduces or increases ecosystem health (5-8). For example, Foster and Rosenzweig (9) suggest that the
51 presence of strong property rights over forest-lands in isolated Indian villages may have caused growing
52 demand for wood products to actually induce greater forest growth (see also (10) and (11) for reef
53 fish/market interactions from the tropics). In contrast, Armsworth and colleagues (5) show that the

54 ecological value of land may determine whether market feedbacks from purchasing land for nature
55 conservation undermine conservation efforts. Here, we build on this literature by investigating how
56 both ecological and institutional factors determine how market driven selective harvest affects
57 populations and revenues.

58 Selective harvesting – where exploitation favors a particular species, stock, body size, sex,
59 season, or geographic location – is common, particularly for marine species (12-14). Across species,
60 selective harvest of large species, especially predators, has changed community structure and trophic
61 interactions in a variety of ecosystems (12, 15, 16). Within species, individual traits, demographics, and
62 the ecology of diverse taxa have been affected by harvest that targets specific size classes, stages, or
63 sexes (12). Size selective harvest, where large species or individuals of a species are preferentially
64 caught, has been especially important in shaping fish populations and fisheries (as reviewed by (13)). It
65 has led to the loss of large individuals and taxa globally (e.g., (17, 18) and in some cases led to
66 demographic or evolutionary changes in fish populations that may have negative consequences for
67 fisheries yields (19-21).

68 Most work on the drivers of size selective fish harvest has focused on the interaction between
69 fishing technology and fish biology and how regulations may mediate this interaction. Fishing gear, such
70 as hook and line, select for large species or individuals (22). These large species and individuals tend to
71 be from upper trophic levels and have slow growth rates and low fecundity, which exacerbate the
72 effects of fishing (23). This correspondence between size, trophic level, and vulnerability has been
73 implicated as the cause of the phenomenon of fishing down the food chain, which refers to sequentially
74 fishing from upper trophic level species to lower trophic level species (17). Similarly, size selective fishing
75 has led to dramatic changes in the median size of individuals within populations (20, 24-26).

76 Size based regulations that protect key size classes, such as juveniles that are needed to recruit
77 to the population and large adults that are disproportionately fecund, are a widely used fishing strategy

78 (13, 27). Minimum-length limits became popular in the 1960s and 1970s after theoretical results by
79 Ricker (28) and Salla and Horton (29) suggested higher stocks and harvests could be achieved by
80 protecting small, fast-growing fish (30). Minimum-length limits are thought to produce the most
81 benefits for fish populations with low recruitment rates and natural mortality, moderate to high growth
82 rates, and high fishing mortality (31). Anderson (32), (33) proposed slot-length limits, which prohibit
83 catching fish within some length range, for fish populations with high recruitment and low growth rates.
84 However, regulations may be difficult to enforce and not flexible enough to take advantages of the
85 dynamic synergies between species life histories and the economic incentives created by market
86 demand.

87 Market demand for fisheries products has the potential to influence the size distribution of the
88 catch – and thus, population abundance, harvest, and revenue – through economic incentives rather
89 than regulations. For instance, Sethi, Branch and Watson (34) argue that profits are a better predictor of
90 the sequence of fisheries development than trophic group or size, in contrast to Pauly's (17) fishing
91 down the food chain hypothesis. Similarly, differences in profits associated with different size classes of
92 fish may be a good predictor of the size distribution of the fish catch. High prices associated with high
93 demand for certain size classes may make it worthwhile for fishermen to focus their effort on that size
94 class. One example of a particular size class with a price premium are so-called "plate-sized" fish that are
95 served whole in restaurants, especially in tourism areas. In this case, demand from the tourism market
96 may have similar effects on catch distributions as a slot-limit regulation, but with the benefit of greater
97 revenues. Whether market demand has positive effects on the fish population and fishermen's profits in
98 the long run will depend, in part, on the biology of the fish populations, fishermen's behavior, and
99 institutional constraints (e.g., practices that limit by-catch). For example, if increased demand for plate-
100 sized fish results in more plate-sized fish being caught without significantly increasing catch overall,
101 market demand may have positive impacts on the fish population and fishermen's revenues because

102 mortality of the smallest (needed to recruit into adult population) and largest (most fecund) individuals
103 is reduced and plate-sized fish can be sold at a premium.

104 With this in mind, we empirically examine how ecological and institutional processes mediate
105 the effect of market demand on the red snapper (or huachinango; *Lutjanus peru*) fishery near La Paz,
106 Mexico. *Lutjanus peru* is relatively slow growing and is among the longest lived species in the Lutjanid
107 family (e.g. exceeding 30 years) (35). These fish constitute a substantial and increasing fraction of
108 commercial finfish landings (34% or 598 tons) and revenue (46% or >\$1 million) in the region (36, 37).
109 However, this fishing mortality around La Paz is still relatively low compared to other regions in Mexico
110 (37). In the tourist zone around La Paz, medium or plate-sized red snapper are the preferred fish for
111 restaurants and hotels (36) and are sold at a premium price compared to smaller and larger sized fish.
112 Plate-sized fish are typically between 20 and 35 cm in length (Aburto-Oropeza, Walsh, pers. obs.), which
113 corresponds to the size of small adults (38). When selling fish, fishermen distinguish the plate-sized fish
114 from small fish (<20 cm) and large fish (>35 cm) (Aburto-Oropeza, Walsh pers. obs.). Fishermen use hook
115 and line to catch *L. peru* and "free the size that does not pay" (Walsh, per. obs.). Interviews with
116 fishermen indicate that they are able to be very selective in fishing particular sizes by their choice of
117 hook, location, and depth (Sievanen, Walsh, pers. obs.). Harvest of small adults may have less of an
118 impact on the fish population than fishing juveniles and large adults, given that large adults produce
119 disproportionately more offspring (27) and juvenile mortality already is significant (39). These aspects of
120 fish biology motivated the management of fisheries using 'slot limits', where only medium size adults
121 are fished, and has been shown to increase stocks and yields for fish with certain biological attributes
122 (30, 32, 33). The relatively slow growth and low fishing mortality of *L. peru* around La Paz suggests that
123 its stock could increase due to a market-driven or regulatory 'slot limit'.

124 Fisheries in Mexico are governed by a set of reasonable laws including size limits for some
125 fisheries. However, the government agency CONAPESCA, which is responsible for enforcing fisheries

126 regulations, has limited resources (40). In this low enforcement capacity setting, market demand
127 combined with local institutional constraints could help incentivize compliance with size limits, when
128 they exist; or create a non-regulatory mechanism to promote better fishing practices. Small-scale
129 fishermen in the Gulf of California generally operate independently, either as boat owners or hired
130 workers, are members of for-profit firms, or belong to cooperatives (41). Although, with few exceptions,
131 cooperatives no longer retain exclusive rights to particular species, cooperatives continue to operate in
132 the La Paz region and elsewhere in Mexico by holding permits (42) and may thus could play an
133 important role in mediating the effects of market demand.

134 Increased tourism demand for plate-sized fish would only be beneficial if (a) it does not induce
135 large supply responses by fishermen; and (b) fishermen selectively harvest plate-sized fish and decrease
136 their harvest of non-plate-sized fish. Fishing cooperatives may be able to control fishing effort in a way
137 that is consistent with both these conditions. The fishing cooperative could encourage this by making
138 lower payments for non-plate-sized fish or mandating the use of certain hook and line technology by
139 cooperative members and fishing in certain habitats. Moreover, effective monitoring and collective
140 action by cooperative members could limit entrance of new fishermen (43-45), who may be attracted by
141 the increase in fish prices. All these solutions depend on the cooperative wielding enough influence; if
142 there are a large number of non-cooperative members in the fishery, it is less likely these conditions will
143 hold.

144 Given this understanding of the fishery, we develop a four-stage analysis using logbook data
145 containing three fishing cooperatives' daily purchases from 2007-2009 in and around La Paz (collected
146 by Aburto-Oropeza and colleagues) and information on the biology of *L. peru* (Fig. 1). First, we examine
147 the differences in price associated with the different size classes and relative influence of the market.
148 Given the location of the fishing cooperatives and time period covered by the logbooks, these data
149 provide significant geographic and temporal variation in fishermen's connections to markets. Second,

150 once we establish the price differences across size classes, we estimate the effect of these price
151 differences on the supply of different size classes of fish. Third, in order to simulate the effect of market-
152 driven size selective fishing on the fish population and fishermen's revenues, we develop a stage-based
153 model of the fish population with harvest using parameter estimates from the literature. Finally, we
154 explore how institutional constraints could further mediate the interaction between market demand
155 and size selective fishing. Our results show how biology and institutions may determine both the sign
156 and magnitude of the influence of market demand on a fishery.

157

158 **Results and Discussion**

159 Based on the empirical data on daily catches, we find that the price of medium or plate-sized fish is as
160 much as 13% greater near the main market in La Paz (Pichilingue: 53 \$/kg, $SD=3$; Sargento: 52 \$/kg,
161 $SD=2$) than away from this market (Dorado: 47 \$/kg, $SD=3$) (Fig. 2). The average price of plate-sized fish
162 across all cooperatives is also greater than the price of small or large fish, indicating potentially far-
163 reaching effects of the market in La Paz on fish prices. In contrast, the average prices of small and large
164 fish across all cooperatives are not different (Fig. 2).

165 Increases in the price of plate-sized fish are associated with increases in the supply of plate-sized
166 fish and decreases in the supply of large fish and other species, but are not associated with changes in
167 the supply of small fish (see Supplementary Information, Table S1 for detailed results). The monthly
168 supply of plate-sized fish increases 0.43% ($SE=0.26$, $p<0.10$) for every 1% increase in its own price. This
169 same increase in the price of plate-sized fish also results in a 0.33% ($SE=0.14$, $p<0.05$) decrease in the
170 monthly supply of large fish and a 1.1% decrease in the supply of other species ($SE=0.64$, $p<0.10$). The
171 increases in the supply of plate-sized fish that are associated with the price of plate-sized fish are in
172 addition to the increase in supply that result when the generic, non-size specific price of *L. peru*
173 increases (0.72%, $SE=0.25$, $p<0.01$). Given the difference in the price (13%) of plate-sized fish near and

174 far from the market, market demand may have resulted in at least a 6% (price difference*price
175 elasticity= $13\% \times 0.43$) increase in the overall supply of plate-sized fish and a 4% (price difference*price
176 elasticity= $13\% \times 0.33$) decrease in the supply of large fish.

177 Using a stage-based model of the fishery, we find that this market-driven size selective fishing
178 may decrease the abundance of plate-sized fish and large fish, with no effect on small fish (Fig 3b),
179 relative to fishing in the absence of market-driven size selective fishing (Fig 3a). The decrease in the
180 abundance of plate-sized fish is a result of direct harvest. In contrast, the decrease in large fish is not a
181 result of direct harvest but of changes in the survival of plate-sized fish. Although market demand
182 reduces the catch of large fish, the reduction in harvest in this stage evidently does not offset the
183 decrease in the number of plate-sized fish surviving and entering the large stage. Market demand had
184 no direct effect on the catch of small fish; however, changes in the abundance of the larger stages
185 should affect recruitment to the small fish stage. In fact, egg production is most sensitive to survivorship
186 in the large stage (see Text S1). However, changes in egg production have limited effects on the
187 abundance of small fish if total egg production is near the saturation level, as defined by the density
188 dependent pre-recruit survival function we employ (see Methods). This suggests that the negative
189 effects of market-driven size selective fishing may be exacerbated for a population with lower
190 population-level egg densities. In total, the change in the size structure of the population and the
191 resulting catch under market-driven size selective fishing resulted in a 3% decrease in the total biomass
192 of the stock and a 14% increase in revenues (Fig. 4b). The increase in the revenue is a result of the
193 relative increase in the catch of plate-sized fish and the price premium for plate-sized fish. The total
194 harvest actually decreased by 1%. We have no way of accounting for differences in costs associated with
195 targeting plate-sized fish, but interviews with fishermen suggest that the differences are small
196 (Sievanen, Walsh pers. obs.).

197 Our modeled harvest scenarios suggest that if institutional constraints increase the selectivity
198 for plate-sized fish by 5% above and beyond market-driven selectivity and impose compensating
199 decreases in the supply of small and large fish, the total biomass of the stock could increase 28% and
200 revenue from harvest could increase 22% (Fig. 4c). This total biomass increase is a result of increases in
201 the abundance of both plate-sized and large fish (Fig 3c). The finding that it is possible to increase the
202 biomass of the stock by shifting catch toward medium or plate-sized fish supports the hypothesis that a
203 slot limit type of fishery may be beneficial to the *L. peru* fishery near La Paz, given its biology and the
204 status of the fishery. However, our results suggest market incentives alone are not sufficient to improve
205 both fish biomass and harvest revenues, and must be complemented by institutional incentives for size
206 selective harvest, as well as limits on entry to the fishery. Based on interviews with fishermen, it seems
207 that fishing cooperatives already encourage some selection against small fish. The price premium on
208 plate-sized fish may increase compliance with these or future institutional constraints by offsetting
209 some of the potential costs associated with more selective fishing.

210 Although fishermen indicate they release small and large fish, there may be unobserved by-
211 catch. We found that the losses in total biomass may be greater (6% vs. 3%) while the gains in revenue
212 may be less (13% vs. 14%) than estimated with market-driven size selection alone, if unobserved by-
213 catch does occur (Fig. 4d). This is a result of even greater decreases in abundance of both plate-sized
214 and large fish under this harvest scenario (Fig. 3d).

215 Our analysis so far only considered changes in catch created by current fishermen. To determine
216 whether new fishermen were entering the market in response to changes in fish price, we estimated the
217 number of unique fishing teams fishing a given size class of *L. peru* or other species at a particular
218 cooperative in a given month using a poisson regression model (see Tables S2 for detailed results)*. The

* Tobit regression models showed similar results, namely increases in the number of small fish given increases in plate-sized fish price and increases in the number of fishermen fishing other species given increases in the price of

219 predictor variables were the same as in the models of fish catch (see Methods). We found that the
220 number of fishing teams fishing small fish increased 11% ($SE=6.1$, $p<0.10$) and the number of teams
221 fishing large fish decreased 11% ($SE=6.1$, $p<0.10$) for every 1% increase in the price of plate-sized fish
222 (see Table S2). The number of fishing teams fishing plate-sized *L. peru* or other species was not affected
223 by the price of plate-sized fish. However, an increase in the generic price of *L. peru* markedly increased
224 the number of fishing teams fishing small (12%, $SE=5.7$, $p<0.05$), plate-sized (12%, $SE=5.3$, $p<0.05$), and
225 large *L. peru* (20%, $SE=5.8$, $p<0.01$). Although it seems likely that more fishing teams are fishing when
226 the prices are high, the extremely large elasticities suggest that our results may be influenced by the fact
227 that some of the catch records in the logbook data are reported by cooperative sub-groups rather than
228 individual fishing teams. Overall, when we incorporated the role of new entrants into our harvest
229 equations, we found that fish biomass was greatly reduced and the gains in revenues from market-
230 driven size selective fishing were eliminated (see Fig S1 ii-b). Even with institutional constraints, large
231 decreases in biomass and small decreases in revenue occurred (Fig S1 ii-c). Despite the uncertainty
232 surrounding the response of new entrants to the change in the plate-sized fish price, these results
233 suggest that market-driven or institutional constraints on size selectivity may need to be complemented
234 by stronger institutional constraints on new entrants and/or total harvest in order to sustain the fishery
235 (i.e., the fish population *and* fishermen's profits). Our finding that total biomass, as well as total
236 population size and egg production, are more sensitive to the total proportion of biomass harvested
237 than to the harvest in a particular size class supports this finding (see Table S3). However, it should be
238 noted that these variables are more sensitive to the harvest of medium-sized fish, followed by small fish,
239 and large fish (see Table S3).

240 Lastly, if we modeled our four scenarios for a more heavily fished population (40% initial harvest
241 rather than 30% percent), we found a similar effect of market-driven size selective fishing as when the

other species. However, the Tobit model results did not show an increase in the number of fishermen fishing large fish given an increase in the price of plate-sized fish.

242 population was less heavily fished (Fig. S3). However, if we modeled both a more heavily fished
243 population and the price premium that enabled both changes in catch and the number of new entrants
244 into the fishery, we found that market-driven size selective fishing resulted in decreases in both biomass
245 and revenues (Fig. S4 ii-b). Under these conditions, market-driven size selective fishing combined with
246 institutional constraints, including both a 5% increase in selectivity and 50% reduction in new entrants,
247 were insufficient to improve biomass but may improve harvest revenues (Fig. S4, ii-c).

248

249 **Conclusions**

250 We find that under certain conditions, market-driven selectivity may have positive outcomes for
251 fishermen's revenues, but that additional institutional constraints (e.g. to enhance selectivity or limit
252 entrants) are needed to enhance and sustain fish stocks. Thus, although market mechanisms may not be
253 sufficient to sustain this fishery, they may increase compliance with institutional constraints by providing
254 an economic incentive in the form of a price premium for plate-sized fish. Yet, if populations are
255 overfished, market-driven and institutionally encouraged size selective fishing may be insufficient to
256 maintain biomass.

257 By showing how biology and institutional design may determine both the sign and magnitude of
258 the influence of market demand on an exploited fish population, we emphasize the importance of
259 understanding the coupled dynamics of human and natural systems (46, 47). These dynamics may be
260 especially important in marine systems and developing countries where people are directly and highly
261 dependent on wild populations (e.g., (48)). Although price premiums for plate-sized fish are a specific
262 example of market demand and selective harvest, we expect that market demand may have widespread
263 and important consequences for selective harvest of particular taxa or sizes and life stages of a given
264 taxon (34). This phenomenon may become more important as demand for specialized products
265 increases with growing global markets for fish and fishery products (49). Market-driven selective

266 harvest; therefore, may have far-reaching effects on community and ecosystems interactions as well as
267 biological population dynamics, with importance consequences for human well-being.

268 Our results show how accounting for biological and behavioral complexity yields a richer
269 understanding of human-environment connections and can help inform institutional design. In Mexico
270 and other low governance capacity contexts, local institutions may play an important role in
271 encouraging compliance with size selective harvest limits, while growing markets may provide economic
272 incentives. However, our analysis also suggests that regional or national governments may need to
273 support local-scale institutions by creating conditions that allow them to be effective, e.g. by
274 establishing/supporting property rights or local monitoring groups (50), and providing higher-level
275 regulations when market and local institutional mechanisms are insufficient, e.g. for overfished or wide-
276 ranging populations.

277

278 **Methods**

279 ***Economic choice model***

280 We tested the effect of market demand on size selective fishing by estimating a linearized economic
281 choice model of fishermen's supply decisions using detailed daily logbook data from three cooperatives
282 over 2007-2009. We assume that fishermen choose whether to fish *L. peru* or another species, and
283 which size class of *L. peru* to fish, based on the profits obtained from fishing. The choice is a two-stage
284 process. First, fishermen determine the maximum profits that can be obtained from targeting a
285 particular fish given his production function for that fish and an optimal choice of inputs. The maximum
286 profits from targeting fish type i can be denoted $\pi_i(\mathbf{p}, \mathbf{r}, C, \mathbf{n})$, where \mathbf{p} is a vector of product prices
287 for the size classes of *L. peru* and fish other than *L. peru*, \mathbf{r} is a vector of input prices, C indicates a set of
288 institutional constraints, and \mathbf{n} is a vector indicating the relative abundance of each size class of *L. peru*
289 or fish other than *L. peru*. Second, the fishermen chooses to target fish type i if $\pi_i(\mathbf{p}, \mathbf{r}, \mathbf{n}, C) >$

290 $\pi_k(\mathbf{p}, \mathbf{r}, \mathbf{n}, C)$ for all $k \neq i$. Note that the entire vector of product prices appears in each expression.
291 Fishermen target types of fish by choosing different technology (e.g., size of hook) or fishing location,
292 which will be reflected in the input prices; however, “targeting” a particular type of fish i does not
293 mean that other size classes of *L. peru* or other species are not caught in the process. Cooperative
294 logbook data shows that 44% of days fishing teams report catching *L. peru* and in only 6% of days do
295 teams only catch one size class of *L. peru*. The most common catch combination is small and medium *L.*
296 *peru* and other species (15%), followed by small *L. peru* and other species (10%), and by medium *L. peru*
297 and other species (6%). If there is by-catch, it can be sold for a rate that depends on the market price for
298 that by-catch. Of course, if institutional constraints penalize the selling of non-plate-sized fish, this will
299 be reflected in the profit functions.

300 The choice of which fish to target leads to supply functions for each fishing team. These
301 functions can be aggregated over time and linearized to get models of fish supply that can be estimated
302 with standard regression techniques. Fishermen's aggregated monthly supply of each size class of *L.*
303 *peru* and all other species are estimated by the following equation:

$$304 \ln(q_i) = \beta_0 + \beta_1 \ln(p_o) + \beta_2 \ln(p_g) + \beta_3 \ln(p_m) + T + C + \varepsilon$$

305 where q_i is the quantity of fish of type i supplied [the three size classes of *L. peru* (m = medium or
306 plate-sized and g = non plate-sized) and all other species (o)], the price of these types of fish, month
307 fixed effects (T), and cooperative fixed effects (C). The prices of non plate-sized fish (small and large
308 fish) were grouped because we found that these prices were statistically indistinguishable. This
309 specification is further validated by the fact that results from models where the price of small and large
310 fish price enters separately are extremely similar to results from this model specification (see Table S1,
311 S4). Direct information on the price of inputs (\mathbf{r}) is not available; however, differences in input prices
312 are captured in part by the buying prices of from the cooperative (\mathbf{p}) because cooperatives typically pay

313 fishermen after subtracting out the cost of fuel. Month and cooperative fixed effects captures temporal
314 and spatial variation in the abundance of the fish (α). Cooperative fixed effects also capture differences
315 in fishing ability that may be common to fishermen in the cooperative because of shared ecological
316 knowledge or capital. Institutional constraints that the cooperative exerts, for instance, on fishing
317 certain size classes also will be captured by this variable. We were unable to control for unobserved
318 heterogeneity across fishermen because the data represent a very unbalanced panel; however, we
319 assert that cooperative fixed effects capture the most important differences across fishermen.

320 These models of supply were estimated using the daily logbook data on catch (kg) and buying
321 price (peso/kg) by fish type from three cooperatives around La Paz over 2007-2009. The logbook data
322 identified the catches by species and, for some species including *L. peru*, by size class. In the logbook
323 data, fishermen distinguish between the three size classes of *L. peru*, "chico" (<20 cm), "mediano" or
324 "orden" (20-35 cm), and "grande" (>35 cm) (Aburto-Oropeza, Walsh pers. obs.). The catch of the three
325 size classes of *L. peru* and all other species combined was aggregated by month for each fishing team or
326 sub-cooperative group. The price associated with these catch records was taken as the average price the
327 fishing team or group received over the time period. If a fishing team or group did not fish a particular
328 type of fish during a given month, the price the fishermen would have observed was assumed to be the
329 average of the price received by other fishermen in the same cooperative for that type of fish in that
330 month. In some cases, it was necessary to match prices by averaging across the year or the entire data
331 set for a given cooperative. In total, the database contained 7,056 observations of monthly catches by
332 fishing teams or groups for the three size classes of *L. peru* and all other species combined.

333 The results of our regression analysis show how changes in prices affected the aggregate
334 monthly catch for a given fishing team but do not provide information on whether the total number of
335 fishing teams in the fishery changes with prices. In order to examine the effect of prices of the number

336 of fishing teams, we estimated a poisson regression model with the same predictor variables as above
 337 using the total number of fishing teams reporting catch to a given cooperative in a given month.

338

339 ***Stage-based Fishery Model***

340 To estimate the effects of market-driven size selective fishing as well as the role of institutional
 341 constraints on the fish stock and fishermen's revenues, we simulated the effects of fishing using a stage-
 342 based non-linear matrix population model of the *L. peru* fishery. We first developed an age-based model
 343 of *L. peru* because age-specific demographic information was available for *L. peru* and related snappers.
 344 However, in order to couple this model with results from the economic choice model, we reduced the
 345 age model to stages that correspond to the size classes recognized in the market (see Text S1). This
 346 process resulted in the following matrix model:

$$347 \begin{pmatrix} n_1 \\ n_2 \\ n_3 \end{pmatrix} (t+1) = \begin{pmatrix} P_1 & l_1 F_2 & l_1 F_3 \\ G_1 & P_2 & 0 \\ 0 & G_2 & P_3 \end{pmatrix} \begin{pmatrix} n_1 \\ n_2 \\ n_3 \end{pmatrix} (t)$$

348 where l_1 is pre-recruit survival, P_i is the probability of staying in the same stage, and G_i is the probability
 349 of surviving and growing to the next stage. Our models employ a compensatory Beverton and Holt
 350 function that determines pre-recruit survival based on total egg density, M . Pre-recruit survival is given

351 by $l_1 = \frac{\alpha}{\beta + M}$ where $M = \sum_{i=1}^S F_i n_i$ and F_i is the fecundity of stage i , n_i is the population size in stage

352 i , and S is the maximum stage. The parameter α represents the maximum number of recruits in the
 353 population and β is the number of eggs needed to produce $\alpha / 2$ recruits. An egg-recruitment

354 relationship was chosen over stock-recruitment because adults and pre-recruits of this species inhabit
 355 separate habitats (35, 51, 52), so we assume that pre-recruit mortality is affected by egg density,

356 through starvation or vulnerability to predators, rather than the adult stock, through processes such as
357 cannibalism.

358 Parameter values were derived from previously published data on *L. peru* and related species.
359 Diaz-Uribe *et al.* (37) provides estimates of the parameters for the Beverton and Holt function for *L.*
360 *peru*. The function was presented in terms of total population size N , so we scaled the parameters in
361 order to use them in a Beverton and Holt function in terms of total egg production M . In addition, we
362 scaled the parameters to account for only females because the model in Diaz-Uribe *et al.* (37) quantified
363 both males and females. The resulting parameter values were $\alpha = 5.94 \times 10^5$ individuals and
364 $\beta = 5.29 \times 10^9$ eggs. Weighted averages of age-specific parameter values from the age-based model
365 were used in the stage-based model, assuming that the in-stage age distributions are the same as the
366 age distributions that result from the age-based model (see Text S1).

367 At equilibrium in the absence of harvest, the vast majority of individuals (94%) are in the first
368 two stages; however, 67% of the biomass was in the third, largest stage. We estimated the proportional
369 sensitivity, or elasticity, of the output variables to the parameters (see Text S1). Total biomass and total
370 egg production were more sensitive to the survival of the large-sized fish than to fish in the two smaller
371 size classes. Total population, however, was less sensitive to all survival parameters than total biomass
372 and total egg production. Total biomass, population, and egg production also were more sensitive to the
373 fecundity of large-sized fish, as opposed to medium-sized fish. The output variables were also more
374 sensitive to the Beverton and Holt parameter α , which bounds the number of recruits to the population
375 and thus the population size, than to the parameter β .

376 The results of the economic choice model were incorporated into the stage-based model of *L.*
377 *peru* such that harvest was a function of the prices for the three stages of *L. peru*. Harvest was assumed
378 to be proportional and defined as $H_t = a \times \sum_{i=1}^S b_i(t)$ where a is the proportion of the total biomass

379 harvested and b_i is the biomass in stage i . Harvest may be distributed differently across the stages,
380 hence, stage specific harvest is $h_i(t) = r_i[(100 + E_{h_i, p_m} \Delta p_m + E_{h_i, p_g} \Delta p_g + C) / 100]H(t)$, where r_i is the
381 proportion of total harvest taken from stage i and $\sum_{i=1}^S r_i = 1$. For simplicity, these harvest equations
382 are represented differently than the equations we used to estimate harvest. The elasticity of the harvest
383 with respect to the price of plate-sized fish (E_{h_i, p_m}) and with respect to the generic, non-size specific
384 price (E_{h_i, p_g}) was estimated by the economic choice model. The elasticities are multiplied by the
385 percentage change in the plate-sized fish price (p_m) and the generic, non-sized specific price of fish (p_g
386). The institutional constraints (C) on the percentage change in selectivity are reasonable assumptions
387 based on interviews with cooperatives members and leaders (Sievanen, Walsh pers. obs.). These
388 assumptions are necessary because we were unable to separate the effect of a given cooperative from
389 its location, which may also affect the stock.

390 These harvest equations give stage specific harvest in terms of biomass but the population
391 model is in terms of individuals. Harvest in terms of individuals is $u_i(t) = h_i(t) / W_i$, where W_i is the
392 average per capita biomass in stage i . In order to calculate the population in the next year as a result of
393 fishing, we subtract $u_i(t)$ from the population vector, $n(t)$. We assume that harvesting takes place
394 directly after the breeding season, such that total egg production is still defined as $M = \sum_{i=1}^S F_i n_i(t)$.

395

396 **Harvest Scenarios**

397 We compared four different harvest scenarios that represent changes in harvest as a result of changes
398 in the price of fish and institutional constraints on size-selective fishing. Prior to running these scenarios,
399 we simulated 20% total harvest for 20 years so that the modeled fish population represented a fished
400 population similar to that in the vicinity of contemporary La Paz. The distribution (\mathbf{r}) of the catch across

401 the size classes (20% small, 40% plate-sized, 40% large) was based on the equilibrium population
402 structure and catch size distributions in lightly fished places (53). For the four harvest scenarios of
403 interest, we then simulated a 30% total harvest for 7 years. The total harvest level was chosen to
404 represent recent increases in catch of *L. peru* (36). The initial distribution (\mathbf{r}) of the catch across size
405 classes for all four scenarios was based on the observed distribution of catch away from the tourism
406 market (40% small fish, 60% plate-size fish, 0% large fish) (Fig. S4). However, given that no catch of large
407 *L. peru* away from the tourism market were reported in the database, we assumed that 10% of the
408 harvest was in the large size class based on other length-frequency distribution data in the area and
409 reduce the proportion of the catch in the plate-size fish category to 50% (35). This is a reasonable
410 assumption because large-sized *L. peru* were likely caught away from the tourism market but not
411 observed in the catch records because of the smaller number of observations or the greater number of
412 fish that were reported without a size designation. The simulation duration was chosen to be long
413 enough so that newly born fish progressed through all the size stages, but short enough that it was
414 reasonable to assume that prices were not responding to changes in catch. In fact, we found that prices
415 for plate-sized fish decreased over the study period and the prices for other sizes of fish did not change.
416 In both the initial population run-down phase and the simulation of the four scenarios of interest, the
417 total harvest levels (20% and 30%) were set at levels that were judged to be sustainable in the short run
418 based on studies of marine protected area design for fisheries (see for example, (53), for empirical and
419 model-based estimates of sustainable harvest derived from no-take marine reserve effects).

420 In scenario a, the "status quo" harvest scenario, the distribution of the catch is the same as the
421 catch distribution we observed away from the tourism market (i.e. 40% small fish, 50% medium fish,
422 10% large fish). We represent this by setting the change in the price of medium or plate-sized fish and
423 the change in the generic, non-size specific price to zero. In scenario b, the "market-driven" harvest
424 scenario, the change in the price of plate-sized fish is the percentage difference in this price that we

425 observed near and far from the tourism center (13%). We assume that there is no change in the generic,
426 non-size specific price of fish. In scenario c ("market-driven + institutional constraints"), we assume that
427 there is the same change in the price of plate-sized fish and no change in the generic price but that
428 cooperatives may increase selectivity for plate-sized fish 5% above and beyond the increases caused by
429 market demand. We chose a 5% increase so that it would be similar to the level of increased selectivity
430 caused by the market (i.e. 6%). We assumed the cooperatives also encouraged decreased selectivity for
431 small and large fish. The decreases in catch of these size classes are at such levels that the gain in
432 revenues from enhanced selectivity of plate-sized fish is off-set by decreased catch of small and large
433 fish. In scenario d ("market-driven + by-catch"), again we assume the same changes in prices as in the
434 second, "market-driven" scenario, but we also assume that there is unobserved by-catch of small and
435 large fish. We represent this unobserved by-catch by setting the elasticity of the catch of both small and
436 large fish with respect to the price of plate-sized fish to the elasticity of plate-sized fish with respect to
437 its own price (e.g. $E_{h_s, p_g} = E_{h_m, p_m} = E_{h_l, p_g} = 0.454$).

438 We also considered three additional drivers of change in this social-ecological system: 1)
439 additional fishermen entering the market; 2) a non-size specific increase in the demand for *L. peru*; and
440 3) variation in the initial condition of the population. We estimated the effect of the change in the price
441 of fish on the number of fishermen entering the market using the same models as we used to estimate
442 the catch. The resulting price elasticities were incorporated into the harvest equations in the stage-
443 based model. We also considered that there may be an increase in the generic, non-size specific price of
444 *L. peru* of similar magnitude to the price premium for plate-sized fish (e.g. 15%). However, we found
445 that including this effect made no qualitative change in the size structure of the population, total
446 biomass, or revenues. Moreover, the price of other size classes of *L. peru* showed no trend over time,
447 while the price of plate-sized fish actually decreased 2% across the study period (SE=0.001, p<0.001).
448 Lastly, we considered the effect of the initial condition of the population by increasing the harvest in the

449 run-down phase to 30% and increasing the initial harvest in the simulation of the four harvest scenarios
450 to 40%.

451 Confidence intervals for the outcome variables were constructed through Monte Carlo
452 simulation methods. Values for the parameters were either drawn 1,000 times from a normal
453 distribution defined by the estimated mean and standard deviation of the parameter or from a uniform
454 distribution when there was no estimate of the error in the parameter. When parameter values were
455 drawn from uniform distributions, they were drawn from values +/- 20% of the parameter value
456 reported in the literature.

457

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464

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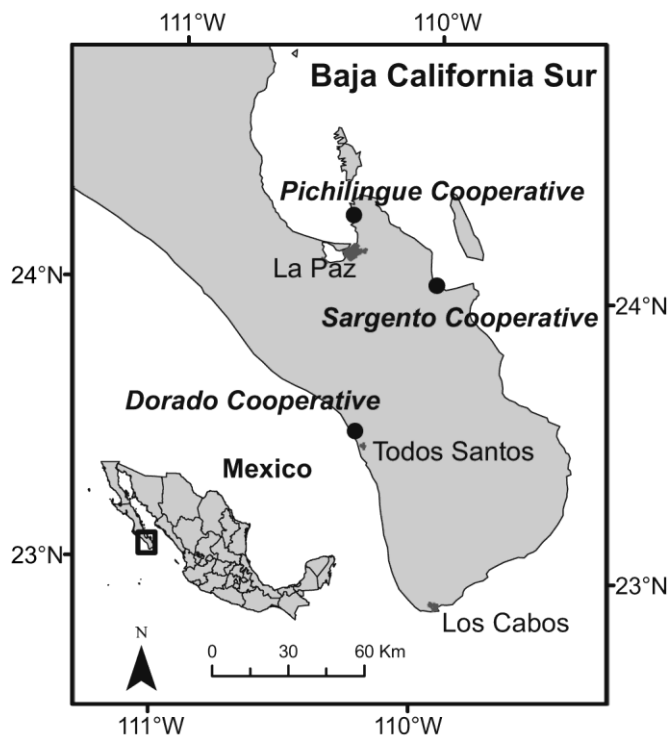
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608 **Figures**



609

610 Figure 1. The location of three fishing cooperatives and the tourism market of La Paz, Baja California-Sur,

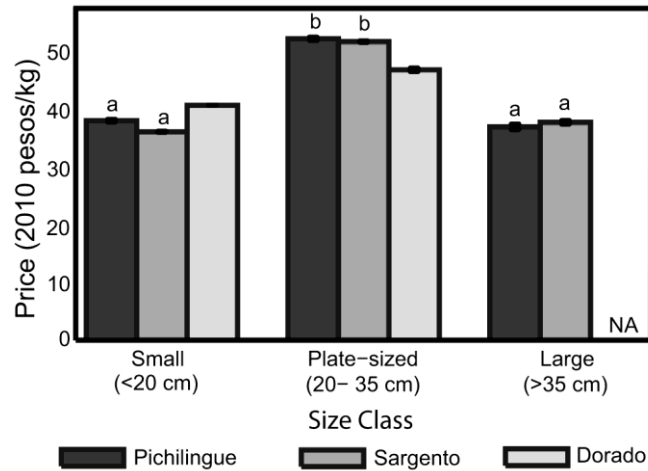
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617 Figure 2. The mean price of *L. peru* by size class and fishing cooperative. Pichilingue, Sargento, and
 618 Dorado are located at increasing distances away from the markets of La Paz. The mean price is
 619 significantly different across size classes ($F_{2,7}=19.26$, $p<0.0001$), cooperatives ($F_{2,7}=0.03$, $p<0.05$), and
 620 certain size classes at a cooperative ($F_{3,7}=2.28$, $p<0.0001$) (Two-way ANOVA). Error bars are standard
 621 deviations and lower case letters indicate means that are not significantly different as determined by
 622 Tukey's HSD post-hoc tests.

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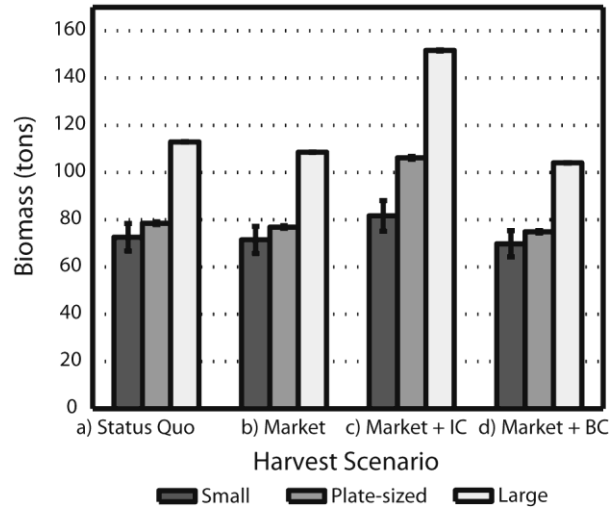
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635 Figure 3. Biomass of *L. peru* by size class and harvest scenario: a) status quo away from the market in La

636 Paz, b) market-driven size selection, c) market-drive size selection plus institutional constraints (IC), and

637 d) market-driven size selection plus by-catch (BC). Error bars are 95% confidence intervals.

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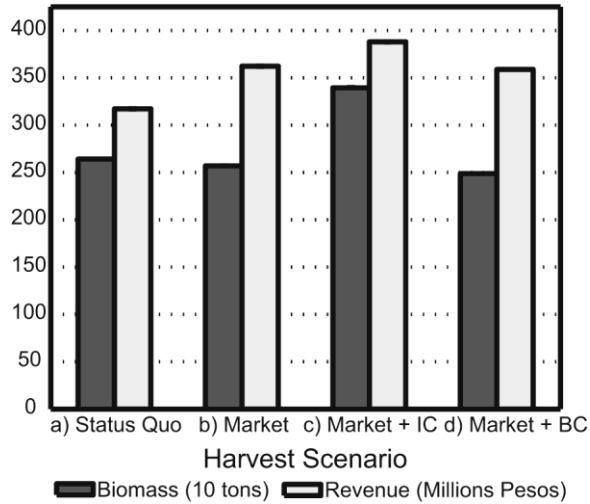
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Figure 4. Total biomass of stock and revenue from harvest of *L. peru* by harvest scenario: a) status quo away from the market in La Paz, b) market-driven size selection, c) market-drive size selection plus institutional constraints (IC), and d) market-driven size selection plus by-catch (BC). Error bars are 95% confidence intervals.

Supplementary Information

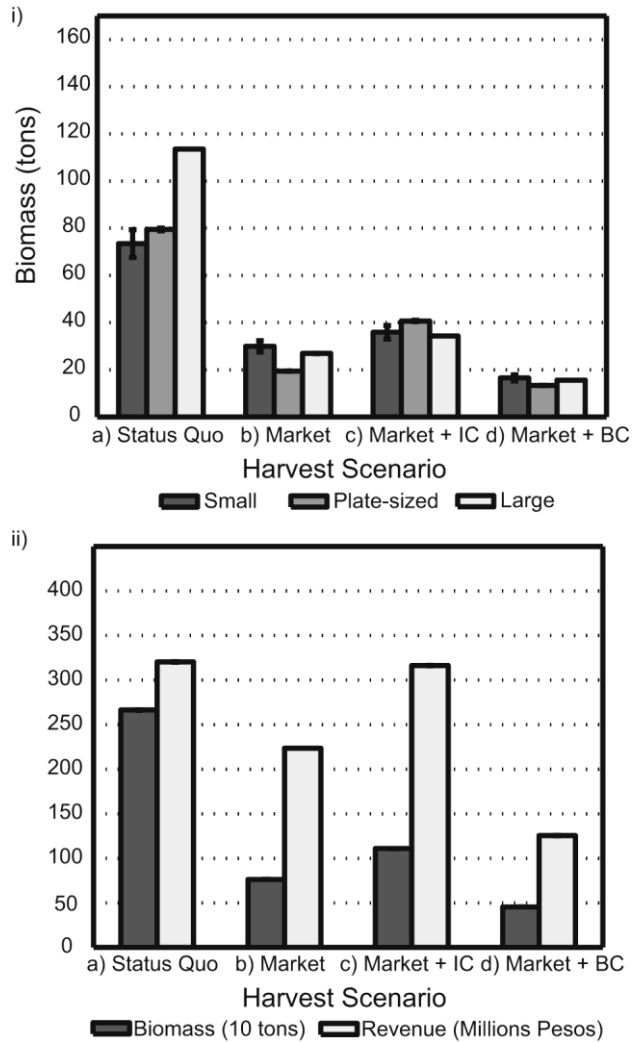


Fig. S1 i) Biomass of *L. peru* by size class and harvest scenario and ii) Biomass and revenue of *L. peru* by harvest scenario, including effects of new entrants to the fishery. The harvest scenario are defined as a) the status quo away from the market in La Paz, b) market-driven size selection, c) market-drive size selection plus institutional constraints (IC), and d) market-driven size selection plus by-catch (BC). Error bars are 95% confidence intervals.

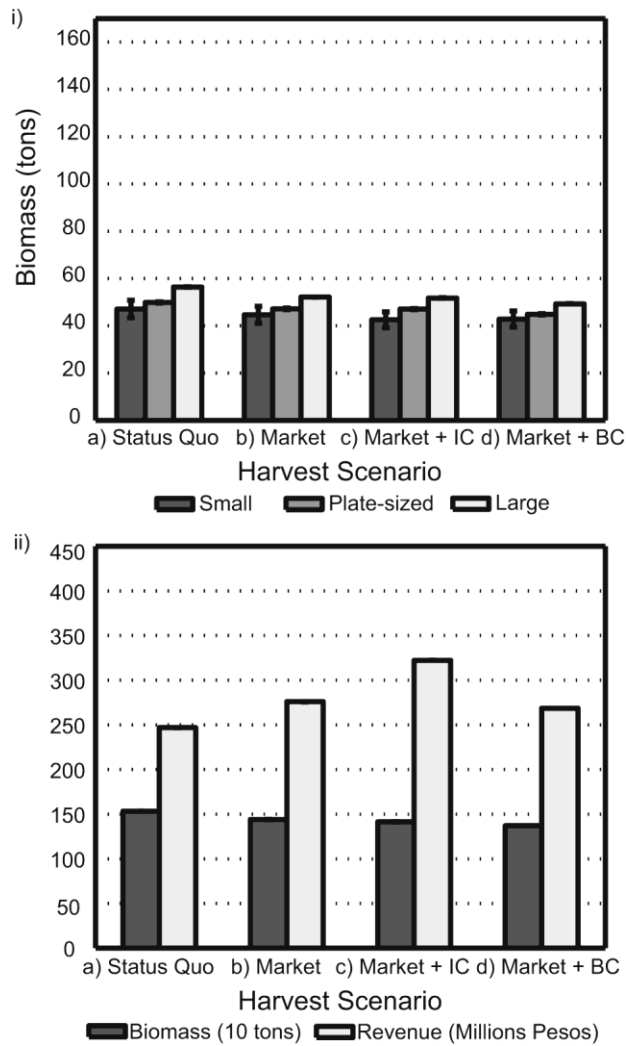


Fig. S2 i) Biomass of *L. peru* by size class and harvest scenario and ii) Biomass and revenue of *L. peru*, under a higher initial harvest rate (40% vs. 30%). The harvest scenario are defined as a) the status quo away from the market in La Paz, b) market-driven size selection, c) market-drive size selection plus institutional constraints (IC), and d) market-driven size selection plus by-catch (BC). Error bars are 95% confidence intervals.

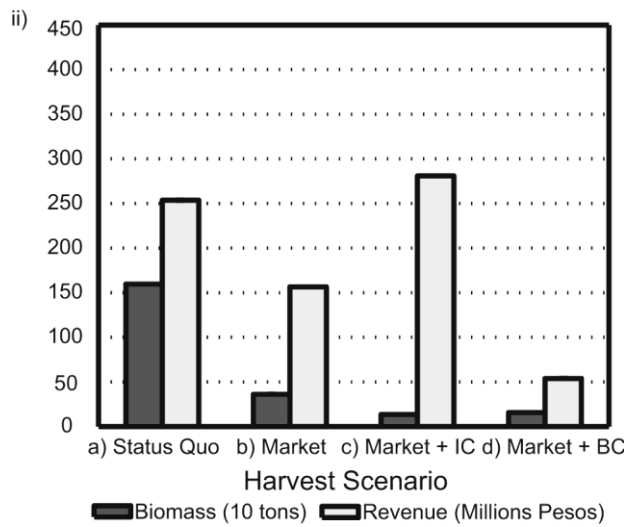
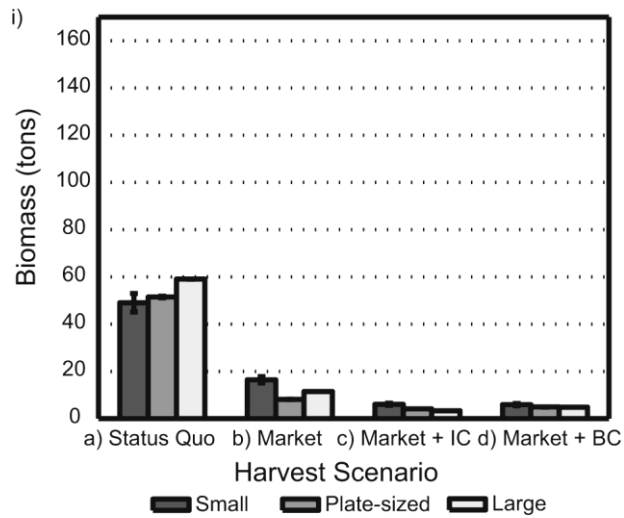


Fig. S3 i) Biomass of *L. peru* by size class and harvest scenario and ii) Biomass and revenue of *L. peru* by harvest scenario, under a higher initial harvest rate (40% vs. 30%) and including effects of new entrants to the fishery. The harvest scenario are defined as a) the status quo away from the market in La Paz, b) market-driven size selection, c) market-drive size selection plus institutional constraints (IC), and d) market-driven size selection plus by-catch (BC). Error bars are 95% confidence intervals.

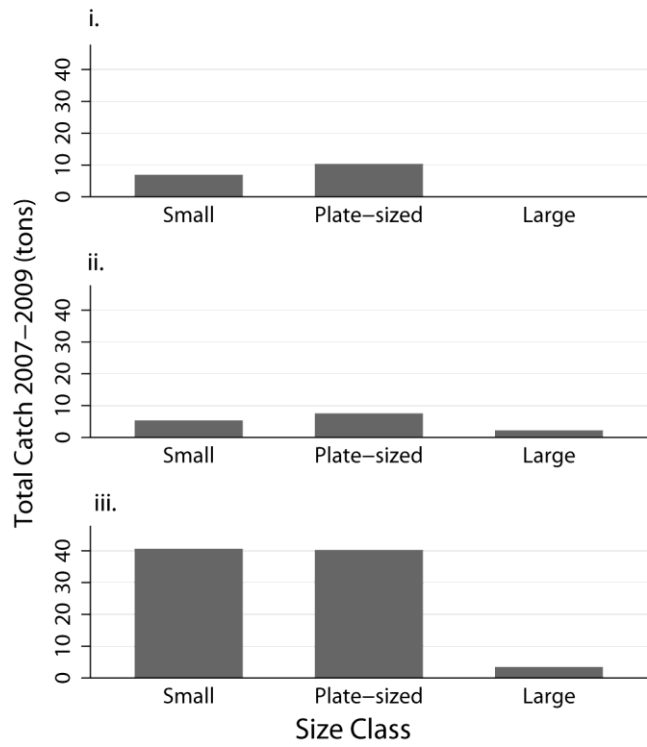


Fig. S4. The total catch of *L. peru* by size class and cooperative as reported in the logbook data over the study period 2007-2009: i) Dorado, ii) Pichilingue, iii) Sargento.

1 **Text S1. Fish Population Model**

2 We developed an age-based non-linear matrix population model of *L. peru* with projection intervals of
3 one year because age-specific demographic information was available for *L. peru* and related snappers.
4 We then reduced the age-based model to stages that correspond to the size classes recognized in the
5 market. Although the age-based model contains more information than the stage-based model, which
6 averages the age-specific information into three stages, the stage-based model is used because it allows
7 harvest to be added.

8 Both models are nonlinear because we assume a dependency between recruitment and adult
9 stock in which the density of the adult stock negatively affects the average fecundity of individuals
10 and/or pre-recruit survival and consequently the size of the recruited class (1-4). Our models employ a
11 compensatory Beverton and Holt function (see equation (2) below) that determines pre-recruit survival
12 based on total egg density, M .

13

14 ***Age-based Model***

15 The population was divided into age classes up to a maximum age of 26 (5).

16
$$\begin{pmatrix} n_1 \\ n_2 \\ \vdots \\ n_{26} \end{pmatrix} (t+1) = \begin{pmatrix} l_1 f_1 & l_1 f_2 & \cdots & l_1 f_{26} \\ l_2 & 0 & \cdots & 0 \\ & \ddots & & \\ 0 & \cdots & l_{26} & 0 \end{pmatrix} \begin{pmatrix} n_1 \\ n_2 \\ \vdots \\ n_{26} \end{pmatrix} (t) \quad (1)$$

17 Survival from age class i to $i + 1$ is given by l_{i+1} , $i = 1, \dots, 25$ and average fecundity of each age class i is
18 given by f_i , $i = 1, \dots, 26$. Pre-recruit survival is defined by the following Beverton and Holt function:

19
$$l_1 = \frac{\alpha}{\beta + M} \quad (2)$$

20 where egg density, M , is defined as $M = \sum_{i=1}^{26} f_i n_i$. The parameter α represents the maximum
21 number of recruits in the population and β is the number of eggs needed to produce $\alpha / 2$ recruits. We
22 use a Beverton and Holt function that determines pre-recruit survival from egg density, M , rather than
23 adult stock, N , because adults and pre-recruits inhabit separate habitats (5-7). The different habitats of
24 adults and pre-recruits suggests that pre-recruit mortality is affected by egg density, through starvation
25 or vulnerability to predators, rather than the adult stock, through problems such as cannibalism.

26

27 **Parameters Estimates**

28 We derived estimates of the age-specific parameters, survivorship and fecundity, and the Beverton-Holt
29 parameters, α and β , from the literature on *Lutjanus peru* and related species to create the age-based
30 model.

31 Survivorship is the complement of mortality. Natural mortality estimates were taken from a
32 relationship between natural mortality and weight in marine fish (8)

33
$$Z = 3.69 \times W^\gamma \quad (3)$$

34 where Z is annual mortality, W is total weight in kilograms, and $\gamma = -0.305$.

35 Fecundity was estimated using a relationship between fecundity and weight determined for the
36 vermillion snapper, *Rhomboplites aurorubens* (9)

37
$$f = \exp(10.21 + 0.002W) \quad (4)$$

38 where W is total weight in kilograms and f is annual fecundity. Because our models count only
39 females, the fecundity estimate was scaled by the sex ratio given by Cruz-Romero *et al.* (10) to account
40 only for the eggs that would grow into adult females. The maximum length of the snappers sampled by
41 Grimes and Huntsman (9) was 57 cm, whereas *Lutjanus peru* may reach 95 cm (5, 11). We truncated the
42 fecundity estimate at age 10, at which point red snappers are 65 cm in length (determined by equation
43 (6) below) because extrapolating beyond the range of data adds uncertainty. We assumed that the
44 fecundity of individuals greater than age 10 remained constant for the remaining ages. We considered
45 this truncation to be plausible because over ninety-nine percent of the population is between the ages
46 1-10 (see Model Characteristics) and fish may experience a natural decrease in fecundity due to
47 senescence despite substantial increases in fecundity with age (12).

48 We transformed the weight-specific mortality and fecundity from equations (3) and (4) into age-
49 specific estimates of mortality and fecundity using known weight-length and length-age relationships.
50 Rocha-Olivares (5) reports the following weight-length relationship and von Bertalanffy growth function
51 (VBGF) for *L. peru*:

$$52 \quad W = 1.816 \times 10^{-5} L^{2.905} \quad (5)$$

$$53 \quad L_t = 92.85(1 - e^{-0.12(t+0.14)}) \quad (6)$$

54 Where L is total length given in centimeters, t is age given in years, and W is total weight in kilograms.
55 These equations were used along with fecundity and survival equations to determine age-specific
56 parameters for the matrix model.

57 Figure S5 shows the resulting age-specific survivorship and fecundity estimates. Fecundity is an
58 increasing function of age after the first year. Fecundity increases at an increasing rate with gains in
59 fecundity increasing dramatically after age 5.

60 The parameters for the Beverton and Holt function were specific to *Lutjanus peru* and taken
61 from Diaz-Urbe *et al.* (13). The Beverton and Holt function presented by Diaz-Urbe *et al.* (13) was in
62 terms of total population size N , so we nondimensionalized the parameters in order to use them in a
63 Beverton and Holt function in terms of total egg production, M . In addition we scaled the parameters
64 to account for only females because the model in Diaz-Urbe *et al.* (13) counted total population. The
65 resulting parameter values were $\alpha_{\text{age}} = \alpha_{\text{stage}} = 5.94 \times 10^5$ individuals, $\beta_{\text{age}} = 6.59 \times 10^9$ eggs, and
66 $\beta_{\text{stage}} = 5.29 \times 10^9$ eggs (the values of β differ because the fecundity estimates differ slightly between
67 the two models).

68

69 **Stage-based Model**

70 We derived a stage-based model from the age-based model in order to incorporate the available harvest
71 data into the population model. Fishermen recognize three size classes or stages: small "chico" (<20 cm),
72 medium or plate-sized "mediano" or "orden" (20-35 cm), and large "grande" (>35 cm). Using equation
73 (6), we estimated the corresponding ages to be: small, 0 to 1 yrs; plate-sized 2-5 yrs; and large, 6 yrs to
74 26 yrs. Just as in the age model, we truncated the stages at a maximum of 26 years to reflect the oldest
75 observed individual. The following non-linear matrix population model is used to represent the
76 evolution of the population as determine by stage-specific parameters:

$$77 \begin{pmatrix} n_1 \\ n_2 \\ n_3 \end{pmatrix} (t+1) = \begin{pmatrix} P_1 & l_1 F_2 & l_1 F_3 \\ G_1 & P_2 & 0 \\ 0 & G_2 & P_3 \end{pmatrix} \begin{pmatrix} n_1 \\ n_2 \\ n_3 \end{pmatrix} (t) \quad (7)$$

78

79 where pre-recruit survival, l_1 , is defined the same as in the age-based model (see equation (2)) above.

80 Because the length of time an individual is in a stage does not necessarily equal the projection
81 interval, in this case one year, a stage-based model must take into account the probability of surviving
82 and progressing to the next stage, G , as well as the probability of surviving but remaining in the same
83 stage, P . To calculate P and G the processes of growth and survival must be separated.

$$84 \quad \sigma_i = \text{Prob}(\text{survival of an individual in stage } i) \quad (8)$$

$$85 \quad \gamma_i = \text{Prob}(\text{growth from stage } i \text{ to } i + 1 \mid \text{survival in stage } i) \quad (9)$$

$$86 \quad G_i = \sigma_i \gamma_i \quad (10)$$

$$87 \quad P_i = \sigma_i(1 - \gamma_i) \quad (11)$$

88 Note that σ_i is the same as l_i in the age-based model and γ_i is not directly measurable but may be
89 inferred through other data (14).

90 We derived the parameters for the stage-based model from the age-based model, assuming
91 that in-stage age distributions are the same as the age distribution that results from the age-based
92 model. The age range of each stage was found using the growth function (equation 6) and the stable age
93 distribution of the nonlinear age-based model (i.e. the eigenvector associated with the eigenvalue $\lambda=1$)
94 was used to weight the averages of the age-specific parameters for each stage:

$$95 \quad F_j = \frac{\sum_{i=t}^{t+S} f_i d_i}{\sum_{i=t}^{t+S} d_i}$$
$$\sigma_j = \frac{\sum_{i=t}^{t+S} l_i d_i}{\sum_{i=t}^{t+S} d_i}$$
$$W_j = \frac{\sum_{i=t}^{t+S} w_i d_i}{\sum_{i=t}^{t+S} d_i}$$

96 Where f_i , l_i , and w_i the fecundity, survivorship and weight of age each class i , $i = 1, \dots, 26$, and
97 F_j , σ_j and W_j the fecundity, survivorship and weight of each stage j , $j = 1, 2, 3$, which contains
98 individuals age t to $t + S$. The parameters P and G for the stage-based model were estimated with
99 σ_j and equations (10) and (11).

100 Figure S6 shows the resulting parameters for the stage-based model. Fecundity in the third
101 stage is much higher than in the second stage and fecundity in the first stage is zero. The probability of
102 growing to the next stage decreases with the stage and is inversely related to the probability of staying
103 in the stage. The probability of staying in the first stage is zero because the duration of this stage is only
104 one year.

105

106 ***Model Characteristics***

107 Running both the age- and stage-based models to equilibrium gives the population size and structure of
108 a pristine population, that is, one free of fishing pressure (*note*: both models count only females) (Figs.
109 S7-S8). The estimates of the population size; however, depend on initial conditions (i.e. the scale of the
110 system). Given that the purpose of these models is to simulate relative changes due to fishing rather
111 than estimate the actual population near La Paz, Mexico, we will focus on differences between the
112 models and different scenarios rather than on absolute estimates from the models.

113 Ideally, the age- and stage-based models would produce the same population estimates,
114 however, in averaging the parameters to reduce the age-based model to a 3-stage model, information is
115 inevitably lost. The equilibrium population sizes for both models were similar ($\hat{N}_{\text{age}} = 6.75 \times 10^5$
116 individuals and $\hat{N}_{\text{stage}} = 6.81 \times 10^5$ individuals) (Figs. S7-i, S8-i); however, the resulting total biomass and
117 total egg production for the two models differed more. Total biomass for the age- and stage-based

118 models was $\hat{B}_{\text{age}} = 8.63 \times 10^4$ kg and $\hat{B}_{\text{stage}} = 1.20 \times 10^5$ kg, respectively (Figs. S7-ii, S8-ii). The stage-
119 based model overestimates the number of individuals in Stage 3 and consequently overestimates the
120 biomass of this stage and the total biomass of the population, as well (Figs. S7-S8). Total egg production
121 was underestimated by the stage-based model, $\hat{M}_{\text{stage}} = 4.06 \times 10^9$, as compared to the age-based
122 model, $\hat{M}_{\text{age}} = 5.01 \times 10^{10}$.

123 In the age-based model, the population is concentrated within the younger age classes. In fact,
124 99.65% of the population is found within ages 1 to 10. Similarly, in the stage-based model, 93.98% of the
125 population falls within the first two stages, in which individuals range from ages 1 to 5. Sixty-seven
126 percent of the population's biomass, however, resides in Stage 3, because, even though there are fewer
127 individuals in this stage, they are heavier than individuals in Stages 1 and 2.

128

129 *Sensitivity Analysis of Stage-based model*

130 We examined the elasticity, or proportional sensitivity, of the output variables (total population size, N
131 , total egg production, M , and total biomass, B) to the stage-based model parameters (F , α , β , P ,
132 G) (Table S5). It is difficult to interpret the elasticity of the output variables to P and G because these
133 parameters must sum to σ and cannot be altered independently; therefore, we present the elasticity of
134 the output variables to σ . Elasticities of N and B were calculated manually while the elasticity of M
135 was derived analytically. It should be noted that in a linear model, elasticities are less than one, but
136 because our models is nonlinear, elasticities may exceed unity.

137 Total egg production and biomass were more sensitive to the survival parameter of Stage 3, σ_3 ,
138 than to the survival parameters of the other two stages, but total population was less sensitive to this
139 parameter. Stage 3 is has the largest average weight and the highest fecundity, explaining why altering

140 survival and consequently the size of this stage may have the largest effect on M and B . The number
141 of individuals, which is determined by egg production, in Stage 1 and their survival has the largest effect
142 on N because the size of this stage bounds the size of the subsequent stages and thus total population
143 size.

144 Reducing or augmenting the survival of Stage 3 will only directly affect the size of Stage 3,
145 however, this may alter total egg production, M , which could affect the size of Stage 1. This presents
146 the question of why survival of Stage 3 doesn't have a greater effect on N . The Beverton and Holt
147 function bounds the amount of eggs that can survive to Stage 1, creating a saturation point after which
148 an increase in M will not affect the number of recruits. If total egg production of the equilibrium
149 population is greater than the saturation level, the new M produced by changes in survivorship of
150 Stage 3 may also be above saturation and Stage 1 will not be affected.

151 The elasticity of M , N , and B with respect to fecundity of Stage 3 is greater than that of Stage
152 2, suggesting that the fecundity of the older, more reproductive fish is more crucial to population
153 dynamics than that of smaller, less reproductive fish.

154 The total population size was the most elastic to the Beverton and Holt parameter α , which
155 bounds the number of recruits to the population and thus the population size. Total biomass and egg
156 production were also highly elastic to α , because the effect of α on total population size will in turn
157 affect total egg production and total biomass. Total population size, total biomass, and total egg
158 production were least elastic to the Beverton and Holt parameter β . As M grows, β becomes
159 insignificant and Stage 1 approaches equilibrium value α . At large values of M , the magnitude of β
160 determines how quickly Stage 1 reaches α rather than population size.

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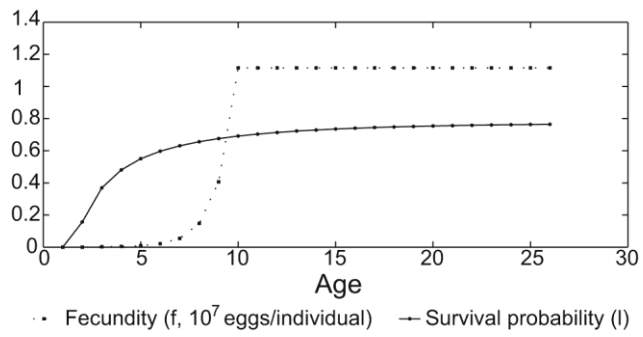
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207 **Figures**



208

209 Figure S5. Estimates of survival probability and fecundity for *L. peru* by age.

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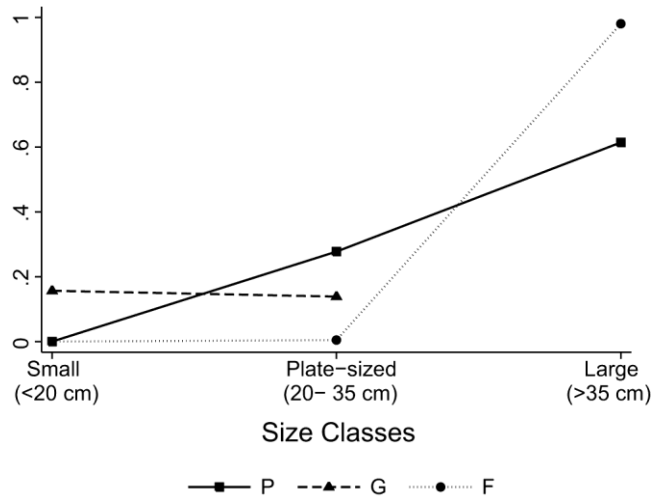
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223 Figure S6. Stage-based model parameters: P, probability of staying in a stage; G, probability of surviving

224 and growing to the next stage; and F, fecundity (millions of eggs).

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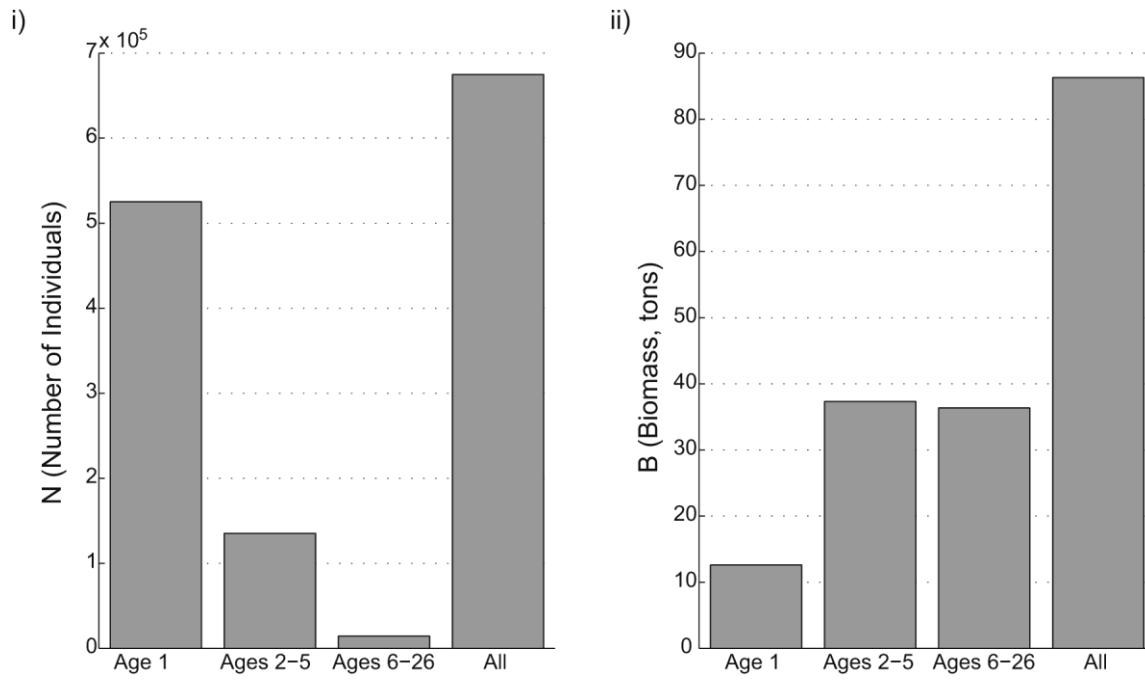
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236 Figure S7. Equilibrium population estimates from the age-based model: i) number of individuals and ii)

237 biomass.

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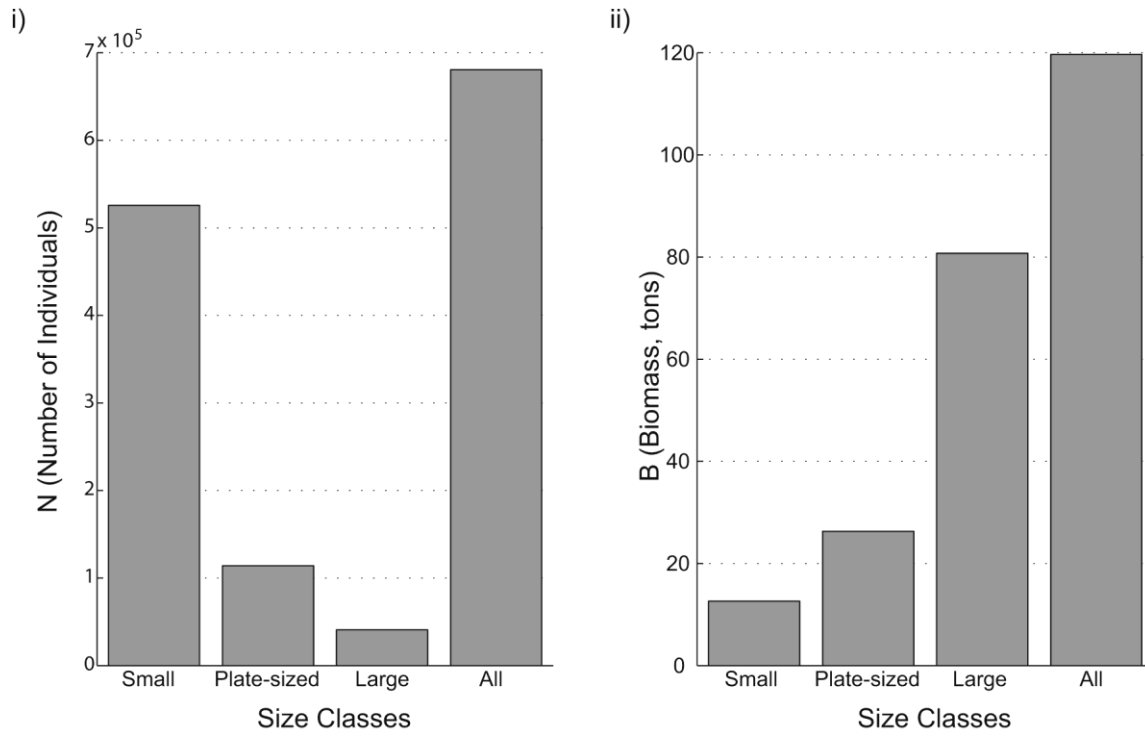
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251 Figure. S8. Equilibrium population estimates from the stage-based model: i) number of individuals and ii)

252 biomass.

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264 Table S5. Elasticity of total egg production (M), total population size (N), and total population
265 biomass (B) with respect to the model parameters.

Parameter	M	N	B
σ (1)	1.13	0.36	1.02
σ (2)	1.39	0.29	1.07
σ (3)	1.65	0.28	1.19
F(1)	NA	NA	NA
F(2)	0.02	0.00	0.00
F(3)	1.12	0.13	0.13
α	1.13	1.13	1.13
β	-0.13	-0.13	-0.13

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