

If you build it, they will come: coastal amenities facilitate human engagement in marine protected areas

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Abstract:	1. Calls for using marine protected areas (MPAs) to achieve goals for nature and people are increasing globally. While the conservation and fisheries impacts of MPAs have been comparatively well studied, impacts on other dimensions of human use have received less attention. Understanding how humans engage with MPAs and identifying traits of MPAs that promote engagement is critical to designing MPA networks that achieve multiple goals effectively, equitably, and sustainably. 2. In this paper, we characterize human engagement in California's MPA network, the largest scientifically-based network of MPAs in the world (124 MPAs spanning 16% of state waters and 1,700 km of coastline), and identify traits associated with higher human engagement. We assemble and compare diverse indicators of human engagement that

	<p>capture recreational, educational, and scientific activities across California's MPAs.</p> <p>3. We find that human engagement is correlated with nearby population density and that site "charisma" can expand human engagement beyond what would be predicted based on population density alone. Charismatic MPAs tend to be located near tourist destinations, have long sandy beaches, and be adjacent to state parks and associated amenities. In contrast, underutilized MPAs were often more remote and lacked both sandy beaches and parking lot access.</p> <p>4. Synthesis and applications: These results suggest that achieving MPA goals associated with human engagement can be promoted by developing land-based amenities that increase access to coastal MPAs or by locating new MPAs near existing amenities during the design phase. Furthermore, managers may want to prioritize monitoring, enforcement, education, and outreach programs in MPAs with traits that predict high human engagement. Understanding the extent to which human engagement impacts the conservation performance of MPAs is a critical next step to designing MPAs that minimize tradeoffs among potentially competing objectives.</p>

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1 If you build it, they will come: coastal amenities 2 facilitate human engagement in marine protected areas

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27 Abstract

- 28 1. Calls for using marine protected areas (MPAs) to achieve goals for nature and people
29 are increasing globally. While the conservation and fisheries impacts of MPAs have
30 been comparatively well studied, impacts on other dimensions of human use have
31 received less attention. Understanding how humans engage with MPAs and identifying
32 traits of MPAs that promote engagement is critical to designing MPA networks that
33 achieve multiple goals effectively, equitably, and sustainably.
- 34 2. In this paper, we characterize human engagement in California's MPA network, the
35 largest scientifically-based network of MPAs in the world (124 MPAs spanning 16% of
36 state waters and 1,700 km of coastline), and identify traits associated with higher human
37 engagement. We assemble and compare diverse indicators of human engagement that
38 capture recreational, educational, and scientific activities across California's MPAs.
- 39 3. We find that human engagement is correlated with nearby population density and that
40 site "charisma" can expand human engagement beyond what would be predicted based
41 on population density alone. Charismatic MPAs tend to be located near tourist
42 destinations, have long sandy beaches, and be adjacent to state parks and associated
43 amenities. In contrast, underutilized MPAs were often more remote and lacked both
44 sandy beaches and parking lot access.
- 45 4. *Synthesis and applications:* These results suggest that achieving MPA goals associated
46 with human engagement can be promoted by developing land-based amenities that
47 increase access to coastal MPAs or by locating new MPAs near existing amenities
48 during the design phase. Furthermore, managers may want to prioritize monitoring,
49 enforcement, education, and outreach programs in MPAs with traits that predict high
50 human engagement. Understanding the extent to which human engagement impacts the
51 conservation performance of MPAs is a critical next step to designing MPAs that
52 minimize tradeoffs among potentially competing objectives.

53

54 **Keywords:** California, marine protected areas, citizen science, community engagement,
55 tourism, recreation, human dimensions

56 1. Introduction

57 Marine protected areas (MPAs) – places where human activity, especially extractive
58 practices such as fishing, is prohibited or restricted – are a common ocean management tool
59 used to achieve a mixture of conservation, fisheries, and cultural objectives (Erskine et al.,
60 2021; Grorud-Colvert et al., 2021; Marcos et al., 2021). By restricting extractive and destructive
61 human activities, adequately designed, funded, and regulated MPAs can increase the diversity
62 and abundance of marine fish and invertebrates (Edgar et al., 2014; Gill et al., 2017; Goetze et
63 al., 2021; Zupan et al., 2018) and the function and resilience of marine ecosystems (Cheng et
64 al., 2019; Mellin et al., 2016). In the long term, and with concerted stakeholder engagement and
65 buy-in, well-designed MPAs can also yield fisheries benefits through increased productivity and
66 spillover resulting from improved biomass and age structure of populations in the MPA (Di
67 Lorenzo et al., 2020; Marshall et al., 2019). Furthermore, MPAs can facilitate and enhance other
68 non-extractive human engagement in ocean ecosystems, such as cultural activities, recreation
69 and tourism, education and outreach, and scientific research (Angulo-Valdés & Hatcher, 2010;
70 Ban et al., 2019; Erskine et al., 2021; Roncin et al., 2008).

71

72 While the ability and prerequisites for MPAs to achieve conservation and fisheries
73 objectives have been comparatively well-studied (e.g., Claudet et al., 2008; Edgar et al., 2014;
74 Giakoumi et al., 2017; Goñi et al., 2010; Lester & Halpern, 2008; Wilson et al., 2020), the
75 enabling conditions for sustainably achieving other human use objectives has received less
76 attention (Ban et al., 2019; Erskine et al., 2021; Gerber et al., 2003; Naidoo et al., 2019;
77 Turnbull et al., 2021). This is surprising given the frequency with which human engagement
78 objectives – such as recreation, education, and scientific research – are identified in
79 international, national, and regional MPA planning documents. For example, the Independent
80 World Commission on the Oceans identifies the “*provision of areas for scientific research,
education, and recreation*” as a key benefit of MPAs (IWCO, 1998). Similarly, the U.S.
82 Framework for the National System of Marine Protected Areas identifies the benefits of U.S.
83 MPAs as: (1) “*supporting social and economic benefits [including] coastal tourism*”, (2)
84 “*providing new educational opportunities*”, and (3) “*enhancing research opportunities*” (NOAA,
85 2015). Evaluating human engagement in MPAs is needed to track progress towards achieving
86 these objectives and for identifying the design principles that promote sustainable human
87 engagement in MPAs. Here, we use California’s MPA network, the largest scientifically-based

88 MPA network in the world, as a case study for identifying conditions that promote human
89 engagement in MPAs.

90

91 In 1999, the California state legislature passed the Marine Life Protection Act (MLPA),
92 which directed the state to use the best available science to redesign and greatly expand its
93 system of MPAs to function as a coherent network and to address six goals in service of
94 conservation, fisheries, and other cultural objectives (Marine Life Protection Act, 1999; Gleason
95 et al., 2013). In addition to goals to preserve biodiversity and ecosystem function and to sustain,
96 conserve, protect, and rebuild marine populations, including those of economic value, the MLPA
97 also included a goal to *"improve recreational, educational, and study opportunities provided by
98 marine ecosystems that are subject to minimal human disturbance, and to manage these uses
99 in a manner consistent with protecting biodiversity."* From 2004 to 2012, a stakeholder-driven
100 and science-guided design process led to a coordinated network of 124 MPAs, containing 16%
101 of state waters, along California's 1,770 km (1,100 miles) coastline. Following implementation,
102 an extensive monitoring effort began to ensure that the network could undergo adaptive
103 management (Botsford et al., 2014). While some monitoring programs were developed around
104 human engagement in MPAs (e.g., the MPA Watch citizen science program; MPA Watch,
105 2022a), the majority of the monitoring effort was focused on the ecological goals of the MLPA
106 and on elucidating ecological responses to MPA implementation.

107

108 In this paper, we characterize human engagement in California's MPA network and
109 identify traits associated with high engagement. We assemble and evaluate diverse indicators of
110 engagement that capture a range of recreational, educational, and scientific activities. We then
111 relate levels of human engagement to population density, accessibility, amenities, and other
112 traits likely to influence engagement. This provides a rare quantification of the ways in which
113 people engage with MPAs and the potential pathways for enhancing or limiting engagement
114 based on management goals. These insights are helpful as California (Executive Order N-82-
115 20, 2020), the United States (Executive Order on Tackling the Climate Crisis at Home and
116 Abroad, 2021), and the world (CBD, 2021) consider expanding MPA coverage to meet an array
117 of conservation, fisheries, and other cultural objectives (Sullivan-Stack et al., 2022).

118 2. Methods

119 2.1 Marine protected areas

120 California's coastal waters are protected by a mosaic of spatial management areas that
121 vary in regulatory authority and protection status (**Fig. 1A; Table S1**). State-managed areas
122 include: (1) state marine reserves (SMRs), which prohibit all fishing; (2) state marine
123 conservation areas (SMCAs), which restrict some types of fishing, except for within special no-
124 take SMCAs, which prohibit all fishing; (3) state marine recreational managed areas (SMRMAs),
125 which restrict fishing but allow hunting of waterfowl; (4) state marine parks (SMPs), which
126 prohibit commercial fishing; and (5) special closures, which restrict activity around seabird
127 colonies and marine mammal haulouts and are the only designation not defined as an MPA by
128 the MLPA (**Table S1**). Federal marine reserves and conservation areas (FMRs and FMCAs,
129 respectively) extend certain SMRs and SMCAs around the Channel Islands into federal waters
130 (**Fig. 1A**).

131

132 We focus on the 124 MPAs that the MLPA identifies as being part of California's state-
133 managed coastal MPA network (**Fig. 1A; Table S1**). This excludes federally managed MPAs
134 around the Channel Islands; SMRAs and SMPs in San Francisco Bay, which were established
135 before the MLPA planning process and are not coastal; and special closures, which are not
136 identified as MPAs by the MLPA. We refer to the resulting network of 49 SMRs, 60 SMCAs, 10
137 no-take SMCAs, and 5 SMRMAs as California's state MPA network. While the Channel Islands
138 MPAs were established before the MLPA planning process, they have been legally incorporated
139 into the network. The four MLPA regions (South, Central, North Central, and North Coasts; **Fig.**
140 **1**) encompass a wide range of ecological dynamics, coastal features and oceanographic
141 environments, cultures, and economies.

142 2.2 Surrounding human communities

143 We characterized the human population living near MPAs using population
144 demographics data from the 2010 U.S. Census (USCB, 2010a). We downloaded total
145 population estimates by census block, the smallest geographic unit used in the census, using
146 the *tidycensus* R package (Walker et al., 2022) and calculated the density of people living within
147 each block. We rasterized (500x500 m resolution) these data and calculated the number of
148 people living within a 50 km radius (~31 miles) of each MPA (**Fig. 1B**). The number of people

149 living within 50 km is generally ($r^2 > 0.8$) correlated with population densities using buffer
150 distances ranging from 10 to 100 km (~6-60 miles) (**Fig. S1**).

151

152 We also estimated the social vulnerability of these populations using twelve indicators
153 identified by (Jepson & Colburn, 2013) and collected by the U.S. Census American Community
154 Survey (USCB, 2010b). These indicators describe various metrics of poverty status, housing
155 characteristics, labor force structure, and population composition (**Table S2; Figures S2-S4**).
156 We downloaded these indicators by census tract, the smallest geographic unit for which all of
157 the indicators were available (one level larger than census block), also using the *tidycensus* R
158 package (Walker et al., 2022). We combined these indicators into a single social vulnerability
159 index by averaging the z-scores of each indicator (i.e., indicators were centered on the
160 statewide average and scaled to unit variance). Thus, a value of zero indicates average
161 vulnerability across all of the various indicators, negative values indicate higher than average
162 vulnerability, and positive values indicate lower than average vulnerability. We rasterized the
163 tract-level index to match the population raster and calculated the average vulnerability of the
164 population within 50 km of each MPA as the population-weighted average of the social
165 vulnerability index.

166 2.3 Human engagement in protected areas

167 We developed indicators of human engagement in California's state MPA network using
168 a mixture of citizen science, naturalist, and state agency datasets (**Table S3**). Data from two
169 citizen science programs (MPA Watch and Reef Environmental Education Foundation) and two
170 naturalist social networks (iNaturalist and eBird) provide spatially referenced records of activities
171 (e.g., surfing, swimming, boating, tidepooling, diving, etc.) or observations of wildlife submitted
172 by individual users. Because social media engagement is correlated with visitation rates
173 (Tenkanen et al., 2017), these datasets provide useful indicators of recreational and educational
174 engagement in MPAs. Data from the California Department of Fish and Wildlife (CDFW) –
175 annual numbers of scientific permits and regulatory citations by MPA – provide useful indicators
176 of scientific research and regulatory compliance within California's state MPA network.

177

178 We used MPA Watch survey data to measure consumptive and non-consumptive
179 human activities in California's MPA network. MPA Watch is a citizen science program that
180 trains volunteers to observe and collect data on human engagement in protected areas (MPA
181 Watch, 2022a). Volunteers use a standardized survey protocol (MPA Watch, 2022b) to record

182 consumptive (e.g., fishing) and non-consumptive (e.g., surfing, boating, tidepooling, running,
183 etc.) activities occurring both on- and off-shore of coastal sampling sites (**Table S4**).
184 Consumptive activities are classified as either active (e.g., fishing line in water) or inactive (e.g.,
185 fishing pole on boat but not being used); we focus on active consumptive activities. MPA Watch
186 has been in operation since 2011 and, as of writing, has conducted over 33,000 surveys in 49
187 MPAs (47 of which meet our inclusion criteria) and 60 control (non-MPA) locations (**Fig. S5**).
188 While some MPAs have been surveyed consistently since 2011, others did not receive
189 consistent visits until 2015 or later (**Fig. S5A**). To allow comparison between sites with variable
190 temporal coverage, we limited analysis to surveys that took place from January 1, 2015 to
191 December 31, 2021. To eliminate spurious results from surveys that were conducted either
192 early in the morning or late at night or were either shorter or longer than the official protocol
193 (MPA Watch, 2022b), we also limited analysis to surveys that occurred between 6AM and 8PM
194 and lasted between 10 and 60 minutes (**Fig. S5BC**). We quantified human engagement by MPA
195 in terms of (1) the percent of surveys in which an activity was observed and (2) the median
196 number of activities observed per hour for surveys in which activities were observed (zeroes
197 excluded because of high zero-inflation) (**Figs. S6 & S7**).
198

199 We used iNaturalist submission records to measure engagement in wildlife observation
200 within and adjacent to MPAs. iNaturalist is a web- and app-based platform that allows observers
201 to submit wildlife photos for identification by amateur and professional naturalists (iNaturalist,
202 2022). iNaturalist was launched in 2008 and as of writing, has more than 100 million
203 observations, 2 million observers, and 380,000 observed species globally. We used the *rnat* R
204 package (Barve et al., 2021) to download all iNaturalist observations submitted by users in a
205 bounding box spanning the California coastline from January 1, 2000 to December 31, 2021
206 (iNaturalist allows back submissions, hence the availability of pre-2008 observations). We
207 defined MPA-associated observations as observations occurring within 100 meters of an MPA
208 and quantified human engagement from 2012 through 2021 by MPA in terms of the number of
209 (1) unique observers (number of iNaturalist users who submitted wildlife observations) and (2)
210 observations (number of entries submitted). More than 5,800 observers have submitted >72,000
211 observations associated with 121 of California's state MPAs (**Figs. S8 & S9**).
212

213 We used eBird submission records to measure engagement in birding within and
214 adjacent to MPAs. eBird is a global program that collates observations of birds submitted by
215 birdwatchers (eBird, 2022). It was launched in 2002 by the Cornell University Lab of Ornithology

216 and the National Audubon Society but allows back submissions from birding diaries. As a result,
217 eBird contains observations dating back centuries in many locations. As of writing, the eBird
218 includes over 69.7 million submissions from nearly 800,000 birders. We downloaded eBird
219 observations from California and, as with the iNaturalist data, identified observations occurring
220 within 100 meters of an MPA from 2012 through 2021. We quantified human engagement by
221 MPA in terms of the number of (1) unique observers and (2) observations. More than 19,000
222 birders have conducted >193,000 surveys and made >3.8 million submissions to eBird
223 associated with 114 of California's state MPAs (**Figs. S10 & S11**).

224

225 We used Reef Environmental Education Foundation (REEF) diver surveys as an
226 indicator of engagement in diving and snorkeling in California's MPAs. REEF is an international
227 marine conservation organization that trains volunteer SCUBA divers and snorkelers to collect
228 and report information on marine fish and select invertebrate and algae species during
229 recreational SCUBA dives and snorkels (REEF, 2022). The diver survey program was launched
230 in 1993 and, as of writing, has >250,000 surveys by 16,000 volunteers at 15,000 sites
231 worldwide. We received records of >14,700 surveys conducted in California and identified 4,085
232 surveys occurring within 41 of California's state MPAs from 2012 through 2021 (**Figs. S12 &**
233 **S13**). We quantified human engagement by MPA in terms of the (1) number of surveys
234 conducted and (2) number of years in which a survey was conducted.

235

236 We used records of scientific permits issued by CDFW for research conducted within
237 California's MPA network as an indicator of the contributions of MPAs to scientific knowledge.
238 While permits are required for any extractive or manipulative research in California's coastal
239 waters, purely observational research (i.e., research without capturing, handling, etc.) does not
240 require permits; thus, the permit data may underestimate the amount of research occurring in
241 the network. From 2012-2021, 5,329 scientific permits were issued for research in all 124 of
242 California's state MPAs (**Figs. S14 & S15**). We quantified human engagement by MPA in terms
243 of the (1) number of permits issued and (2) number of years in which permits were issued.

244

245 We used records of citations issued by the CDFW Law Enforcement Division for
246 regulatory violations occurring within California's MPA network as an indicator of compliance.
247 From 2016-2021, 2,812 citations were issued for violations occurring within 85 of California's
248 state MPAs (**Figs. S16 & S17**). We quantified noncompliance by MPA in terms of the (1)
249 number of citations issued and (2) number of years in which citations were issued. We used

250 generalized linear models assuming a Poisson distribution to evaluate the correlation between
251 the total number of citations issued within an MPA and human population density, human
252 engagement (defined using the iNaturalist observer data), and observations of active fishing
253 (defined using the MPA Watch survey data).

254

255 To compare human engagement across indicators (**Fig. 2**), we selected key metrics for
256 each indicator (**Table S3**) to display in an engagement scorecard (**Fig. 3**). We centered each
257 metric on its mean and scaled it to unit variance to facilitate comparisons across indicators. We
258 also measured and compared the degree to which engagement is concentrated within specific
259 MPAs, a metric of the selectivity of users, by developing the engagement accumulation curves
260 shown in **Figure 4**. We developed these curves by first calculating the percent contribution of
261 each MPA to network-wide engagement for each of the metrics selected for the scorecard. We
262 then plotted the accumulation of these contributions beginning with the MPA with the highest
263 engagement and ending with the MPA with the lowest engagement. The steeper the resulting
264 curve, the more network-wide engagement is dominated by a few MPAs.

265 2.4 Drivers of human engagement

266 We hypothesized that human engagement in MPAs would be correlated with nearby
267 population density (Cinner et al., 2018; Ravenstein, 1885) except for (1) “charismatic” MPAs
268 that draw participation from afar and thus generate more engagement than would be predicted
269 based on nearby population density, and (2) “underutilized” MPAs that are difficult to access
270 (e.g., located offshore, limited road access, etc.) and thus generate less engagement than
271 would be predicted based on nearby population density. To distinguish charismatic and
272 underutilized MPAs, we regressed human engagement (as measured by the number of
273 iNaturalist observers) against population density and extracted the MPAs that fell above
274 (charismatic) or below (underutilized) 75% of the fitted values (**Fig. 5**). For this model, we used
275 the number of iNaturalist observers as our measure of human engagement because it was the
276 most spatially comprehensive indicator (i.e., describes engagement in the greatest number of
277 MPAs) and it correlates with all of the indicators of non-extractive engagement (i.e., it is not
278 correlated with citations or consumptive activities; **Fig. S18**).

279

280 We used logistic regression to identify traits associated with charismatic and
281 underutilized MPAs (**Fig. 6**). We considered 13 traits describing a range of MPA design features
282 (age, size, protection level), habitats (sandy beach, rocky intertidal, kelp, estuary), accessibility

283 and amenities (distance to port; number of parks, parking lots, campgrounds, and picnic areas
284 within 1 km), and the social vulnerability index. See **Table S5** for the source of each explanatory
285 variable. We then used a series of logistic regressions to evaluate the association between
286 engagement (charismatic vs. typical and underutilized vs. typical) and these traits. We defined
287 the logistic target level for each model based on “typical” MPAs (response of 0) versus
288 charismatic or underutilized (response of 1). Logistic models were constructed stepwise after a
289 *priori* identifying relevant drivers of engagement. The best fitting models were selected using
290 Akaike Information Criterion (AIC) (Akaike, 1974) to identify the most parsimonious model of the
291 relationship between engagement and the evaluated traits.

292 2.5 Comparison to non-MPA areas

293 The methods described above were used to determine which MPAs within California’s
294 MPA network generate the most human engagement and to identify the factors that drive
295 differences in the levels of engagement; however, they are unable to reveal whether MPAs
296 generate more, less, or equivalent human engagement as similar non-MPA areas. To
297 understand the degree to which MPA designations impact human engagement in coastal areas,
298 we rasterized California’s state waters into 200 m raster cells and paired each MPA cell with a
299 non-MPA counterfactual cell with otherwise similar properties. We identified non-MPA
300 counterfactual cells that were similar to their MPA reference cells in their depth (m), distance
301 from shore (km), nearby population density, proximity to parks, and proximity to public beaches.
302 These matching variables were selected based on their association with engagement as
303 revealed through the regression analysis (**Fig. 6**). We derived these values for both MPA and
304 counterfactual cells using the sources listed in **Table S6**. We identified suitable counterfactuals
305 through statistical matching using the MatchIt package (Ho et al., 2011), using one-to-one
306 Mahalanobis distance matching with replacement and propensity score calipers of 0.20
307 standard deviations (Ho et al., 2007). After an appropriate counterfactual was identified for each
308 MPA cell (**Figure S19**), we calculated the log-response ratio of the sum of activities within each
309 MPA’s cells and its paired counterfactual cells for the three engagement indicators with
310 activities reported inside and outside MPAs using GPS coordinates (i.e., the iNaturalist, eBird,
311 and REEF indicators). We tested whether the mean log-ratio of these sums differed from zero
312 using t-tests (i.e., whether MPAs and non-MPAs generate different levels of human
313 engagement). Log-response ratios were calculated after adding 1 to the engagement values
314 occurring in both the numerator and denominator to avoid non-finite ratio values.
315

316 All data analysis and visualization was done in R (R Core Team, 2021) and all data and
317 code are available on GitHub here: <https://github.com/NCEAS/ca-mpa>

318 3. Results

319 3.1 Human engagement in protected areas

320 MPA Watch volunteers observed non-consumptive activities in the vast majority of
321 surveys conducted coastwide and within all of the 47 surveyed MPAs (**Fig. 2A**). MPA visitors
322 were most commonly observed walking and recreating on the beach, often with their pets.
323 Offshore recreation included boating, surfing, bodyboarding, and swimming. MPA visitors were
324 also often observed viewing wildlife and exploring tidepools (**Fig. S6BC**). MPAs in the South
325 Coast region were most popular, especially those near the metropolitan areas of San Diego and
326 Los Angeles (**Fig. 2A**).

327

328 MPA Watch volunteers observed active consumptive activities (i.e., fishing and hand
329 collection of organisms) in all but four of the 47 surveyed MPAs (**Fig. 2B**) but at rates
330 substantially lower than those observed for non-consumptive activities (**Fig. S7BC**). Hook and
331 line fishing was the most commonly observed consumptive activity and was observed in ~6% of
332 surveys within SMCAs (MPAs in which certain types of fishing are often allowed). However,
333 active hook and line fishing was also reported by volunteers in surveys in no-take SMCAs
334 (~1.8% of surveys) and SMRs (~2% of surveys) (**Fig. S7B**). Hand collection of organisms, trap
335 fishing, and spear fishing were the next most frequently reported consumptive activities. Net
336 fishing, dive fishing, commercial passenger fishing vessel (CPFV) fishing, and kelp harvest were
337 more rarely reported (**Fig. S7BC**). Observations of consumptive activities were more frequent in
338 South Coast MPAs and within SMCAs, which allow some types of harvest.

339

340 The number of people submitting wildlife observations to iNaturalist from within
341 California's MPA network increased through time (**Fig. S8BC**). The majority of observers submit
342 observations from only one MPA per year, but some observers make submissions from up to 21
343 MPAs per year (**Fig. S8C**). Observers are especially interested in plants (often land-based),
344 shells (mollusks), and seabirds (**Fig. S8B**). iNaturalist participation is especially high in the
345 touristic Monterey Bay area and secondarily high in the densely populated San Diego, Los
346 Angeles, and San Francisco areas (**Fig. 2C**). MPA engagement was less selective than

347 predicted by human population density for this form of human engagement (**Fig. 4**). On
348 average, California's MPAs have not generated more iNaturalist engagement than
349 counterfactual sites ($p=0.12$), indicating that non-MPA areas with similar features generate just
350 as much engagement as MPAs for this type of activity (**Fig. 7**).
351

352 Birders have been visiting California's MPAs since before they were designated as
353 protected areas (**Fig. S11BC**). The participation of birders in the eBird citizen science program
354 increased linearly from the 1960-2005 and exponentially since 2005 (**Fig. S11B**). Participation
355 has been greatest, in terms of number of birders submitting eBird observations, at popular
356 birding hotspots such as Bolsa Chica Basin SMCA, Elkhorn Slough SMR, Matlahuayl SMR,
357 Morro Bay SMRMA, and Point Reyes SMR (**Figs. 2D & 3**). MPAs within estuaries -- including
358 Bolsa Chica Basin, Elkhorn Slough, and Morro Bay -- generate a disproportionate amount of
359 eBird activity: despite representing only 2% of California's state MPA network by area (17% by
360 count), around 40% of recent annual visits to the network logged by eBirders have been within
361 estuarine MPAs (**Fig. S11C**). Despite the tendency for eBirders to visit estuarine MPAs, the
362 selectivity of birders was generally proportional to that predicted by population density (**Fig. 4**),
363 suggesting that estuarine MPAs are located in areas with high population density. On average,
364 California's MPAs have generated slightly more eBird engagement than counterfactual sites
365 ($p=0.02$), indicating that MPA status attracts engagement for this type of activity (**Fig. 7**).
366

367 The number of recreational divers and snorkelers contributing to the REEF citizen
368 science survey program from within California's MPA network increased from the program's
369 inception in 1994 to a peak in 2011, then decreased until a resurgence during the COVID-19
370 pandemic (2020-2021) (**Fig. S13BC**). Participants visited a range of habitats and depths but
371 generally favored kelp forests and rocky reefs (**Fig. S13BC**). The majority of participation has
372 come from MPAs with high profile dive sites including, in decreasing order of prevalence,
373 Matlahuayl SMR, Edward F. Ricketts SMCA, Point Lobos SMR, Pacific Grove Marine Gardens
374 SMCA, and Carmel Bay SMCA (**Figs. 2E & 3**). REEF divers have been more selective in their
375 MPA visitation than any of the other evaluated user groups (**Fig. 4**). California's MPAs have, on
376 average, generated much more REEF survey engagement than counterfactual sites ($p<0.0001$),
377 indicating that MPA status attracts engagement for this type of activity (**Fig. 7**).
378

379 The number of scientific permits issued for research within California's MPA network has
380 been variable through time and decreased during the COVID-19 pandemic (2020-2021) (**Fig.**

381 **S15B).** The distribution of scientific research throughout the MPA network has been more even
382 than other types of human engagement (**Fig. 4**). In general, fewer permits have been issued for
383 research in the North and North Central Coast regions and more permits have been issued for
384 research in the Central (especially Monterey Bay) and South (especially Los Angeles and San
385 Diego) Coast regions (**Figs. 2F & 3**), where academic institutions and marine science non-
386 profits are more highly concentrated. Scientific research in MPAs of different designations has
387 generally occurred in proportion to the representation of the different MPA designations within
388 the network (i.e., no bias towards no-take areas) (**Fig. S15C**).
389

390 The number of citations issued for regulatory violations was highest in MPAs in the
391 South Coast region, especially in the MPAs around Catalina Island, a major tourist destination
392 off the coast of Los Angeles (**Fig. S17A**). In general, the number of citations is positively
393 correlated with nearby human population size ($p<0.001$; **Fig. S17B**) and human engagement
394 ($p<0.001$; **Fig. S17C**) in MPAs, where engagement is defined as the total number of people
395 contributing iNaturalist observations from within an MPA from 2012-2021. Interestingly, the
396 number of citations was negatively correlated with the observation of active consumptive activity
397 by MPA Watch observers (**Fig. S17D**), which might indicate that the active consumptive activity
398 reported by MPA Watch observers is sanctioned. Citations were more highly concentrated in
399 certain MPAs than would be predicted by human population density alone (**Fig. 4**).

400 3.2 Drivers of human engagement

401 Across all indicators, human engagement in MPAs was highest in the populous South
402 Coast region and the touristic Monterey Bay area in the Central Coast region, and lowest in the
403 remote North Coast region (**Figs. 2 & 3**). We found that human engagement in MPAs was
404 correlated to nearby population density ($r^2=0.14$; $p<0.001$) but that MPA traits can enhance or
405 reduce engagement beyond what would be predicted based on population density alone (**Fig.**
406 **5**). Elevated engagement in 20 “charismatic” MPAs (MPAs whose engagement is greater than
407 would be expected based on population density) was associated with older MPAs with long
408 sandy beaches and many adjacent land-based parks (**Fig. 6; Table S7**). Reduced engagement
409 in 42 “underutilized” MPAs (MPAs whose engagement is lower than would be expected based
410 on population density) was associated with remoteness (i.e., far from the nearest port), lack of
411 sandy beaches, and lack of parking lot access (**Fig. 6; Table S7**).

412 4. Discussion

413 Understanding the ability and prerequisites for MPAs to achieve human use objectives is
414 central to designing MPA networks that provide multiple benefits to people and nature.
415 California's MPA network supports a diverse array of recreational, educational, and scientific
416 activities. Its MPAs are commonly used for recreational activities such as walking, playing, or
417 relaxing on the beach or boating, surfing, swimming, or SCUBA diving in the ocean.
418 Engagement in these activities makes important contributions to local economies (Pendleton &
419 Kildow, 2006) and to cultural, emotional, and physical health (Hipp & Ogunseitan, 2011;
420 Jacobson, 2020). Wildlife viewing is also common within California's MPAs and provides a
421 platform for education and research. Many visitors engage in MPAs through citizen science
422 programs that provide opportunities both to learn about the natural world and to contribute to
423 meaningful scientific datasets (Freiwald et al., 2018; Rapacciulo et al., 2021). Finally, scientific
424 researchers have utilized the MPA network as a "large-scale ecological experiment" (*sensu*
425 Jensen et al., 2012) to derive globally-relevant insights into MPA performance, marine ecology,
426 and fisheries and conservation science (e.g., Starr et al., 2015; White et al., 2021; Ziegler et al.,
427 2022).

428

429 However, not all MPAs generate equal levels of human engagement. In general,
430 engagement is positively correlated with surrounding human population density: the more
431 people living near an MPA, the more engagement an MPA generates. Charismatic MPAs,
432 MPAs that receive more engagement than would be expected based on nearby population
433 density, likely draw additional users because they have adjacent land-based attractions (i.e.,
434 parks) and associated amenities (e.g., parking lots, restrooms, campgrounds). These MPAs
435 also have higher amounts of sandy beaches, which based on the MPA Watch surveys, tend to
436 generate higher engagement than rocky beaches. Furthermore, many of the charismatic MPAs
437 are located in areas spanning the Monterey Bay and Big Sur coastlines and the city of San
438 Diego, which attract high numbers of tourists. These results are consistent with studies of land-
439 based protected areas that find that visitation rates are driven primarily by the availability of
440 amenities such as parking lots, walking paths, and campgrounds and the accessibility of parks
441 to human populations (see (Heagney et al., 2018) and references within). Finally, engagement
442 is moderated by the selectivity of different user groups. For example, whereas divers are highly
443 selective in their choice of MPAs to visit, scientists have conducted research much more evenly

444 across the statewide MPA network. Birders disproportionately visit estuarine MPAs, which tend
445 to harbor large bird populations due to their high productivity (Paracuellos & Tellería, 2004).

446

447 It is also critical to understand patterns of unsanctioned use within California's MPA
448 network. Overall, consumptive use was observed in a higher proportion of surveys conducted in
449 MPAs that allow some types of harvest (i.e., SMCAs and SMRMAs) than in fully no-take MPAs
450 that prohibit all fishing (i.e., SMRs and no-take SMCAs). However, MPA Watch surveys, which
451 we caution are conducted by citizen scientists and not by law enforcement officers, document
452 fishing inside many of California's no-take MPAs. While observed much less frequently than
453 non-consumptive activities, fishing was still reported in 10% of all MPA Watch surveys
454 conducted in no-take MPAs. The vast majority of reported fishing in no-take areas was by
455 recreational anglers using hook-and-line fishing gear. In most cases, we suspect this was due to
456 a lack of education on the location of MPA boundaries by recreational anglers, as opposed to
457 deliberate poaching activities. The rare observation of commercial fishing in MPAs suggests
458 high compliance by the commercial fleet, which is highly informed about the location and
459 regulations of MPAs. This is consistent with official summaries showing that, in 2011 (the most
460 recent year with publicly available data), 271 citations were issued to commercial fishers while
461 10,052 citations were issued to recreational fishers (~4 times larger than the number issued to
462 recreational hunters) (CDFW, 2011). This suggests that outreach within the recreational fishing
463 community could be especially effective at increasing compliance with MPA regulations.

464

465 Our findings have several key management implications. If promoting human
466 engagement in MPAs is a management objective, our results suggest that MPA planners could
467 improve access and promote engagement by either (1) locating new MPAs in areas with
468 adjacent land-based parks and amenities or (2) investing in the development of new land-based
469 parks and/or amenities adjacent to existing MPAs. Furthermore, aligning protections on land
470 and sea could improve MPA performance by preventing pollution, sedimentation, or
471 eutrophication resulting from run-off from land-based activities (Cicin-Sain & Belfiore, 2005).
472 Alternatively, if reducing human engagement is desired — for example, to enhance protection of
473 biodiversity or other ecosystem or cultural services sensitive to human visitation — then
474 planners could locate MPAs far from people or land-based parks and amenities (Campbell et
475 al., 2020). Our results could also help guide decisions about where to invest in the monitoring,
476 enforcement, and outreach programs required to ensure compliance (Murray & Hee, 2019). We
477 found that the citation frequency for MPA rule violations increased with engagement and

478 adjacent population size. These programs may want to prioritize MPAs in areas of high
479 population density and with adjacent land-based amenities and sandy beaches. However,
480 remote MPAs can also be areas of elevated non-compliance due to lower levels of perceived
481 risk of detection (Crawford et al., 2004; Rojo et al., 2019), and enforcement should not entirely
482 abandon these areas. In addition to monitoring and enforcement, expanded education and
483 outreach is needed to prevent non-compliance before it happens, especially amongst
484 recreational anglers (Bergseth & Roscher, 2018).

485

486 Equitable human engagement in California's MPA network is also an important
487 socioeconomic objective. Unfortunately, the indicators of engagement evaluated here do not
488 include demographic information on the identity of human users, limiting our ability to evaluate
489 the equity of engagement among different user groups. The collection of information in the
490 identity of MPA users is thus a vital first step towards considering equity in future MPA planning
491 and outreach. Knowledge of the representativeness of current users is necessary to design and
492 implement programs that promote access and engagement among underrepresented groups.
493 This knowledge could be gained by interviewing MPA visitors in intercept surveys and
494 assessing the composition of these users relative to that of surrounding communities (e.g.,
495 (Scully-Engelmeyer et al., 2021). It could also be gained through focus groups with the various
496 stakeholder organizations that engage with MPAs, such as fishing, diving, and/or birding clubs,
497 or direct interaction with communities (e.g., Diedrich et al., 2017). The equity of access and
498 engagement should be considered at the outset of any additional MPA planning, including the
499 identification of methods for tracking and benchmarking progress towards these objectives.

500

501 MPAs with low human engagement can still provide valuable contributions to the human
502 engagement, conservation, and fisheries goals of the MPA network. While total engagement at
503 some MPAs is low, these MPAs could be more important to small but underserved human
504 populations in the neighboring area. This is a key benefit of the MLPA's spacing requirements,
505 which mandated that California's MPAs be placed within 50-100 km of each other (Saarman &
506 Carr, 2013). This spacing ensures that coastal populations have relatively similar access to
507 MPAs along the entire California coast. Thus, while MPAs in low population areas have lower
508 engagement, the people living in these areas have opportunities for access similar to people
509 living in higher population areas. Furthermore, MPAs also aim to achieve conservation and
510 fisheries benefits and MPAs with low human engagement can be critical contributors to these
511 goals. This is especially true given that human engagement with MPAs has the potential to

512 negatively impact ecosystem function and MPA performance (Milazzo et al., 2002). Thus, MPAs
513 with low human engagement are key in the design of effective MPA networks, as they can
514 buffer or offset the impacts of human activities in MPAs with greater engagement. A network of
515 MPAs, like that in California, provides the opportunity to design individual MPAs that meet
516 differing criteria and perspectives regarding human-nature relationships (Pereira et al., 2020)
517 while contributing to overall network performance across a range of axes.

518

519 The methodological framework developed here presents a useful starting point for
520 assessing human engagement in any MPA network. To start, the iNaturalist and eBird citizen
521 science programs already have wide global coverage and REEF has high participation in many
522 regions. Other social media platforms, such as Instagram, Twitter, and Flickr, may also be used
523 to assess how, when, and where people engage in MPAs (Retka et al., 2019; Tenkanen et al.,
524 2017). However, these indicators do not capture all types of human engagement or all of the
525 information needed to understand the ecological impacts of human engagement or the equity of
526 engagement amongst different human populations. Notably, our indicators do not capture
527 information on: (1) user demographics, which are key for understanding equality in access
528 (Nicholls & Shafer, 2001); (2) activities that have negative ecological impacts, such as
529 anchoring (Creed & Amado Filho, 1999); or (3) money spent on licenses, entry fees, food, gas,
530 and lodging, among other expenses associated with human engagement in MPAs, which are
531 helpful in quantifying the broader impact of MPAs to local economies (Sala et al., 2013).
532 Furthermore, the types of engagement evaluated here, especially engagement in science and
533 tourism, likely undercount underserved and disadvantaged communities, as the geoscientific
534 community remains largely white (Dutt, 2020) and the expense of tourism and even coastal
535 parking can be a barrier to engagement. Notably, our analysis does not explicitly account for
536 tribal and indigenous engagement with MPAs, which is an important consideration for
537 California's MPA network. In addition, some of our datasets have known biases. For example,
538 iNaturalist observations require the use of a smartphone, which may exclude some user groups.
539

540 Understanding the ability and enabling conditions for MPAs to achieve human
541 engagement objectives is important as entities around the world consider expanding protected
542 area coverage to meet objectives for people and nature. This paper presents a transferable
543 framework for evaluating human engagement with MPA networks and our analyses indicate that
544 human engagement can potentially be increased by placing or developing MPAs near people in
545 concert with existing land-based attractions or amenities. Critical next steps in MPA and human

546 engagement research are to identify strategies for designing MPA networks to promote
547 equitable human engagement, capturing the full extent and value of MPAs in promoting
548 sustainable recreation and tourism, education and outreach, and scientific research, and
549 minimizing negative impacts of engagement on the conservation and fisheries objectives.

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563 data upon request under a formal agreement. Data are provided as-is and in good faith, but
564 CDFW does not endorse any particular analytical methods, interpretations, or conclusions
565 based upon the data it provides. Unless otherwise stated, use of CDFW's data does not
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567 recommends users consult with CDFW prior to data use regarding known limitations of certain
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569 Author Contributions Statement

570 CMF, JGE, JEC, JGS, KJN, and TBF conceived the ideas and designed methodology; CMF,
571 JGE, JGS, JB, KJN, and TBF collected the data; CMF, JGS, and JB analyzed the data; CMF led
572 the writing of the manuscript. All authors contributed critically to the drafts and gave final
573 approval for publication.

574 Conflict of Interests Statement

575 The authors have no conflicts of interest to declare.

576 Data Availability Statement

577 All code and data are available on GitHub here: <https://github.com/NCEAS/ca-mpa>

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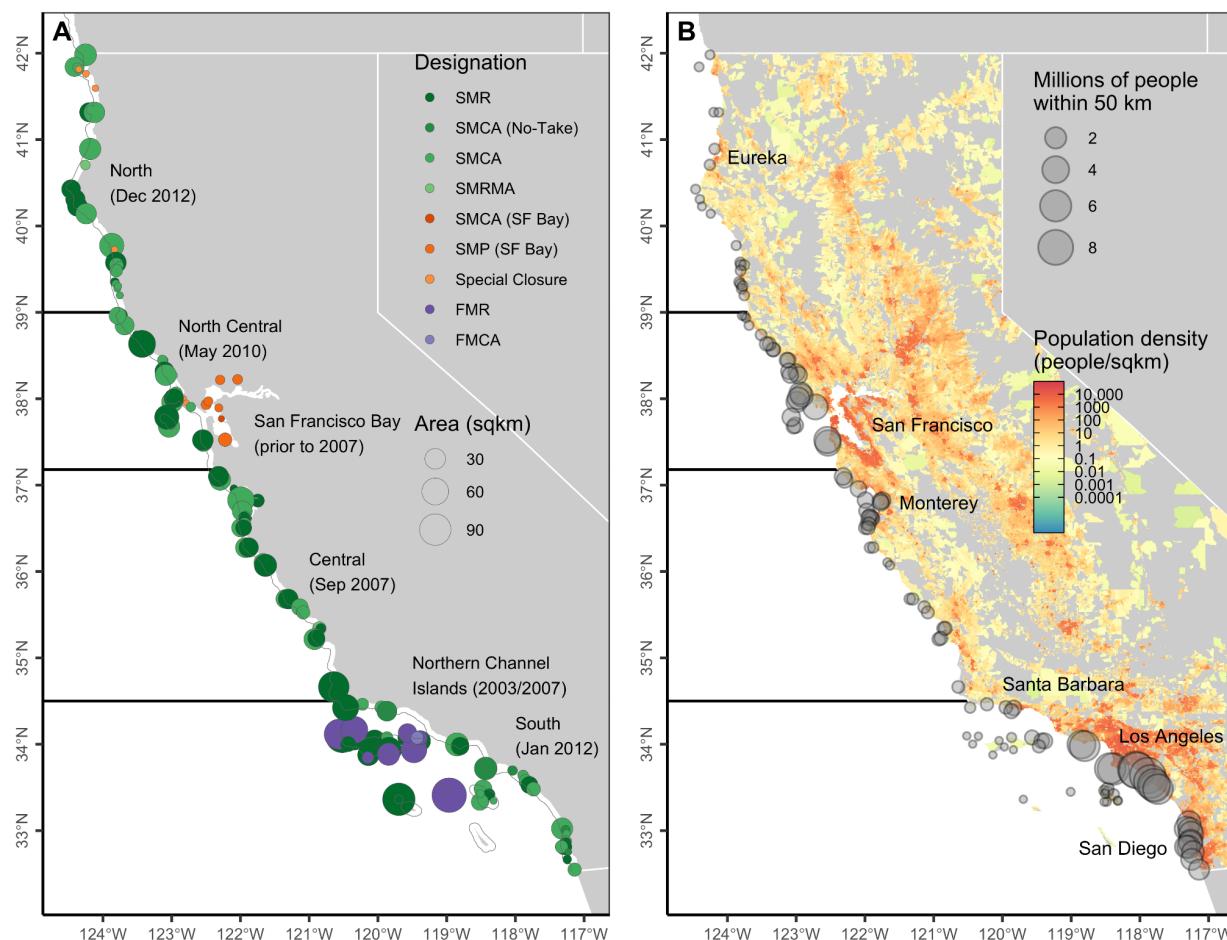
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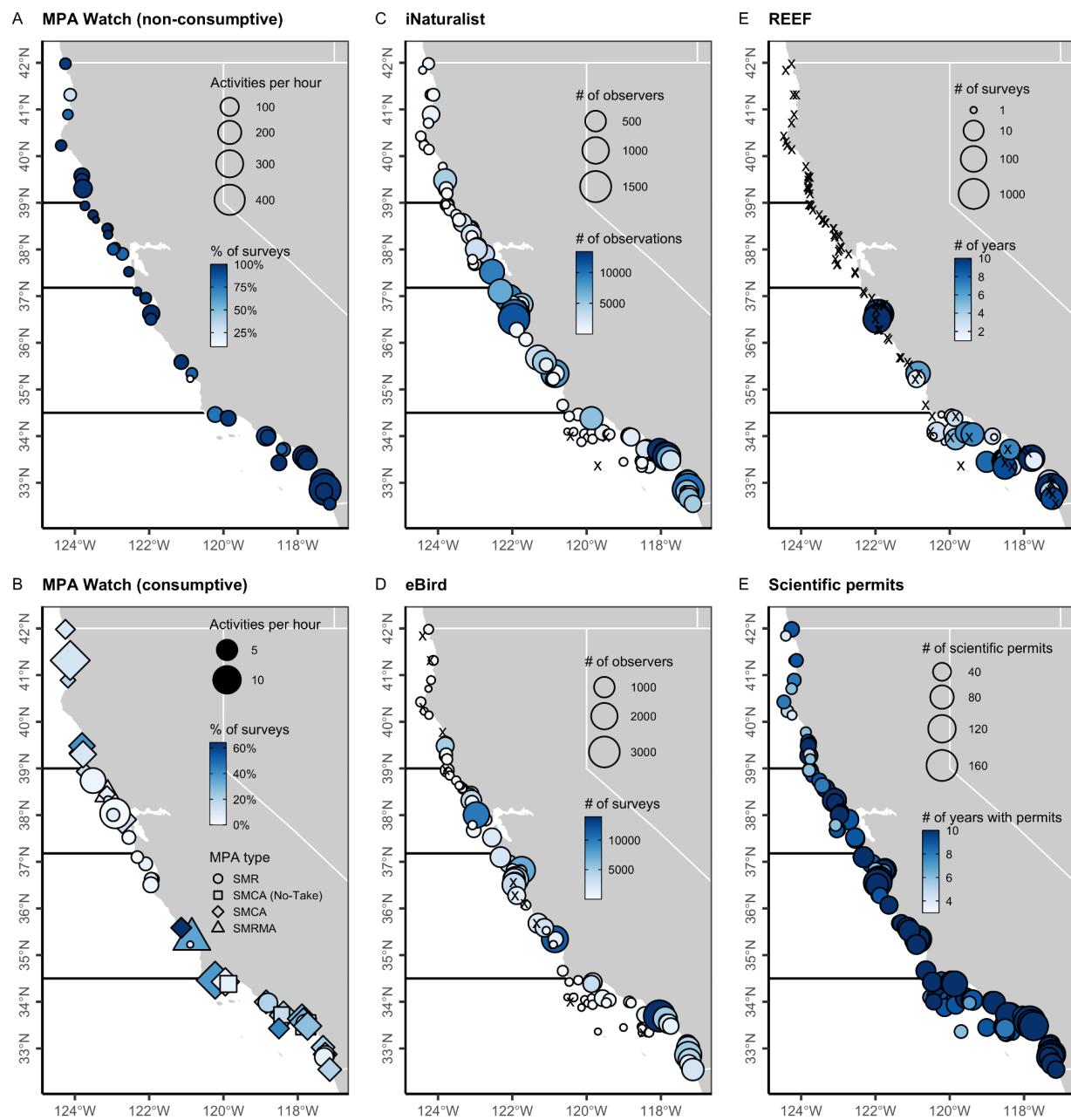
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848 Tables & Figures

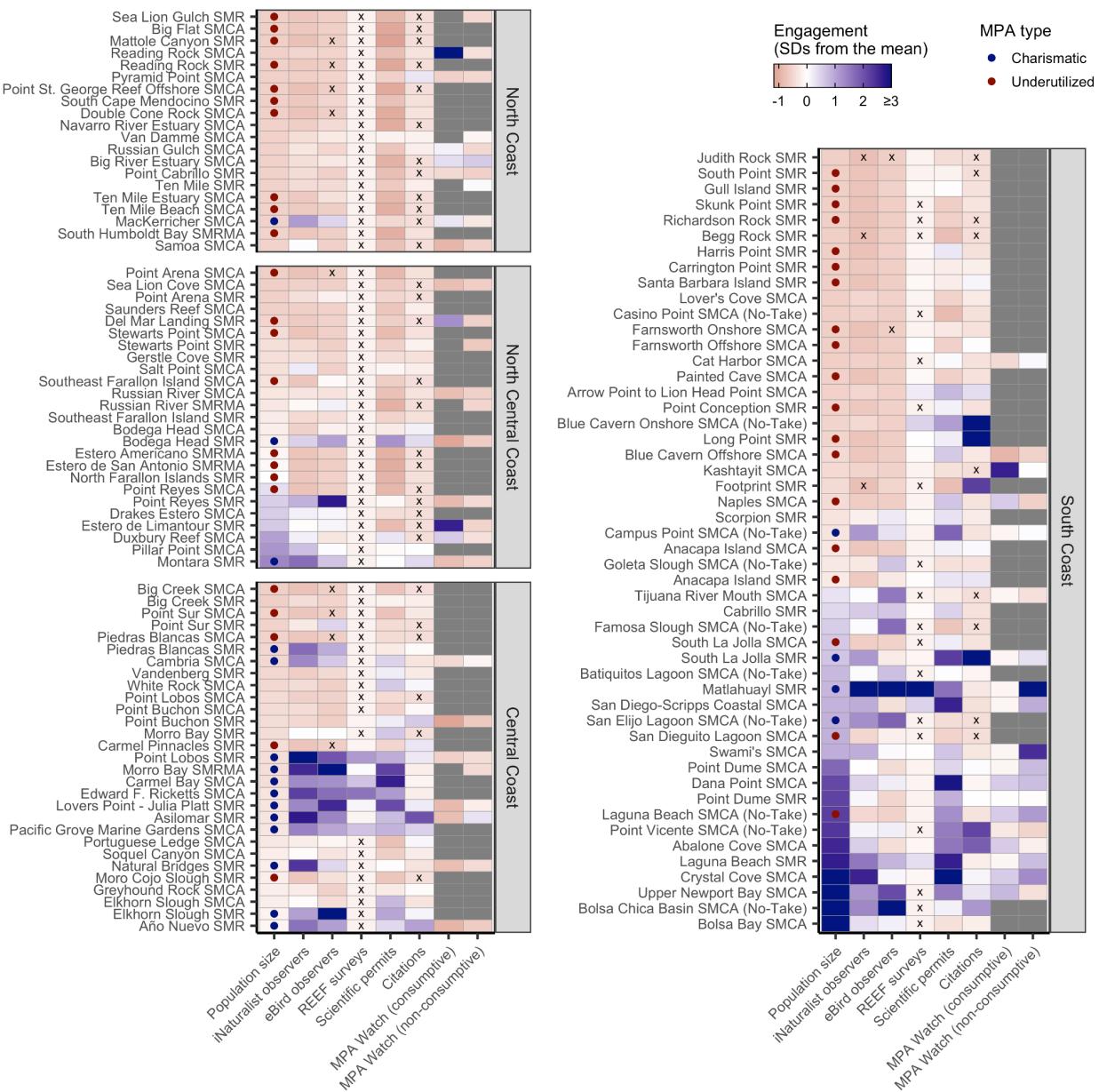


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850 **Figure 1.** Maps illustrating **(A)** California's marine protected area (MPA) network and **(B)** nearby
851 human population density. In **(A)**, greens indicate state MPAs established by the Marine Life
852 Protection Act (MLPA), oranges indicate state MPA designations excluded from the analysis,
853 and purples indicate federal MPAs excluded from the analysis. See **Table S1** for the definition
854 of each MPA designation. Point size indicates MPA area (km^2). Dark horizontal lines delineate
855 the four primary MLPA regions (labeled with month of implementation). MPAs in the San
856 Francisco Bay region were established before 2007 and were not part of the MLPA planning
857 effort. MPAs in the Northern Channel Islands were also established before MLPA (2003 and
858 2007 in state and federal waters, respectively) but have been officially incorporated into the
859 network. The thin gray line indicates state waters (3 nautical miles offshore). In **(B)**, point size
860 indicates the number of people living within 50 km of each MPA. Colors indicate population
861 density by census block in the 2010 U.S. Census. A few key coastal cities are labeled for
862 reference.



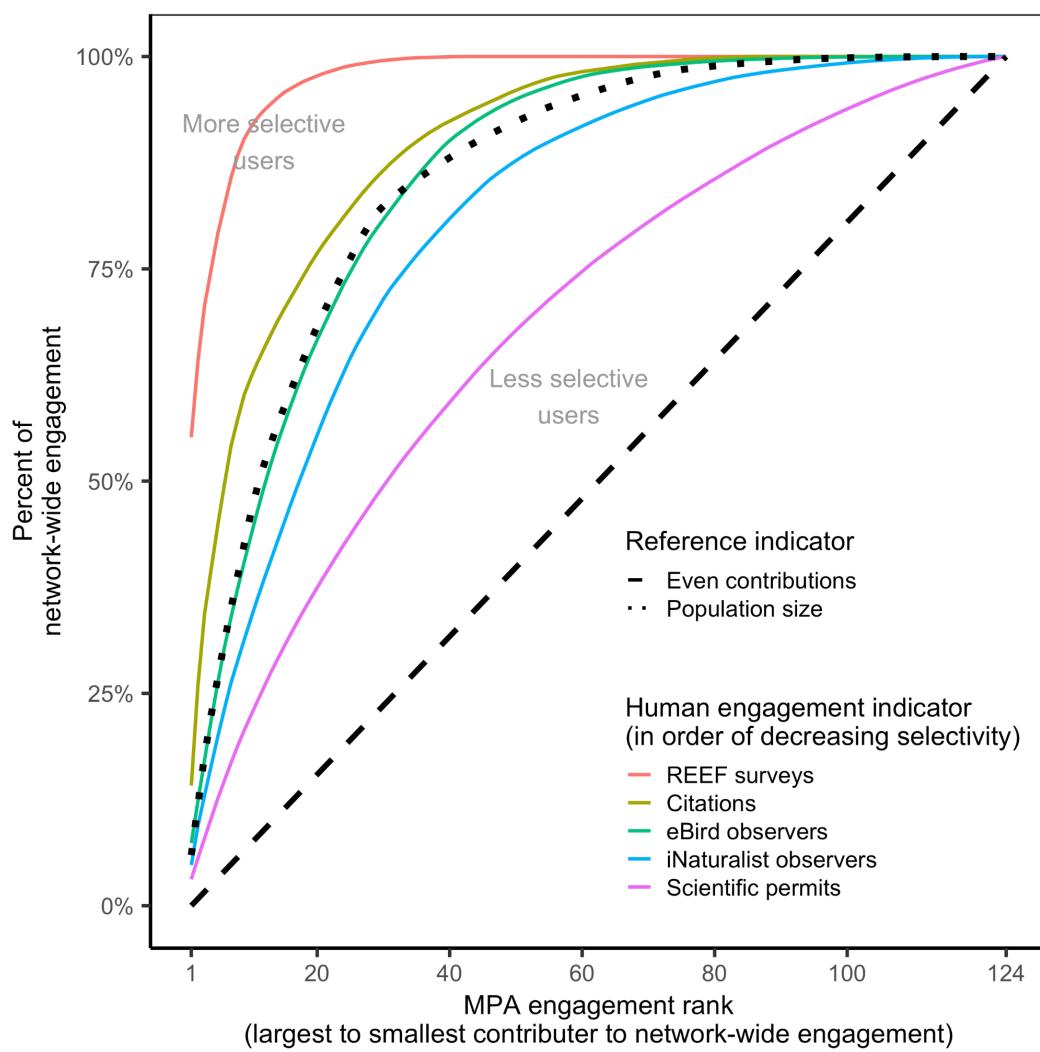
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864 **Figure 2.** Maps illustrating six indicators of human engagement in California's state marine
 865 protected area (MPA) network. Multiple metrics are used to measure engagement for each
 866 indicator; see **Table S3** for definitions of these metrics. Across indicators, larger symbols and
 867 deeper colors indicate higher engagement. In C-F, black x's mark MPAs without any reported
 868 engagement. Dark horizontal lines delineate the four MLPA regions. See **Figure S17** for a map
 869 of the regulatory citations indicator.



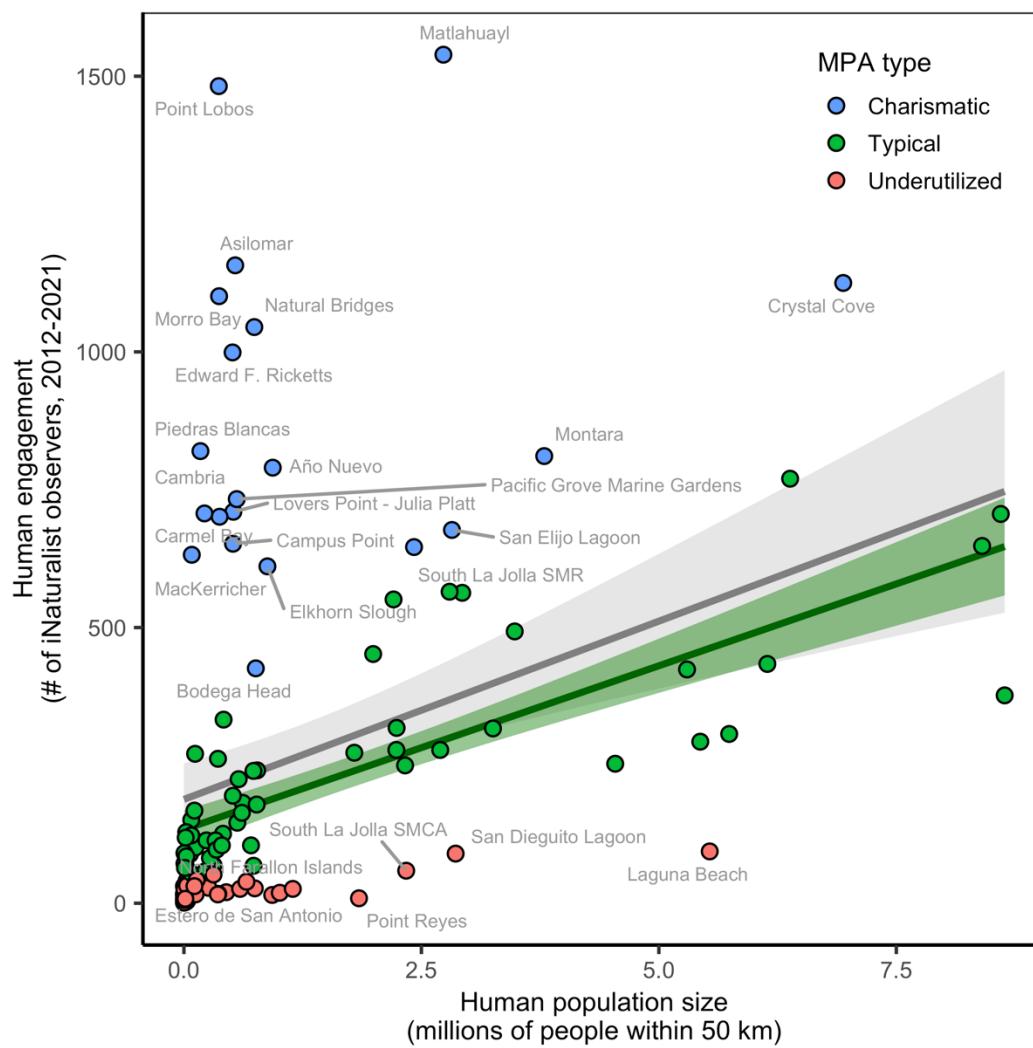
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Figure 3. A synthesis of human engagement indicators within California's state marine protected areas (MPAs). MPAs are sorted by population density within 50 km (first column of each plot) within each region. Engagement indicators are centered on the average of each indicator and scaled to unit variance to ease comparison across indicators; thus, color indicates the number of standard deviations (SDs) from the mean where blue shades indicate MPAs with above average engagement and red shades indicate MPAs with below average engagement. Gray indicates MPAs without data and x's indicate MPAs with true zeros. MPAs with greater ("charismatic") and less ("underutilized") engagement than expected based on surrounding population density are marked in the population size column. See **Table S3** for definitions and metrics of the displayed indicators.



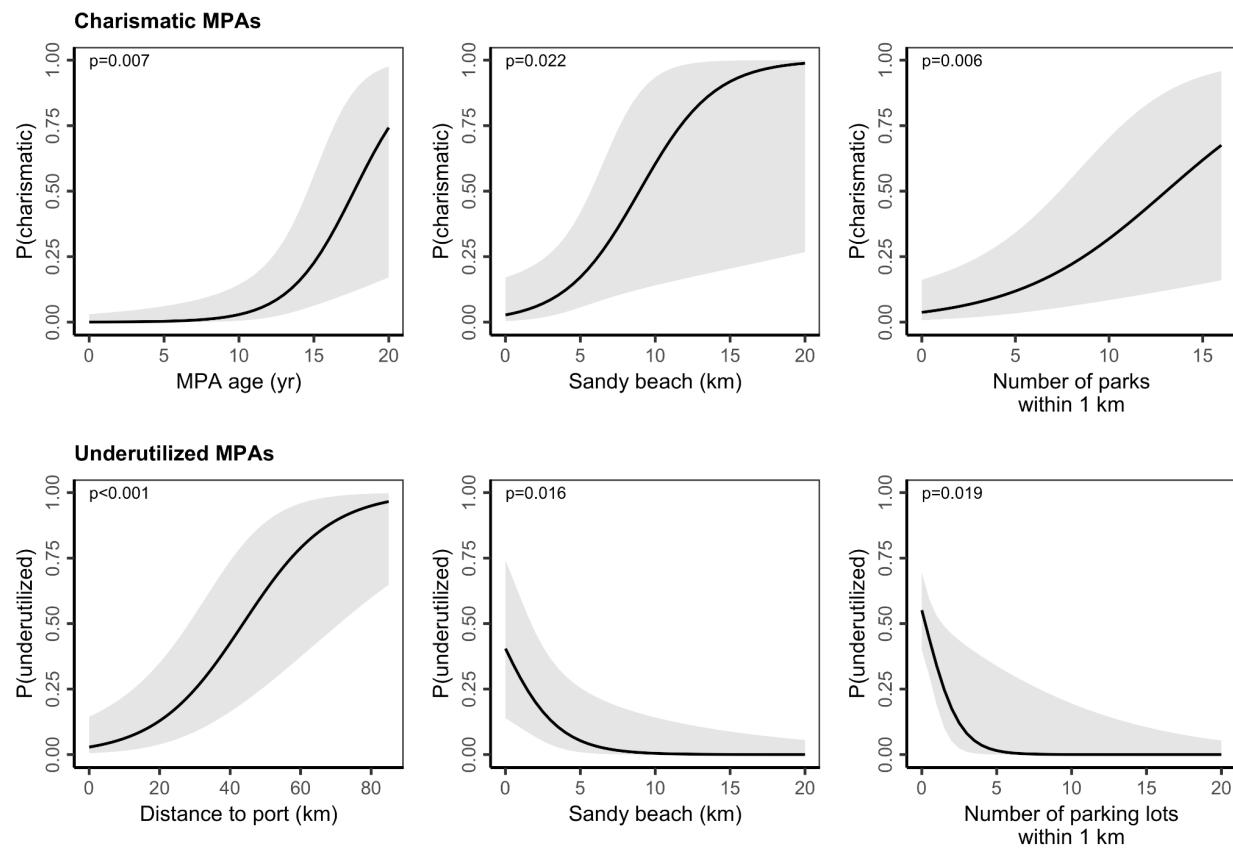
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Figure 4. Cumulative contributions of individual marine protected areas (MPAs) to network-wide engagement based on several indicators of human engagement. The diagonal dashed line indicates a theoretical accumulation curve in which individual protected areas contribute equally to engagement within the overall network. Curved lines above this reference line indicate accumulation curves in which some protected areas make larger contributions (higher performers) to network-wide engagement than others (lower performers); the steeper the curve, the more network-wide engagement is dominated by a few protected areas. The accumulation curve for population size (dotted black line) provides an additional frame of reference: if human engagement were proportional to population size, engagement would accumulate according to this curve. Thus, curves steeper than this line indicate that benefits are more concentrated than would be predicted by population density (i.e., engagement is more selective) whereas curves shallower than this line indicate a more even distribution of benefits than would be predicted by population density (i.e., engagement is less selective). The MPA Watch indicators are excluded because they are not available for all MPAs within the network.



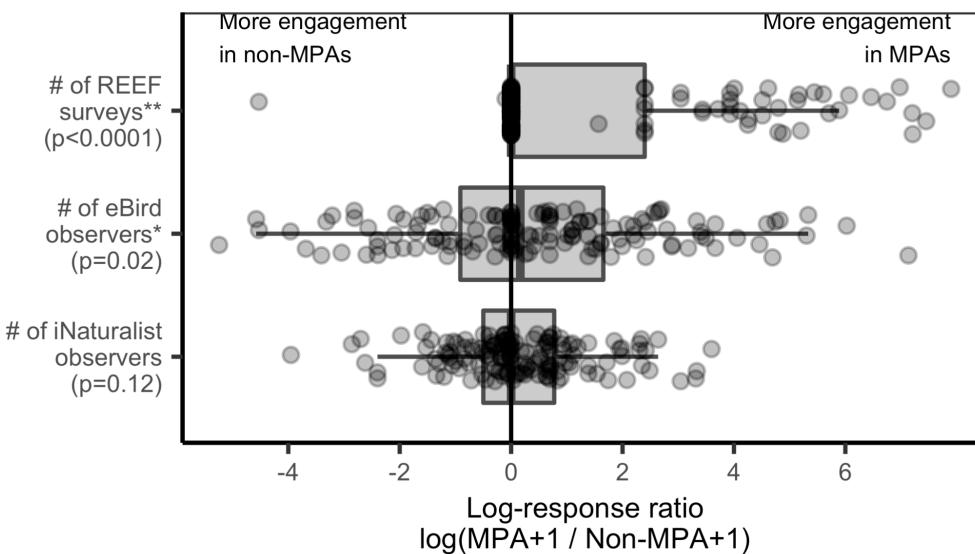
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897 **Figure 5.** Correlation between human engagement in an MPA and the number of people living
 898 within 50 km of the area. Human engagement is measured as the number of iNaturalist
 899 observers submitting observations within 100 m of an MPA from 2012 through 2021. The gray
 900 line and 95% confidence interval illustrate a linear regression ($r^2=0.14$; $p<0.001$) fit to all points.
 901 Blue points with residuals greater than 75% of the fitted values were classified as “charismatic”
 902 MPAs, whose engagement is higher than would be expected based on population density. Red
 903 points with residuals less than 75% of the fitted values were classified as “underutilized” MPAs,
 904 whose engagement is lower than would be expected based on population density. The
 905 charismatic and selected underutilized MPAs are labeled with their abbreviated names. The
 906 green line and 95% confidence interval illustrate a linear regression ($r^2=0.62$; $p<0.001$) fit to the
 907 “typical” protected areas (green points), whose engagement is largely determined by population
 908 density.



909

910 **Figure 6.** Marginal effects of significant predictors of “charismatic” (top row) and “underutilized”
 911 (bottom row) MPAs as identified through stepwise logistic regression. Marginal effects represent
 912 the predicted probability when varying the variable of interest while fixing the other variables at
 913 their means. Shading depicts 95% confidence intervals. See **Table S5** for the list of predictors
 914 included in each model and **Table S7** for the results of each model fit.



915

916 **Figure 7.** The level of human engagement in marine protected areas (MPAs) compared to non-
 917 MPA counterfactuals for indicators with the required data. Log-response ratios were calculated
 918 after adding 1 to the engagement values occurring in both the numerator and denominator to
 919 avoid non-finite values. Log-response ratios greater than zero indicate MPAs where the MPA
 920 designation is associated with higher engagement relative to the counterfactual whereas ratios
 921 less than zero indicate MPAs where the MPA designation is associated with lower engagement
 922 relative to the counterfactual. Asterisks indicate indicators whose mean response ratio is
 923 significantly different from zero (* p<0.01, ** p<0.05). P-values are shown parenthetically. In the
 924 boxplots, the solid line indicates the median, the box indicates the interquartile range (IQR; 25th
 925 to 75th percentiles), the whiskers indicate 1.5 times the IQR, and the points beyond the
 926 whiskers indicate outliers. Points represent log-response ratios for each MPA and
 927 counterfactual pair.

928 **Supplemental Tables & Figures**

929 **Table S1.** California marine protected area (MPA) designations.

930

Designation	# / area (km²)	Restrictions
<i>State marine protected areas</i>		
State marine reserve (SMR)	124 / 2207 km²	Prohibits comm/rec take of all marine resources*
State marine conservation area (SMCA)	49 / 1229 km ²	Prohibits comml/rec take of selected marine resources
State marine conservation area (no take)	60 / 880 km ²	Prohibits comm/rec take of all marine resources but allows permitted activities that cause damage (e.g., dredging)
State marine recreational management area (SMRMA)	10 / 86 km ²	Limits comm/rec take of marine resources but allows legal waterfowl hunting
<i>Other state management areas</i>		
State marine park (SMP) - all in SF Bay	22 / 20 km²	Prohibits damage or commercial take of all marine resources; recreational take is allowed
State marine conservation area (SMCA) - SF Bay	7 / 17 km ²	Prohibits comml/rec take of selected marine resources
Special closure	14 / 8 km ²	Prohibits or restricts activities in waters adjacent to seabird rookeries or marine mammal haul-out sites
<i>Federal marine protected areas</i>		
Federal marine reserve (FMR)	9 / 394 km²	Extends SMRs around the Channel Islands into federal waters
Federal marine conservation area (FMCA)	8 / 388 km ²	Extends SMCAs around the Channel Islands into federal waters
1 / 6 km ²		

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932 * Marine resources can be living, geologic, or cultural

933 **Table S2.** Social vulnerability indicators and metrics used to calculate the social vulnerability
 934 index. Direction of influence indicates whether the metric was assumed to increase (positive) or
 935 decrease (negative) vulnerability. Data used were from the 2010 American Community Survey.
 936 Geographic unit for all data is the census tract.
 937

Indicator	Direction of Influence
<i>Housing Characteristics</i>	
Median monthly mortgage (USD)	Negative
Median monthly rent (USD)	Negative
Median number of rooms per housing unit	Negative
Percent of all family households that live in mobile homes	Positive
<i>Labor Force Structure</i>	
Percent of age 16+ population that are working females	Negative
Percent of age 16+ population that are working	Negative
<i>Population Composition</i>	
Percent of families with single females as head of household	Positive
Percent of population age 5 and older that speak English less than “very well”	Positive
Percent of population whose race is white, with no other descriptors	Negative
Percent of the population younger than age 6	Positive
<i>Poverty Status</i>	
Percent of families living below the poverty line	Positive
Percent of people under age 18 living below the poverty line	Positive
Percent of people receiving cash assistance or SNAP payments	Positive
Percent of people age 65 and over living below the poverty line	Positive

939 **Table S3.** Indicators of human engagement evaluated in this paper. The bolded metric indicates
 940 the metric used in the scorecard and accumulation curve analysis.
 941

Indicator and source	Description	Metrics
MPA Watch (www.mpawatch.org)	Recreation: MPA Watch is a community science program that trains volunteers to observe and collect data on human uses of protected areas (MPA Watch, 2022a). Volunteers use a standardized survey protocol (MPA Watch, 2022b) to record consumptive (e.g., fishing) and non-consumptive (e.g., surfing, boating, tidepooling, running, etc.) activities occurring offshore and onshore of coastal sampling sites.	(1) the median number of activities observed per hour for surveys in which activities were observed (i.e., zeroes excluded); (2) percent of surveys in which an activity was observed
iNaturalist (www.inaturalist.org)	Recreation/education: iNaturalist is a web- and app-based platform that allows observers to submit wildlife photos for identification by amateur and professional naturalists (iNaturalist, 2022).	(1) number of iNaturalist users who submitted observations; (2) number of submitted observations
eBird (www.ebird.org)	Recreation/education: eBird is a global citizen science program that collates observations of birds submitted by birdwatchers (eBird, 2022).	(1) number of eBird users who submitted observations; (2) number of submitted observations
REEF (www.reef.org)	Recreation/education: REEF is an international marine conservation organization that trains volunteer divers and snorkelers to collect and report information on marine fish and selected invertebrate and algae species (REEF, 2022).	(1) number of surveys conducted; (2) number of years in which a survey was conducted
Scientific permits (CA Dept. Fish & Wildlife)	Scientific research: Permits issued by CDFW for scientific research provide an indicator of scientific research activity throughout California's MPA network.	(1) number of permits issued; (2) number of years in which permits were issued.
Law enforcement citations (CA Dept. Fish & Wildlife)	Non-compliance: Regulatory citations from CDFW's Law Enforcement Division provide an indicator of where non-compliance occurs throughout California's MPA network.	(1) number of citations issued; (2) number of years in which citations were issued.

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945 **Table S4.** Human use activities recorded by MPA Watch volunteers.

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Activity type	Activity	Subcategories
<i>Non-consumptive</i>		
Onshore recreation	Beach recreation	sandy/rocky
Onshore recreation	Wildlife watching	sandy/rocky
Onshore recreation	Domestic animals	sandy/rocky; on/off leash
Onshore recreation	Driving on the beach	
Onshore recreation	Tide-pooling	
Offshore recreation	Offshore recreation (e.g. swimming)	
Offshore recreation	Surfing	
Offshore recreation	Other board sports	
Offshore recreation	SCUBA diving or snorkeling	
Boating	Kayaking	
Boating	Paddleboarding	
Boating	Other paddleboating	
Boating	Sailing	
Boating	Windsurfing	
Boating	Jet skiing	
Boating	Power boating	
Boating	Whale watch boat	
Boating	Dive boat	
Boating	Work boat	
Boating	Law enforcement boat	
Boating	Other boating	
<i>Consumptive</i>		
Fishing	Hand collection of biota	sandy/rocky
Fishing	Hook and line fishing	onshore/boat; sandy/rocky (if shore); rec/comm/unknown (if boat); active/inactive (if boat)
Fishing	Trap fishing	onshore/boat; sandy/rocky (if shore); rec/comm/unknown (if boat); active/inactive (if boat)
Fishing	Net fishing	onshore/boat; sandy/rocky (if shore); rec/comm/unknown (if boat); active/inactive (if boat)
Fishing	Spear fishing	onshore/offshore/boat; sandy/rocky (if shore); rec/comm/unknown (if boat); active/inactive (if boat)
Fishing	Dive fishing	offshore/boat; rec/comm/unknown (if boat); active/inactive (if boat)
Fishing	Kelp harvesting	active/inactive
Fishing	Passenger fishing	active/inactive/unknown
Fishing	Unknown fishing	

947

948 **Table S5.** Sources of explanatory variables included in logistic regressions evaluating traits
 949 associated with charismatic and underutilized MPAs.

950

Variable	Source
<i>Design feature</i>	
MPA age (yr)	CDFW (2019) MPA GIS file. Available at: https://filelib.wildlife.ca.gov/Public/R7_MR/ MANAGEMENT/MPA/
MPA size (km ²)	CDFW (2019) MPA GIS file. Available at: https://filelib.wildlife.ca.gov/Public/R7_MR/ MANAGEMENT/MPA/
Protection status (no-take, some take)	CDFW (2019) MPA GIS file. Available at: https://filelib.wildlife.ca.gov/Public/R7_MR/ MANAGEMENT/MPA/
<i>Habitat type</i>	
Sandy beach (km)	CDFW MPA habitat mapping
Rocky intertidal (km)	CDFW MPA habitat mapping
Estuary (km)	CDFW MPA habitat mapping
Maximum kelp canopy (km ²)	CDFW MPA habitat mapping
<i>Accessibility and amenities</i>	
Distance to port (km)	CDFW (2022) Fishing ports. Available from CDFW.
Number of parks within 1 km	ESRI (2022) USA Parks. Available at: https://www.arcgis.com/home/item.html?id=578968f975774d3fab79fe56c8c90941
Number of parking lots within 1 km	CDPR (2022) Parking. California Department of Parks and Recreation. Available at: https://www.parks.ca.gov/?page_id=29682
Number of picnic areas within 1 km	CDPR (2022) Picnic Grounds. California Department of Parks and Recreation. Available at: https://www.parks.ca.gov/?page_id=29682
Number of campgrounds within 1 km	CDPR (2022) Campgrounds. California Department of Parks and Recreation. Available at: https://www.parks.ca.gov/?page_id=29682
<i>Social vulnerability</i>	
Social vulnerability index	See methods for details.

951

952 **Table S6.** Matching variables used in the design of counterfactual areas and their sources.

953

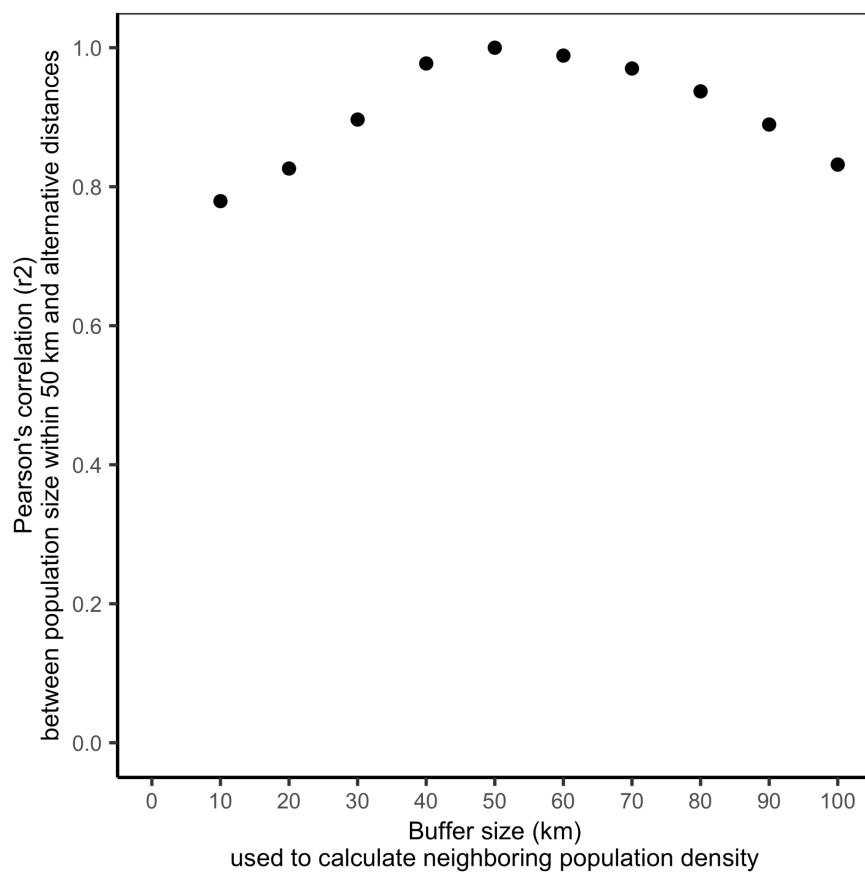
Matching variable	Source
Depth (m)	CDFW (2011) Bathymetry. California Department of Fish and Wildlife. Available at: https://filelib.wildlife.ca.gov/Public/R7_MR/BATHYMETRY/
Distance from shore (km)	CDFW (2011) Coastline. California Department of Fish and Wildlife. Available at: https://filelib.wildlife.ca.gov/Public/R7_MR/BASE/
Number of people within 50 km	USCB (2010) US Census Data. United States Census Bureau. Available at: https://www.census.gov/programs-surveys/decennial-census/decade/2010/about-2010.html
Number of park entry points within 600 m	CDPR (2022) Park Entry Points. California Department of Parks and Recreation. Available at: https://www.parks.ca.gov/?page_id=29682
Distance to nearest park entry point (m)	CDPR (2022) Park Entry Points. California Department of Parks and Recreation. Available at: https://www.parks.ca.gov/?page_id=29682
Number of public beach access points within 600 m	CCC (2022) Public Access Points. California Coastal Commission. Available at: https://gis.data.ca.gov/datasets/coastalcomm::public-access-points/about
Distance to nearest public beach access point (m)	CCC (2022) Public Access Points. California Coastal Commission. Available at: https://gis.data.ca.gov/datasets/coastalcomm::public-access-points/about

954

955 **Table S7.** Attributes of ‘charismatic’ and ‘underutilized’ MPAs by type of engagement, based on
 956 the results of stepwise logistic regressions. Missing values indicate the best fit model does not
 957 include the associated predictors*. In each model, “typical” MPAs were set as the reference
 958 level and evaluated against charismatic or underutilized MPAs. Coefficients returned by each
 959 model are reported as odds ratio. CI = 95% confidence interval; AIC = Akaike Information
 960 Criterion.
 961

<i>Predictors</i>	Charismatic vs. typical			Underutilized vs. typical		
	Odds Ratios	CI	p	Odds Ratios	CI	p
(Intercept)	0.00	0.00 – 0.13	0.007	0.62	0.24 – 1.53	0.302
Distance to port (km)	1.00	1.00 – 1.00	0.065	1.00	1.00 – 1.00	<0.001
MPA size (km ²)	0.94	0.87 – 1.01	0.121			
Take? (yes/no)	0.26	0.05 – 1.18	0.093			
Sandy beach (km)	1.49	1.08 – 2.19	0.022	0.61	0.39 – 0.87	0.016
MPA age (yr)	1.58	1.15 – 2.29	0.007			
# of parks within 1 km	1.28	1.09 – 1.56	0.006			
Rocky intertidal (km)				0.80	0.61 – 1.03	0.101
# of parking lots within 1 km				0.42	0.15 – 0.71	0.019
Observations	71			92		
R ² Tjur	0.466			0.446		
AIC	59.527			84.254		

962
 963 * Predictors not included in the reduced models include: maxim kelp canopy (km²), estuary extent (km),
 964 number of campgrounds within 1 km, number of picnic areas within 1 km (see **Table S5** for details).

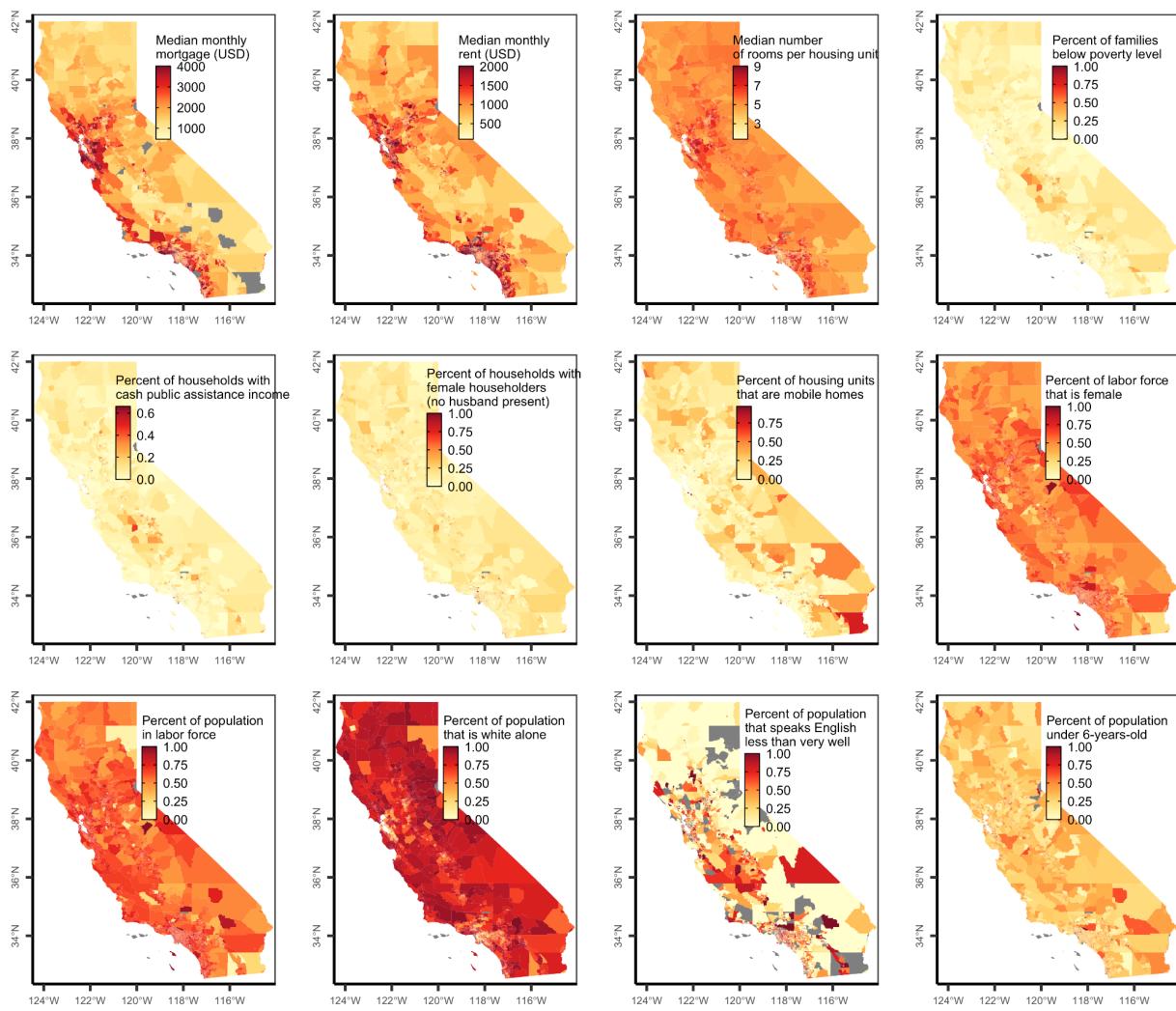


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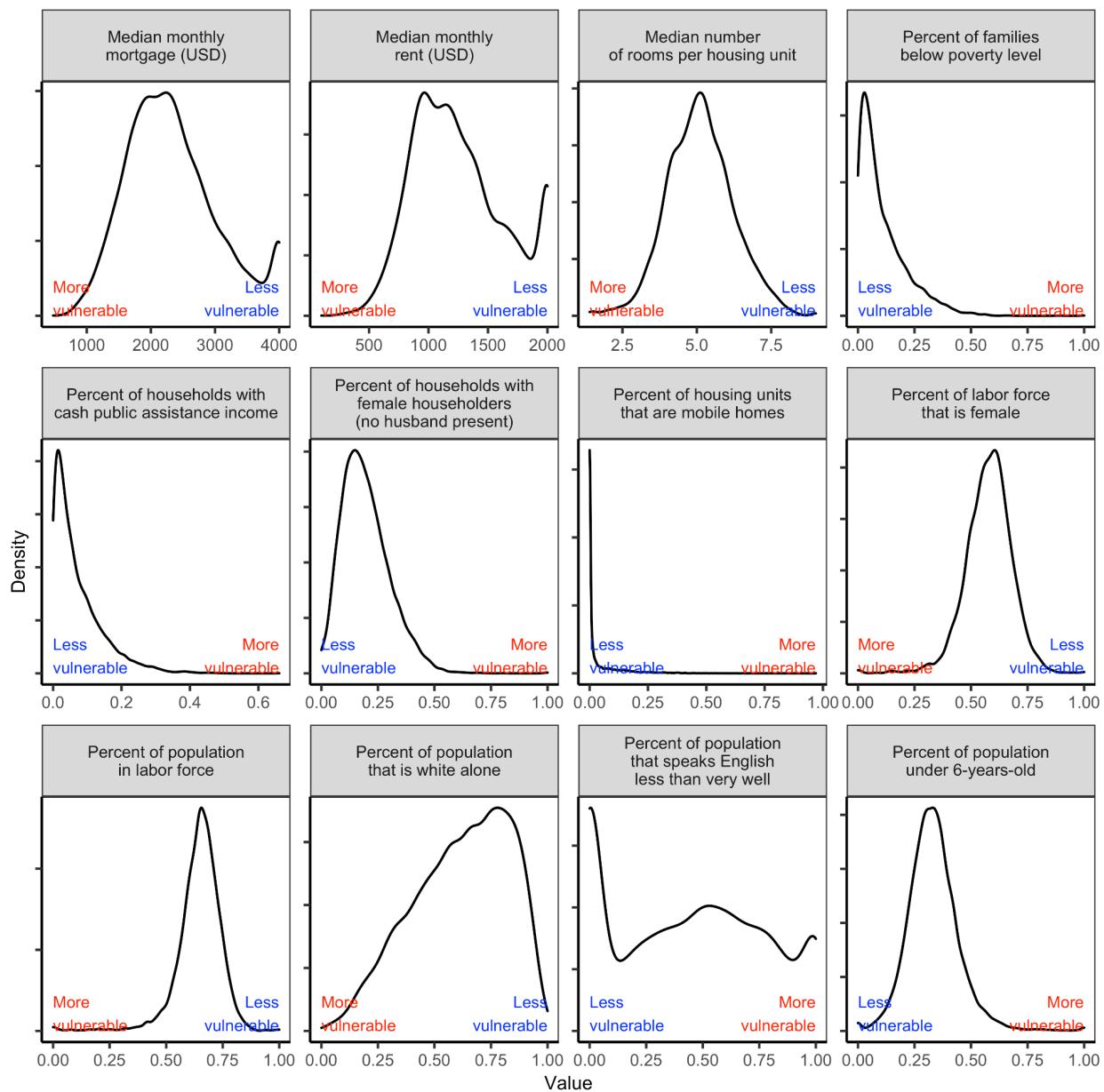
967

Figure S1. The correlation between population density calculated using the selected 50 km buffer and population densities calculated using alternative buffer distances.



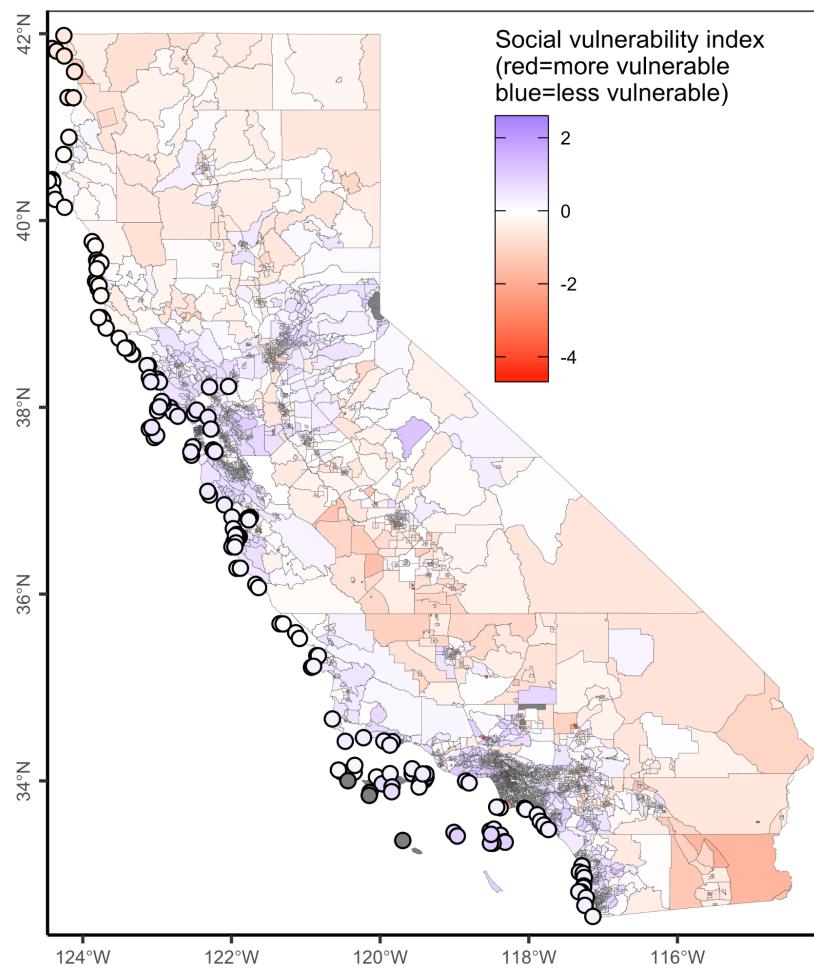
968

969 **Figure S2.** Maps of the social vulnerability indicator used to calculate the social vulnerability
970 index by California US Census tract.



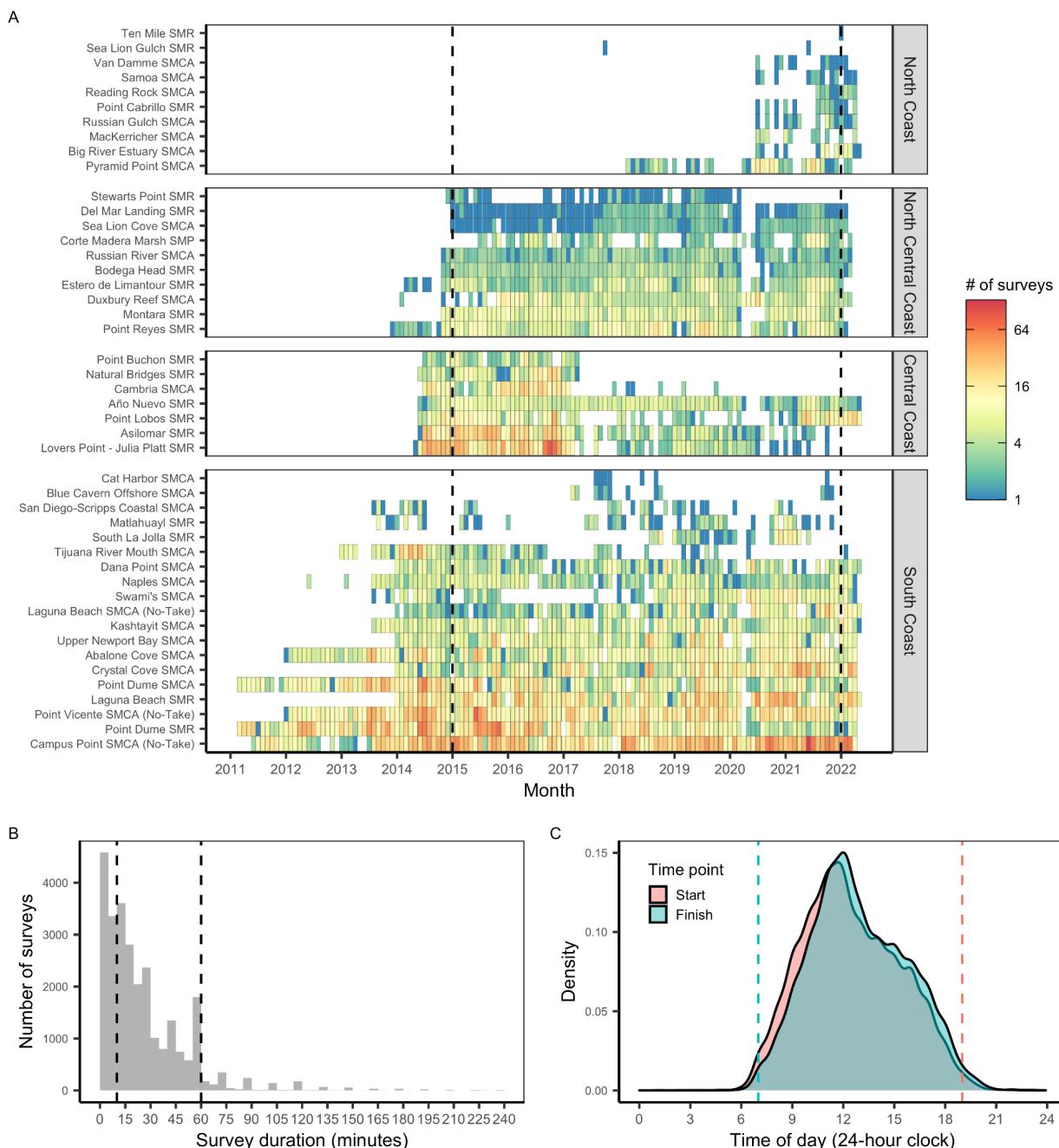
971

972 **Figure S3.** Distribution of the social vulnerability indicator values by California US Census tract
 973 used to calculate the social vulnerability index. Values were centered on the statewide average
 974 and scaled to unit variance. Indicators in which higher vulnerability is indicated by higher values
 975 (e.g., percent of families below poverty level, percent of households with cash public assistance
 976 income) were multiplied by -1 so that higher vulnerability is represented as low values for all
 977 indicators. The social vulnerability index, mapped in **Figure S4**, was calculated as the average
 978 of the centered, scaled, and standardized indicators.



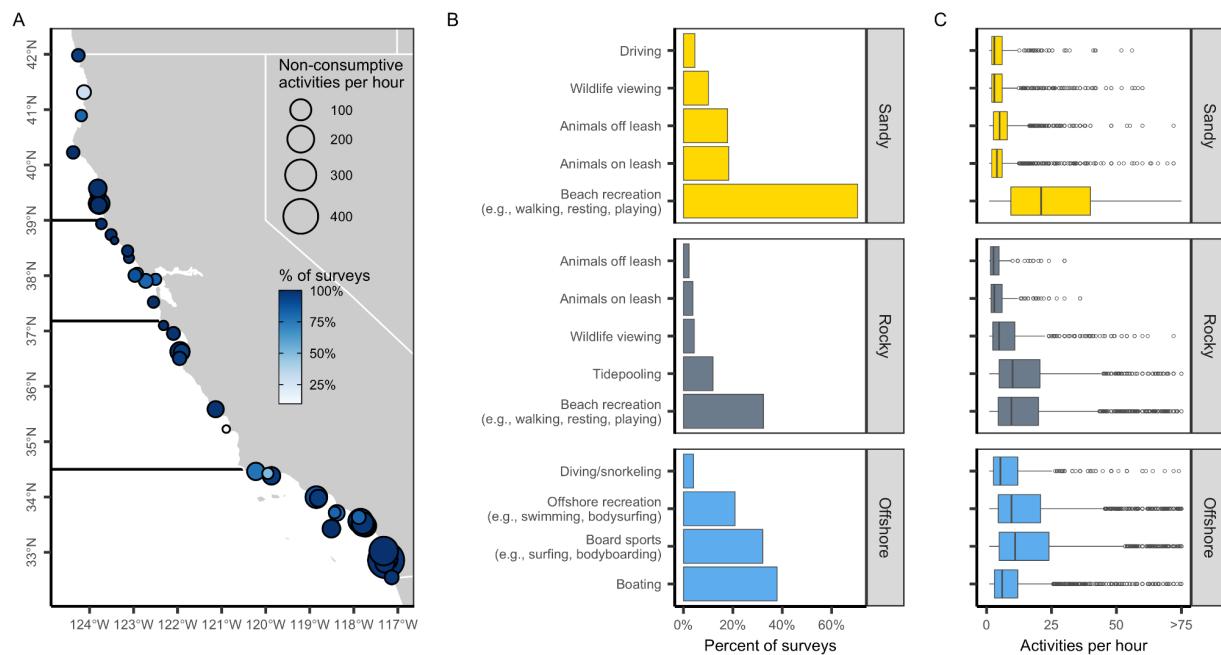
979

980 **Figure S4.** Social vulnerability index by US Census tract (polygons on land) and average social
981 vulnerability index within 50 km of each MPA (points at sea). The social vulnerability index is
982 calculated as the average of the 12 indicators of social vulnerability described in **Table S2**.
983 Indicators were centered on their statewide average and scaled to unit variance before the
984 index was calculated. Negative (red) values indicate higher social vulnerability and positive
985 (blue) values indicate lower social vulnerability.



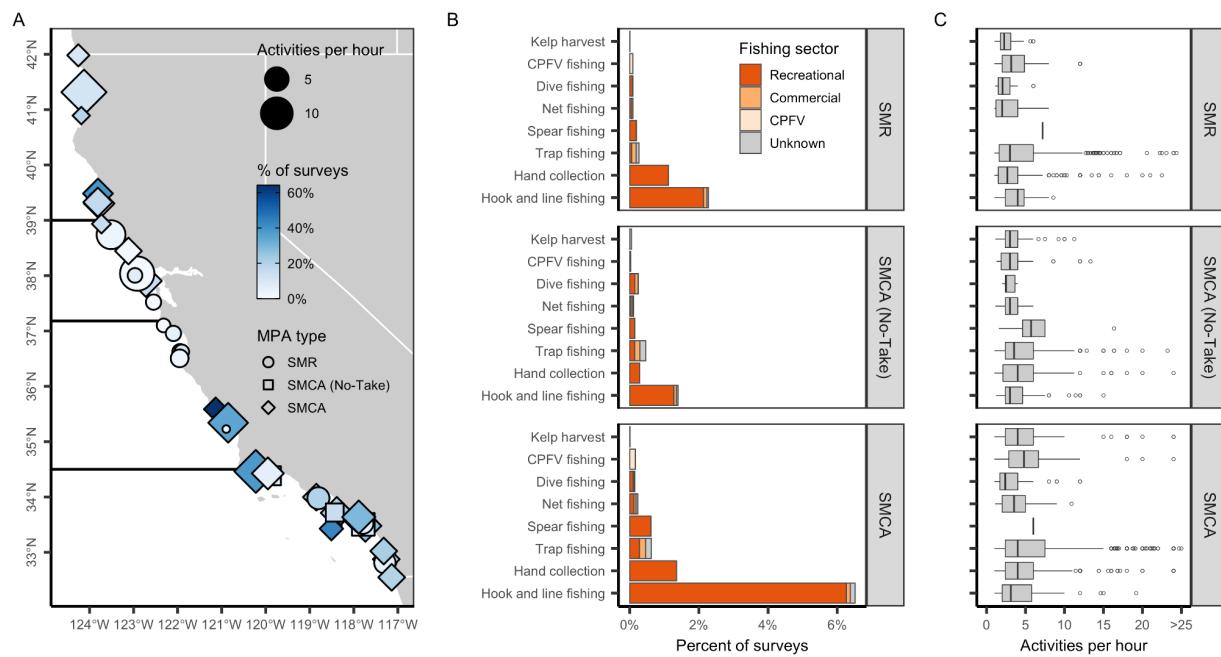
986

987 **Figure S5.** The (A) coverage of usable MPA Watch surveys over time by marine protected area
 988 (MPA). A usable survey is a survey in which the duration was accurately recorded (i.e., end time
 989 occurs after start time). Note log-scale for fill color. San Francisco Bay MPAs are plotted in the
 990 North Central Coast region for simplicity. Only surveys occurring between January 1, 2015 and
 991 December 31, 2022 were considered in the analysis. We also excluded (B) surveys shorter than
 992 10 minutes or longer than 60 minutes and (C) surveys ending before 7AM or starting after 7PM.



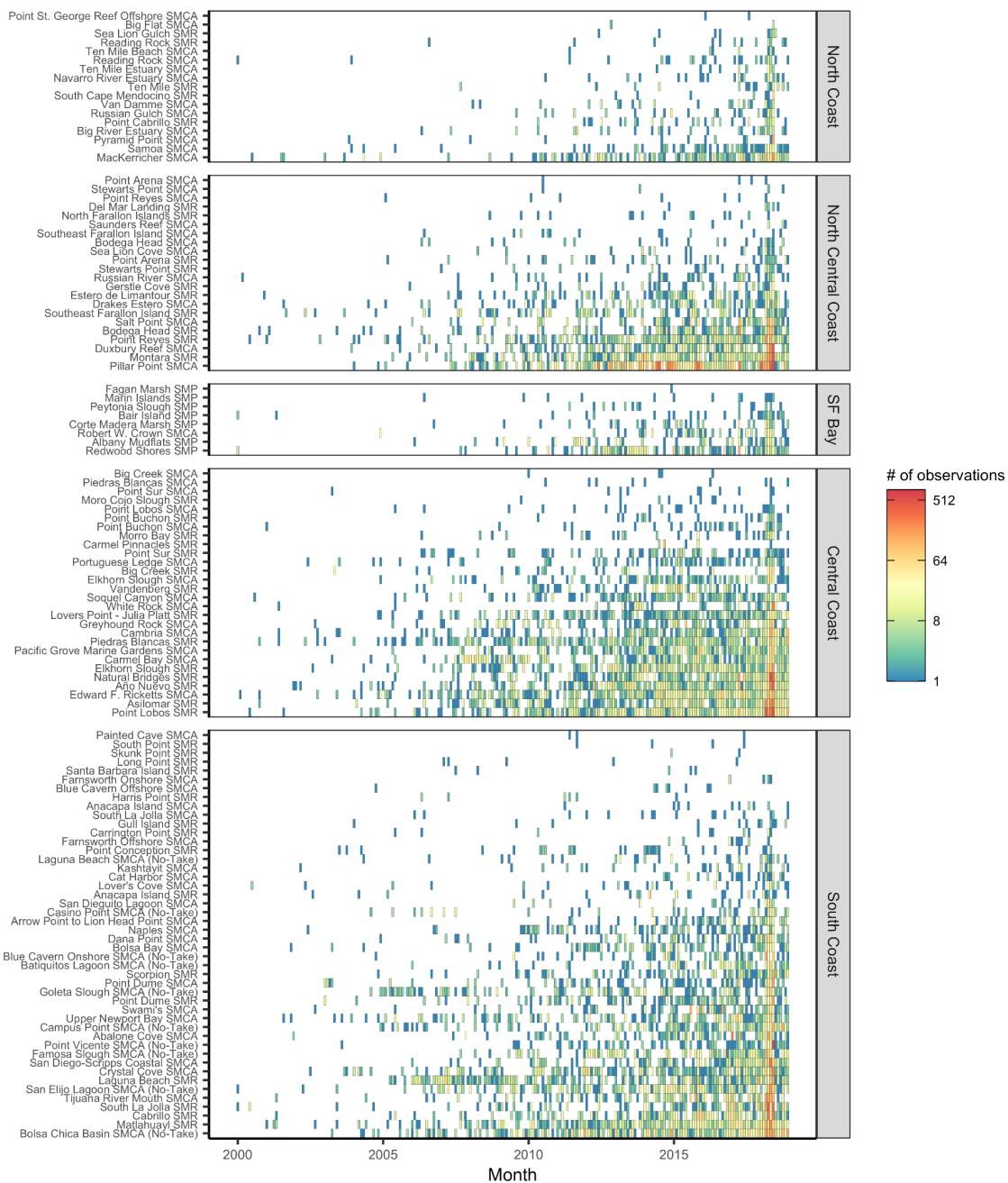
993

994 **Figure S6.** Non-consumptive activities in California's state marine protected areas (MPAs)
 995 based on surveys conducted by MPA Watch. Panel **A** shows the percent of surveys within an
 996 MPA in which non-consumptive activities were observed (color ramp) and the median number of
 997 non-consumptive activities observed per hour (point size) for surveys in which such activities
 998 were observed (i.e., zeroes excluded). Dark horizontal lines delineate the four MLPA regions.
 999 Panel **B** shows the percent of surveys in which non-consumptive activities were observed by
 1000 habitat area. Panel **C** shows the number of non-consumptive activities observed per hour for
 1001 surveys in which such activities were observed (i.e., zeroes excluded). In the boxplots, the solid
 1002 line indicates the median, the box indicates the interquartile range (IQR; 25th to 75th
 1003 percentiles), the whiskers indicate 1.5 times the IQR, and the points beyond the whiskers
 1004 indicate outliers.



1005

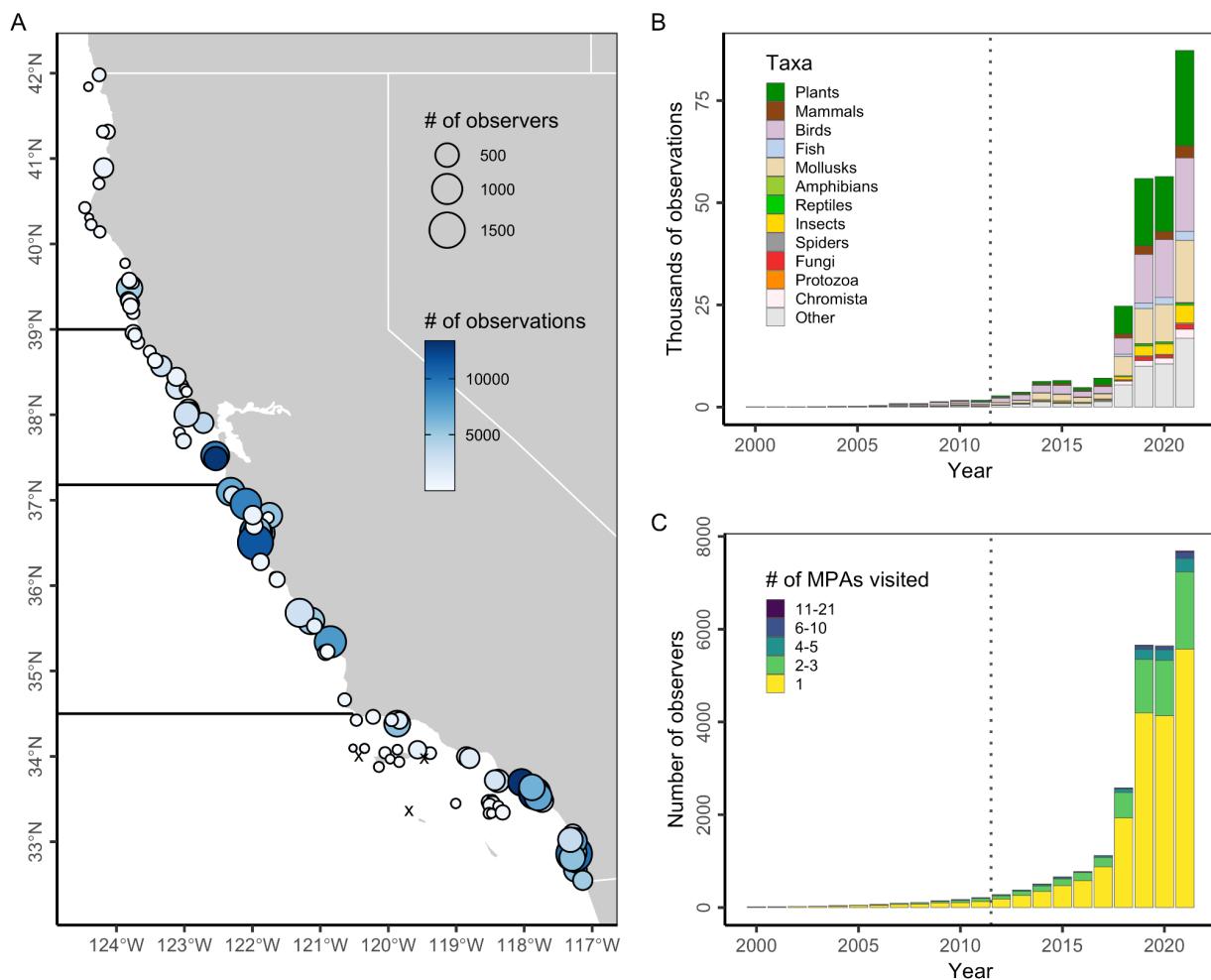
1006 **Figure S7.** Active consumptive activities in California's state marine protected areas (MPAs)
 1007 based on surveys conducted by MPA Watch. Two SMRAs are categorized as SMCAs to
 1008 increase visibility. Panel **A** shows the percent of surveys within MPAs of varying levels of
 1009 protection (point shape) in which active consumptive activities were observed (color ramp) and
 1010 the median number of active consumptive activities observed per hour (point size) for surveys in
 1011 which such activities were observed (i.e., zeroes excluded). Dark horizontal lines delineate the
 1012 four MLPA regions. Panel **B** shows the percent of surveys in which active consumptive activities
 1013 were observed by fishing sector (CPFV=commercial passenger fishing vessel). Panel **C** shows
 1014 the number of active consumptive activities observed per hour for surveys in which such
 1015 activities were observed (i.e., zeroes excluded). In the boxplots, the solid line indicates the
 1016 median, the box indicates the interquartile range (IQR; 25th to 75th percentiles), the whiskers
 1017 indicate 1.5 times the IQR, and the points beyond the whiskers indicate outliers.



1018

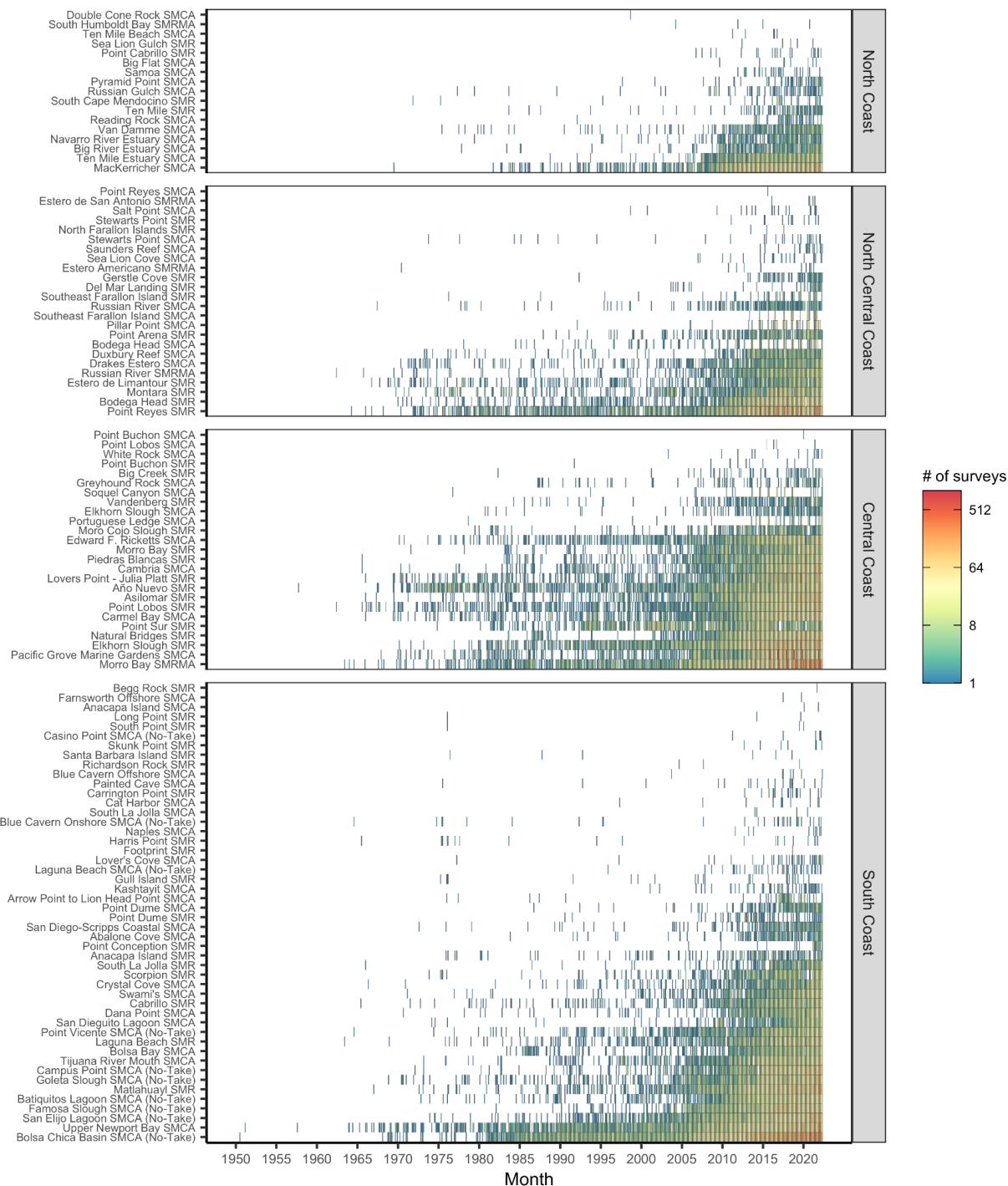
1019 **Figure S8.** Coverage of iNaturalist observation data over time by marine protected area (MPA).

1020 Note log-scale for fill color. MPAs are listed in order of overall sample size within each region.



1021

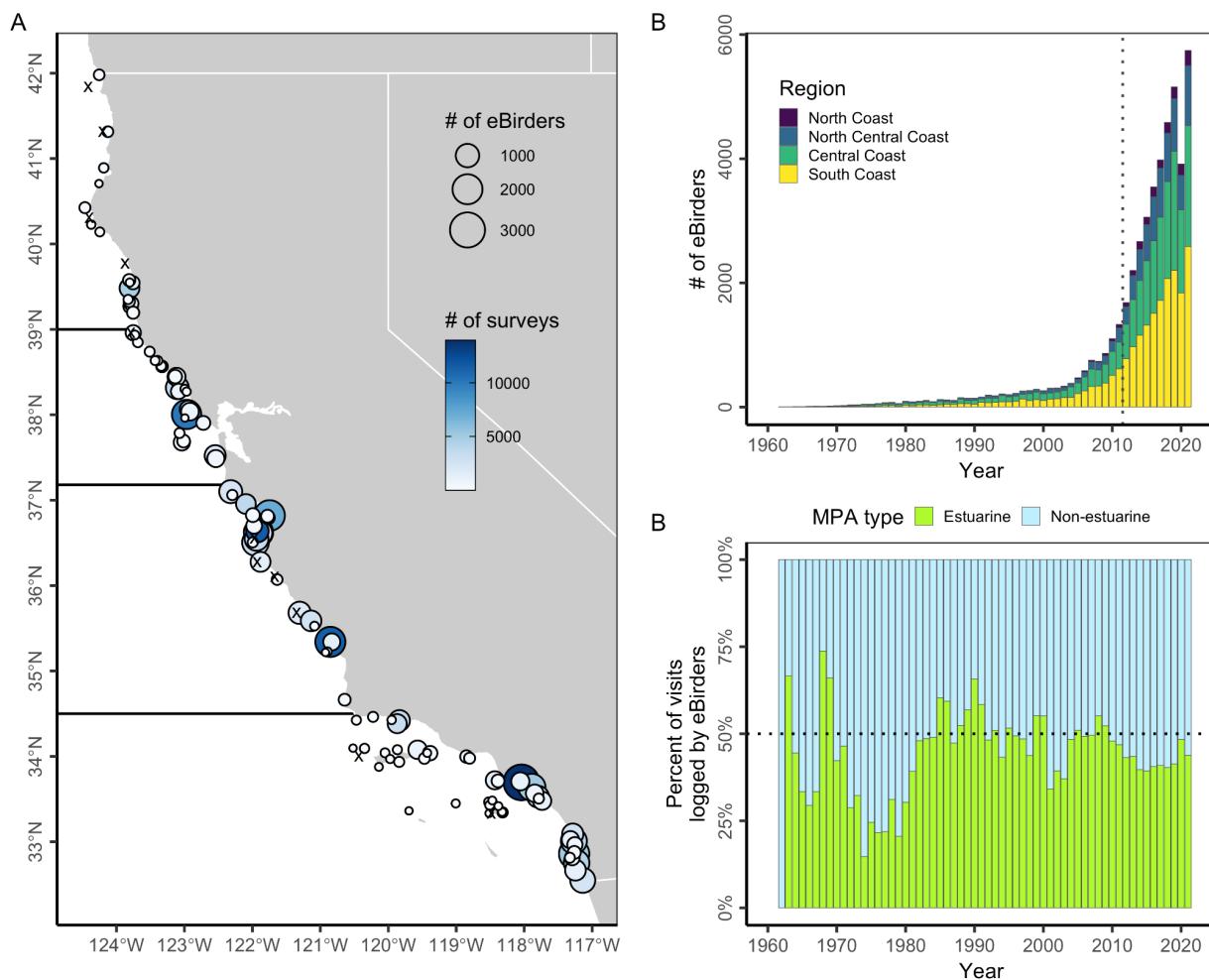
1022 **Figure S9.** Human interest in wildlife within California's state marine protected areas (MPAs)
 1023 based on usage of the iNaturalist web- and app-based application. Panel **A** shows the number
 1024 of observers (point size) and observations (color ramp) within 100 m of California's MPAs from
 1025 2012 through 2021. Note log-scale in fill color. Black x's mark the 4 MPAs without any
 1026 iNaturalist submissions. Dark horizontal lines delineate the four MLPA regions. Panel **B** shows
 1027 the number of observations made within 100 m of California MPAs from 2000-2021 by
 1028 taxonomic group. Panel **C** shows the number of observers making observations within 100 m of
 1029 California MPAs from 2000-2021 grouped by the number of MPAs that they visited.



1030

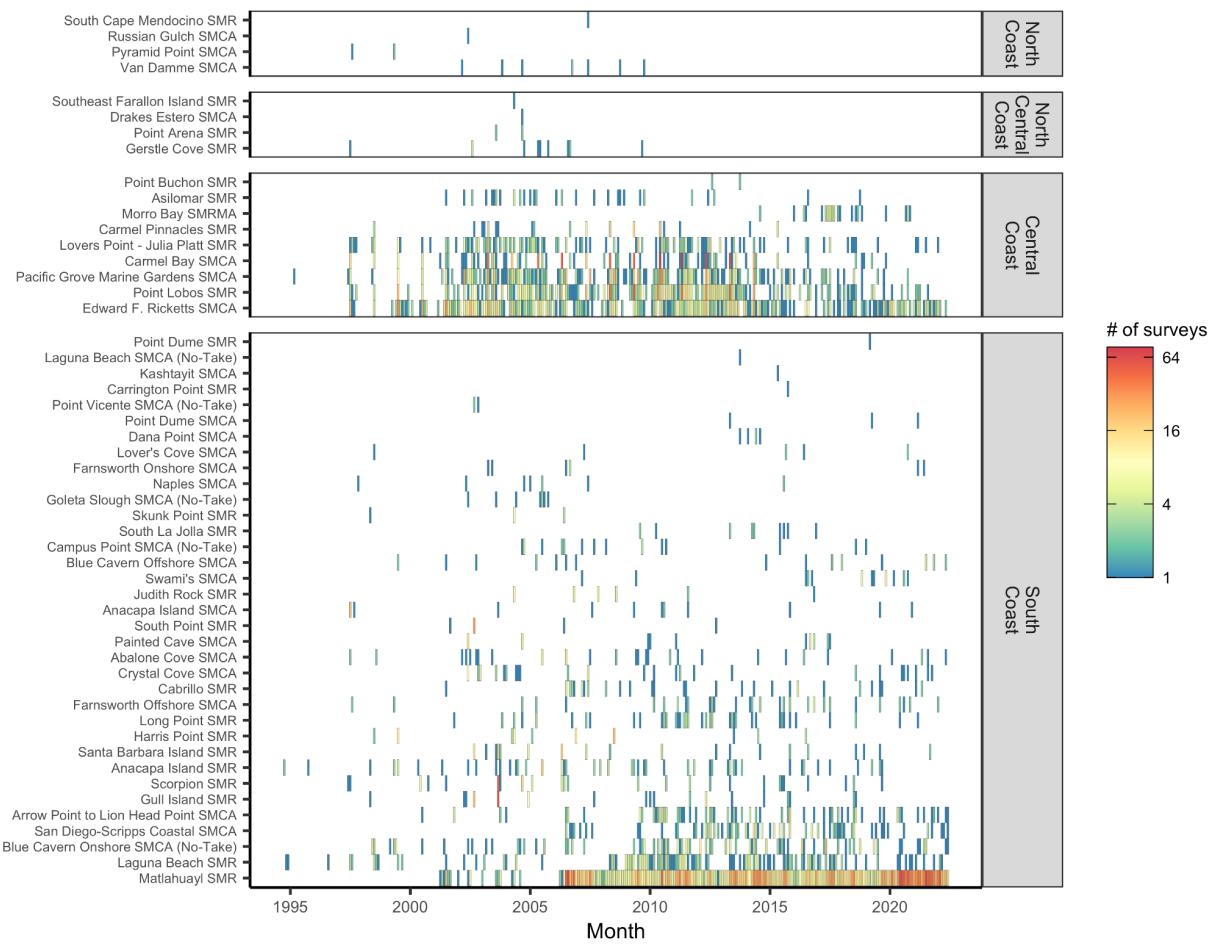
1031 **Figure S10.** Coverage of eBird observation data over time by marine protected area (MPA).

1032 Note log-scale for fill color. MPAs are listed in order of overall sample size within each region.



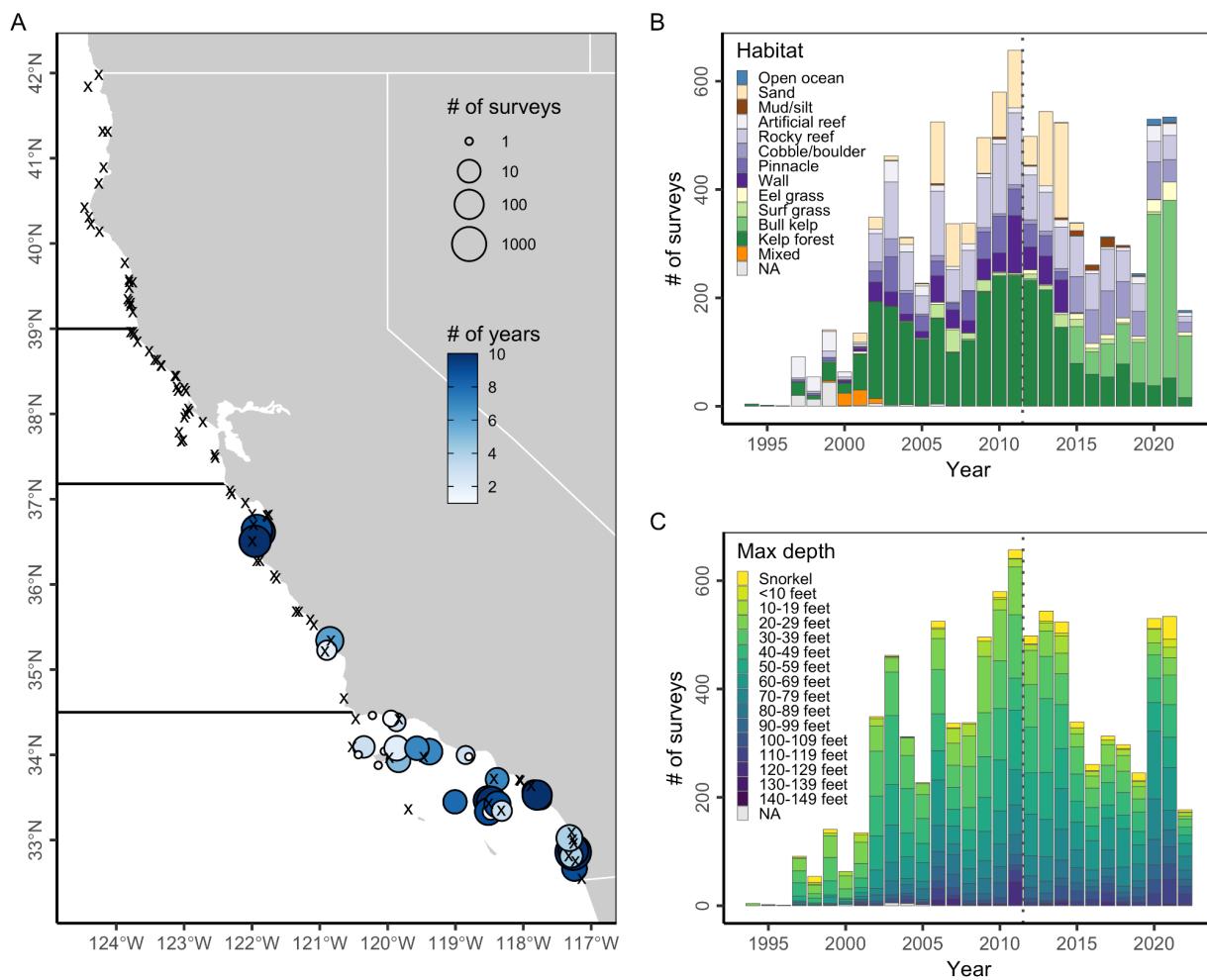
1033

1034 **Figure S11.** Human engagement in birding within California's state marine protected areas
 1035 (MPAs) based on submissions to the eBird citizen science program. Panel **A** shows the total
 1036 number of eBirders (point size) and surveys (color ramp) submitted by eBirders from within 100
 1037 m of California's MPAs from 2012 through 2021. Black x's mark the 11 MPAs without any eBird
 1038 submissions. Dark horizontal lines delineate the four MLPA regions. Panel **B** shows the number
 1039 of eBirders making observations from within 100 m of California MPAs from 1960-2021. Panel **C**
 1040 shows the percent of visits to MPAs logged by eBirders occurring from within estuarine and
 1041 non-estuarine MPAs from 1960-2021. Estuarine MPAs represent 2% of the network by area and
 1042 17% by count.



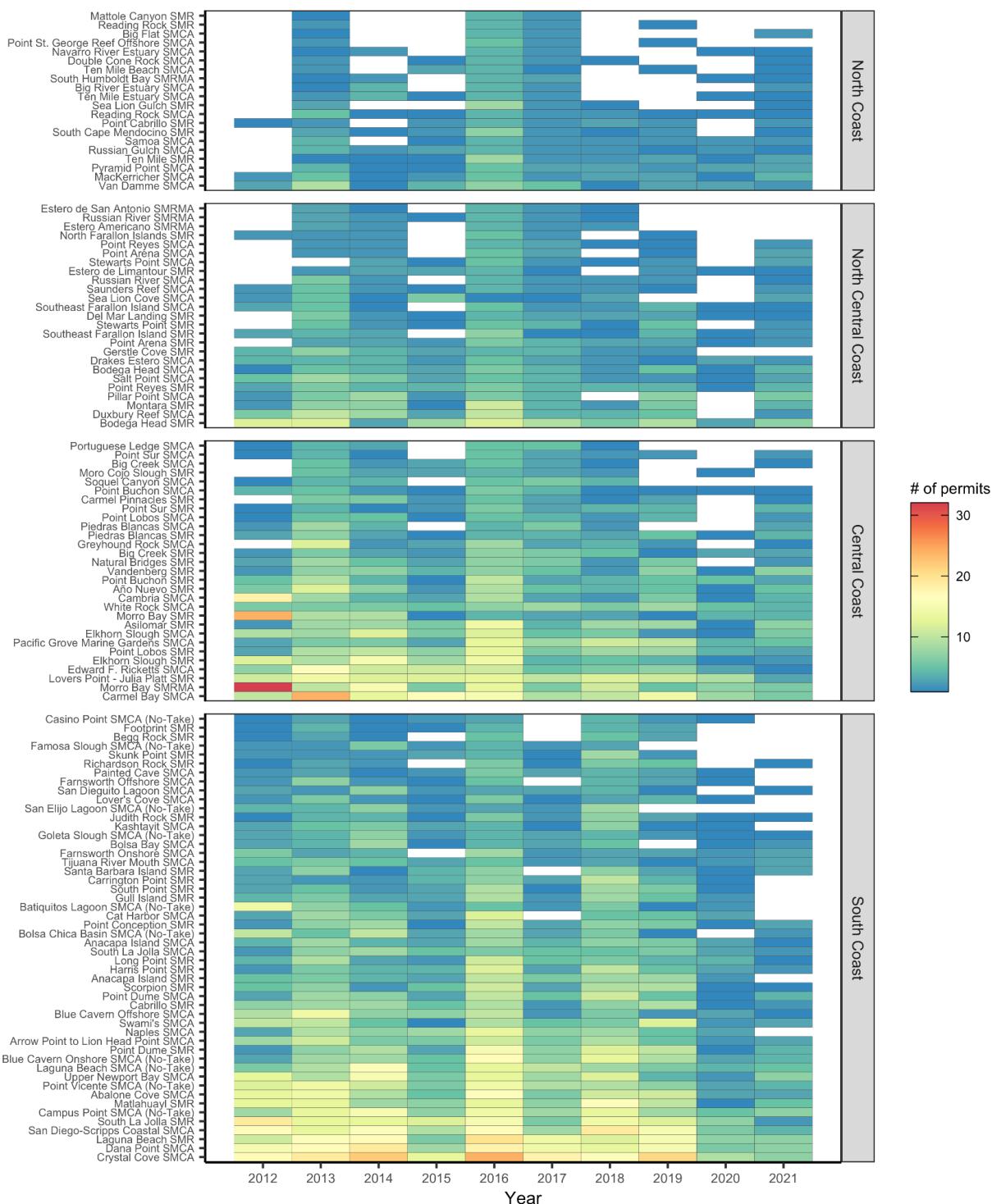
1043

1044 **Figure S12.** Coverage of REEF survey data over time by marine protected area (MPA). Note
 1045 log-scale for fill color. MPAs are listed in order of overall sample size within each region. One
 1046 San Francisco Bay MPA (Redwood Shores SMP) is plotted in the North Central Region for
 1047 simplicity.

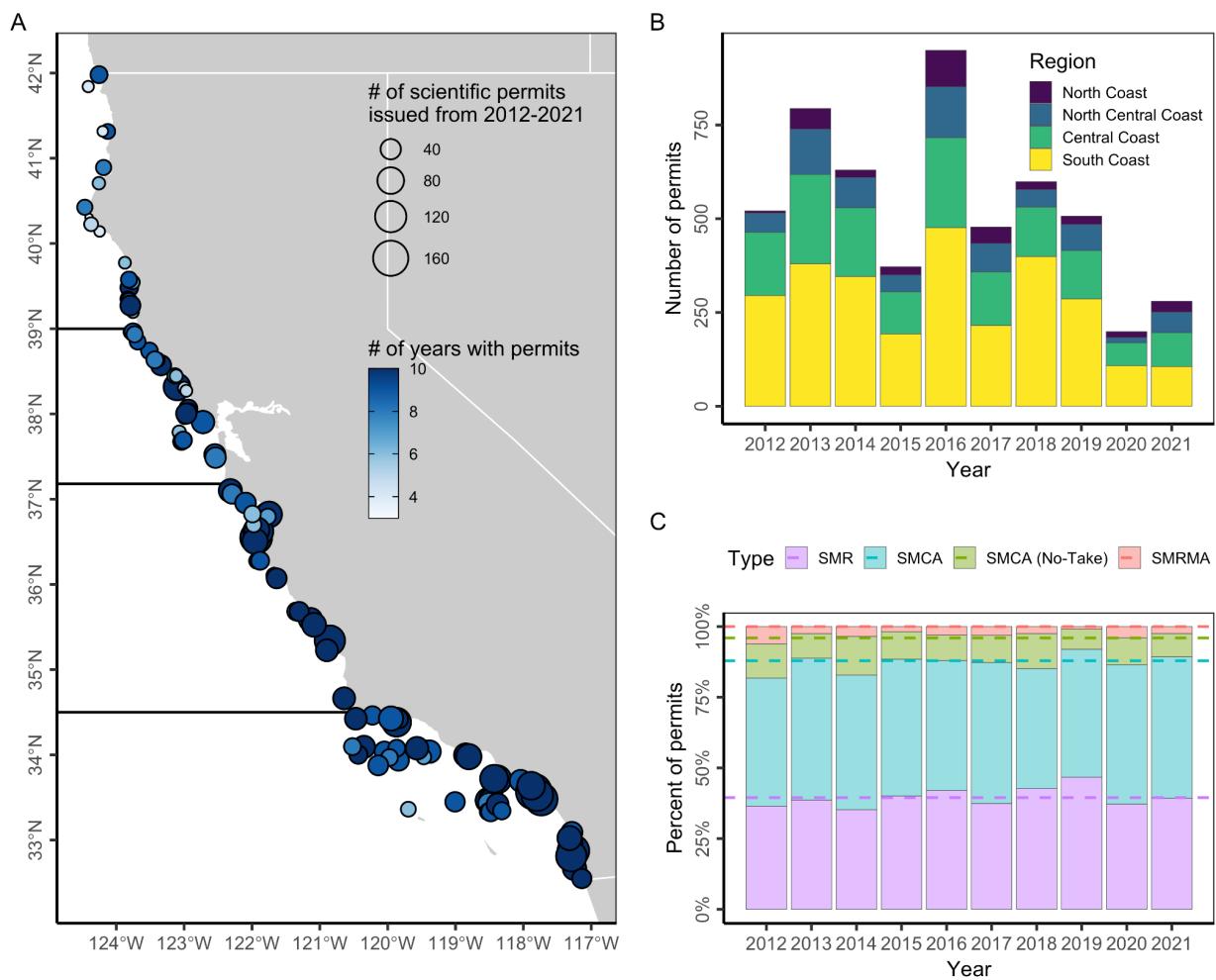


1048

1049 **Figure S13.** Engagement of recreational divers and snorkelers in the REEF citizen science
 1050 survey program within California's state marine protected areas (MPAs). Panel **A** shows the
 1051 number of surveys (point size) conducted in California's MPAs from 2012 through 2021 and the
 1052 number of years with survey data (color ramp) for each MPA. Note log-scale in point size. Black
 1053 x's mark the 83 MPAs without any REEF surveys. Dark horizontal lines delineate the four MLPA
 1054 regions. Panel **B** shows the number of surveys within California's MPA network from 1994-2022
 1055 by habitat type. Panel **C** shows the number of surveys within California's MPA network from
 1056 1994-2022 by depth zone.

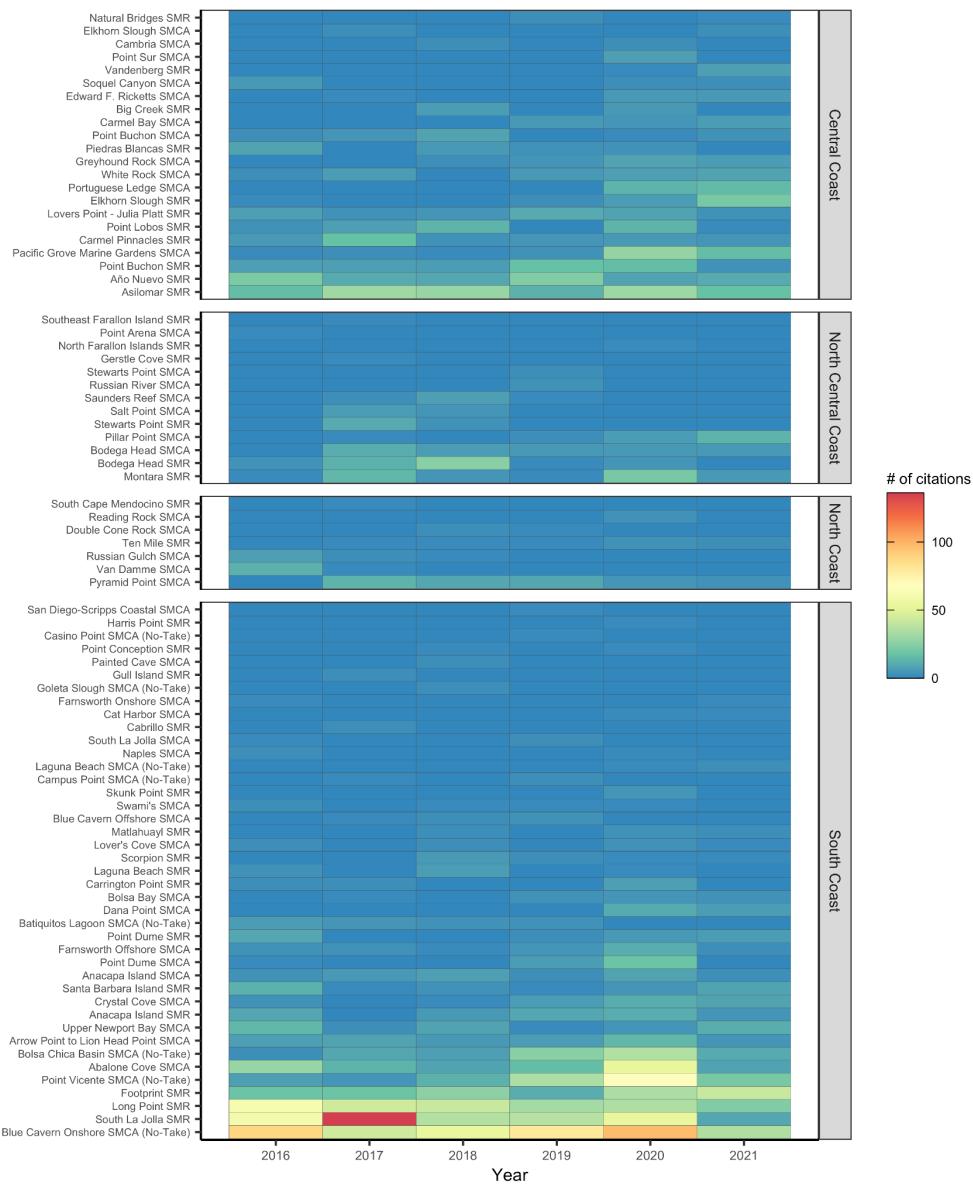


1057
1058 **Figure S14.** Number of scientific permits issued annually from 2012 to 2021 by marine
1059 protected area (MPA). MPAs are listed in order of overall sample size within each region.



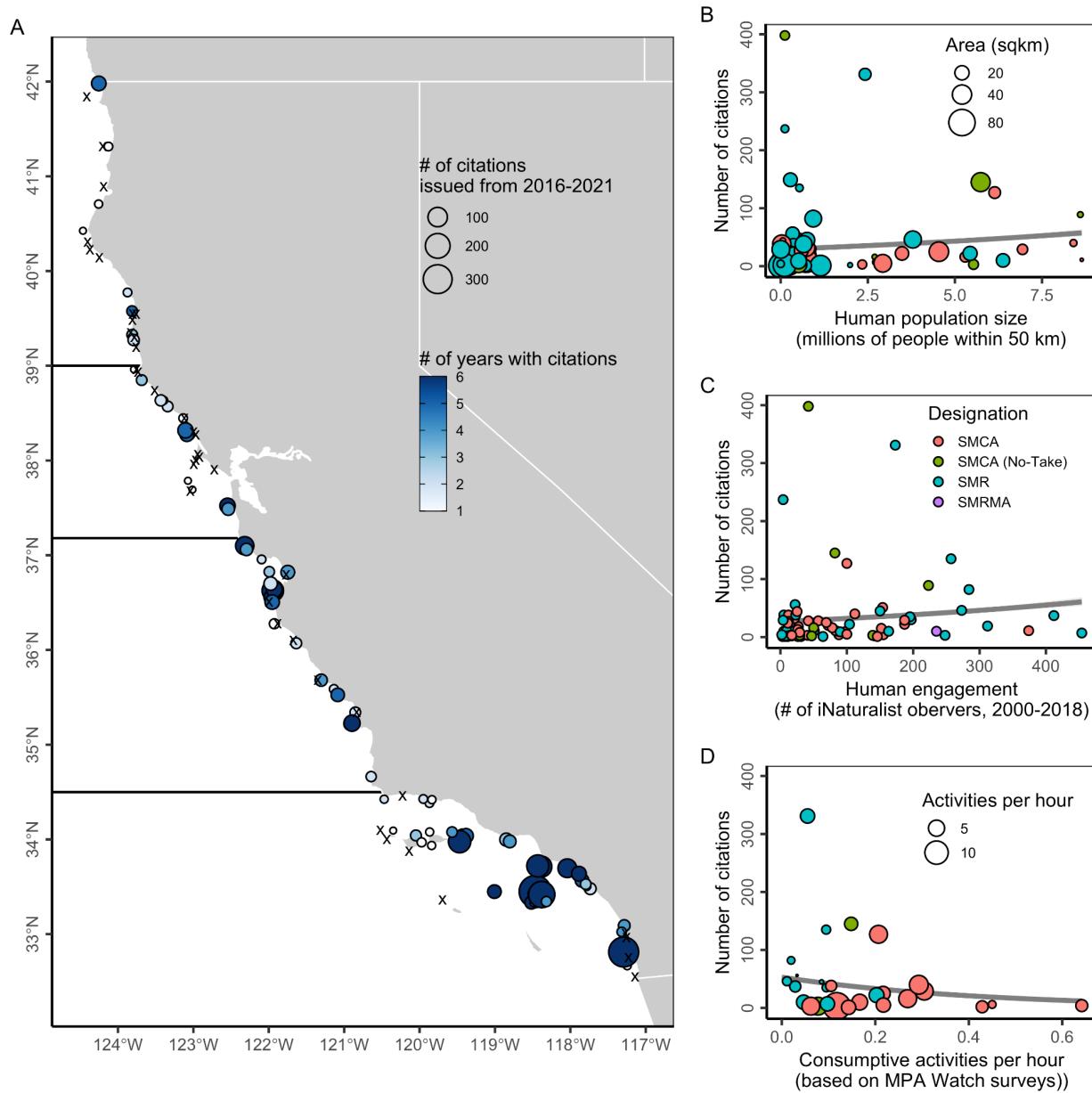
1060

1061 **Figure S15.** Number of scientific permits issued for research within California's state marine
 1062 protected areas (MPAs) from 2012 through 2021. Panel **(A)** shows the number of scientific
 1063 permits issued (point size) and number of years in which permits were issued (color ramp) for
 1064 each MPA. Dark horizontal lines delineate the four MLPA regions. In **(B)**, bars indicate the
 1065 percentage of annual permits issued to MPAs of different designations and lines indicate the
 1066 representation of MPAs of those designations in the network.



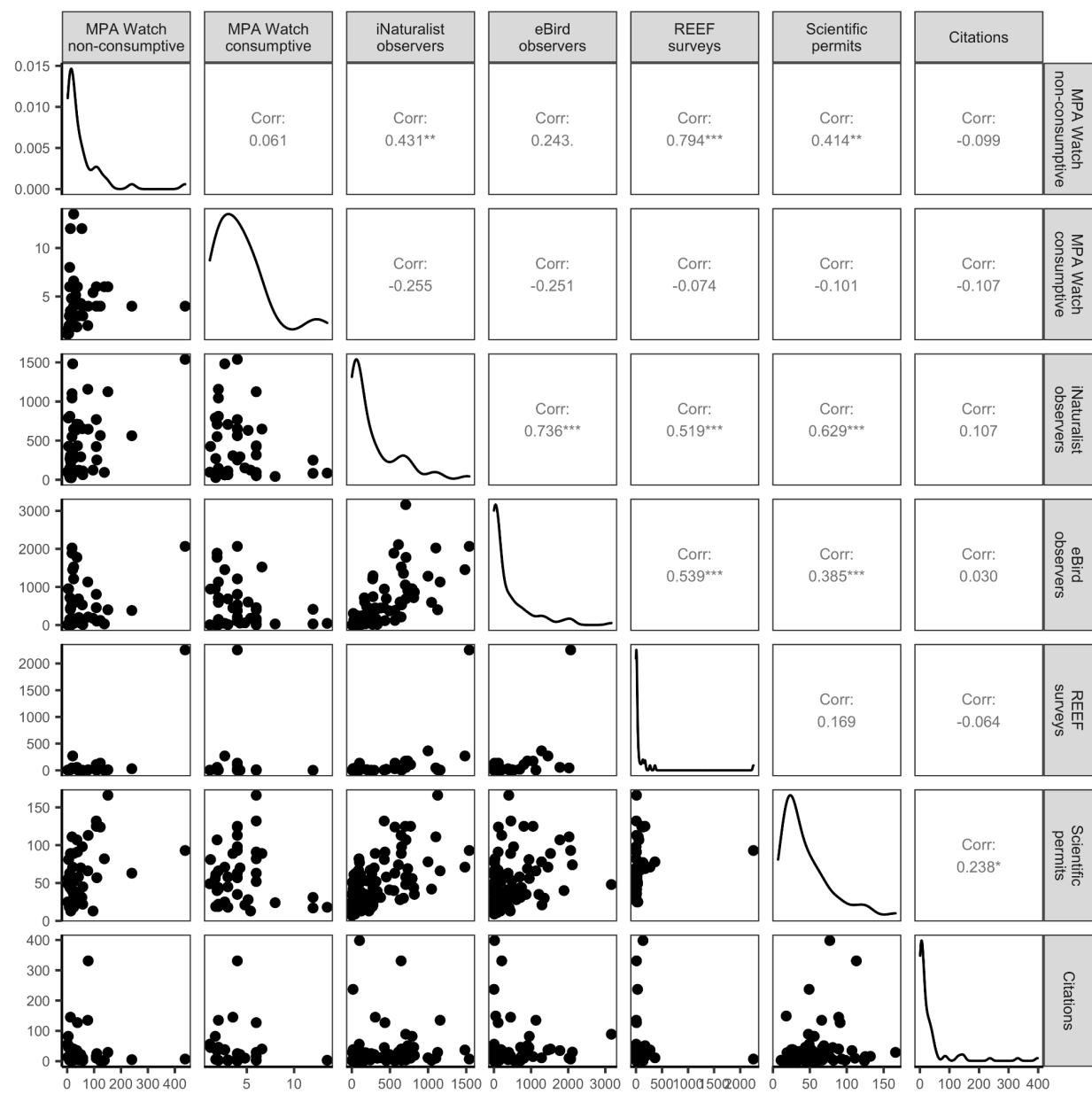
1067

1068 **Figure S16.** Number of citations issued by CDFW Law Enforcement for regulatory violations
 1069 occurring within California's MPAs from 2016 to 2021. MPAs are listed in order of overall
 1070 sample size within each region.



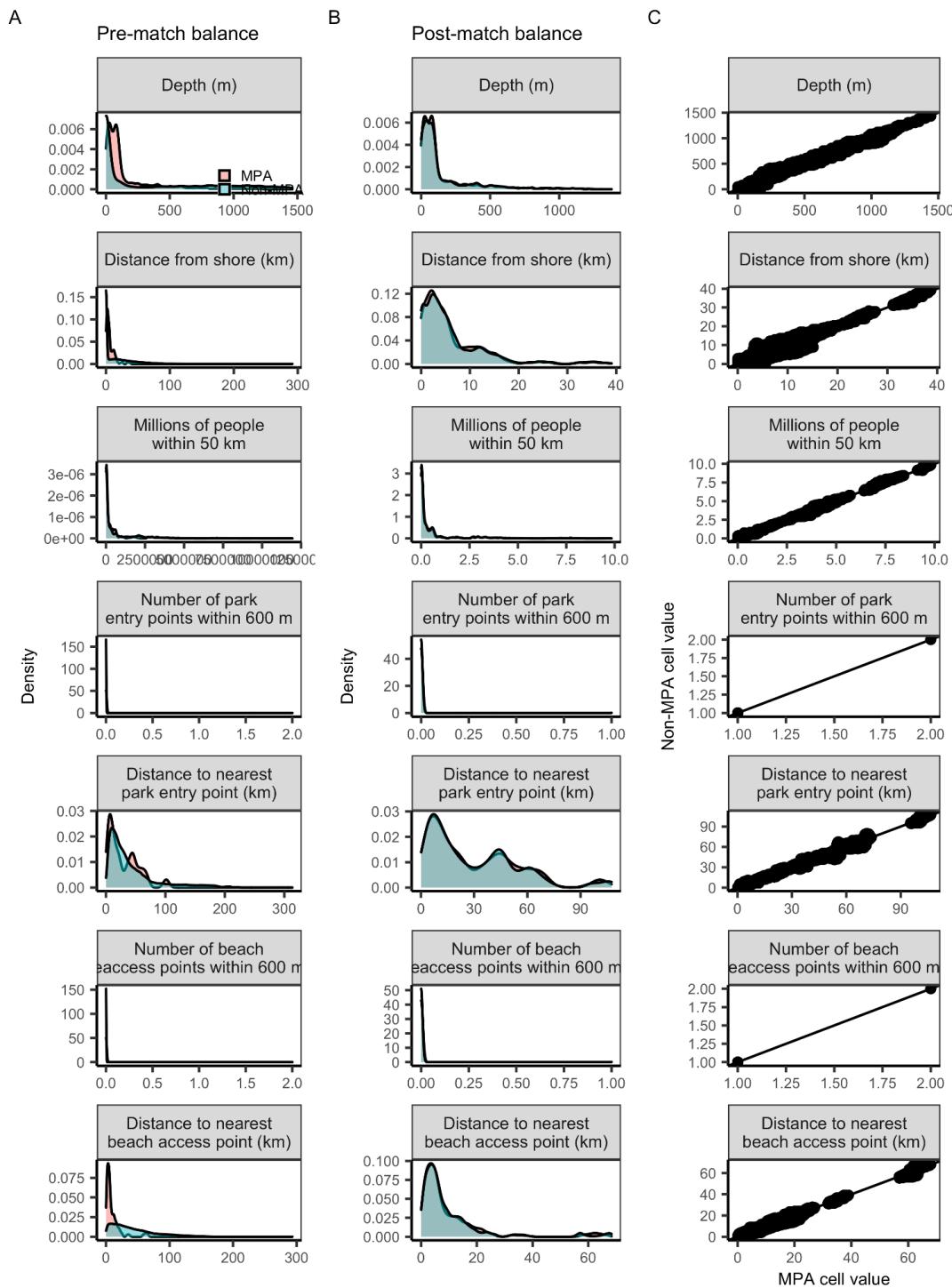
1071

1072 **Figure S17.** Number of citations issued by CDFW Law Enforcement for regulatory violations
1073 occurring within California's state marine protected areas (MPAs) from 2016 through 2021. In
1074 Panel **A**, black x's mark the 39 MPAs without any citations and dark horizontal lines delineate
1075 the four MLPA regions. In Panels **B-D**, the gray line and 95% confidence interval illustrate a
1076 generalized linear model assuming a Poisson distribution fit to the data.



1077

1078 **Figure S18.** Correlation between human engagement indicators. The lower section shows
 1079 pairwise comparisons of engagement indicators. The upper section shows the correlation
 1080 between each pairwise combination of indicators and the statistical significance of this
 1081 correlation (* = $p < 0.05$; ** = $p < 0.01$; and *** = $p < 0.001$). The diagonal indicates the
 1082 distribution of each engagement indicator. See **Table S3** for the choice of displayed indicator.



1083

1084 **Figure S19.** The balance of matching variables (A) pre- and (B) post-matching and the (C)
 1085 correlation between the values of MPA and matched non-MPA raster cells. In (C), the black line
 1086 is the one-to-one line.