

1 **Notes from the Past Show How Local Variability can Stymie Urchins**
2 **and the Rise of the Reds in the Gulf of Maine**

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39 **Supplemental Materials**

40 Supplementary Materials 1: Extended Methods

41 Supplementary Tables S1-S2

42 Supplementary Figures S1-S15

43 Supplementary Code and Data File

44 Supplementary Web Application

45 **Abstract**

46 The impacts of global change — from shifts in climate to overfishing to land use change — can
47 depend heavily on local abiotic context. Building an understanding of how to downscale global
48 change scenarios to local impacts is often difficult, however, and requires historical data across
49 large gradients of variability. Such data are often not available — particularly in peer reviewed
50 or gray literature. However, these data can sometimes be gleaned from casual records of natural
51 history — field notebooks, data sheet marginalia, course notes, and more. Here, we provide an
52 example of one such approach for the Gulf of Maine, as we seek to understand how
53 environmental context can influence local outcomes of region-wide shifts in subtidal community
54 structure. We explore a decade of hand-drawn algal cover maps around Appledore Island made
55 by Dr. Art Borrer while teaching at the Shoals Marine Lab. Appledore’s steep wave exposure
56 gradient — from exposed to the open ocean to fully protected — provides a living laboratory to
57 test interactions between global change and local conditions. We then recreate Borrer’s methods
58 two and a half-decades later. We show that overfishing-driven urchin outbreaks in the 1980s
59 were slowed or stopped by wave exposure and benthic topography. Similarly, local variation
60 appears to have curtailed current invasions by filamentous red algae. Last, some formerly
61 dominant kelps have disappeared over the past forty years — an observation verified by subtidal
62 surveys. Global change is altering life in the seas around us. While underutilized, solid natural
63 history observations stand as a key resource for us to begin to understand how global change will
64 translate to the heterogeneous mosaic of life in a future Gulf of Maine and other ecosystems
65 around the world.

66 **Introduction**

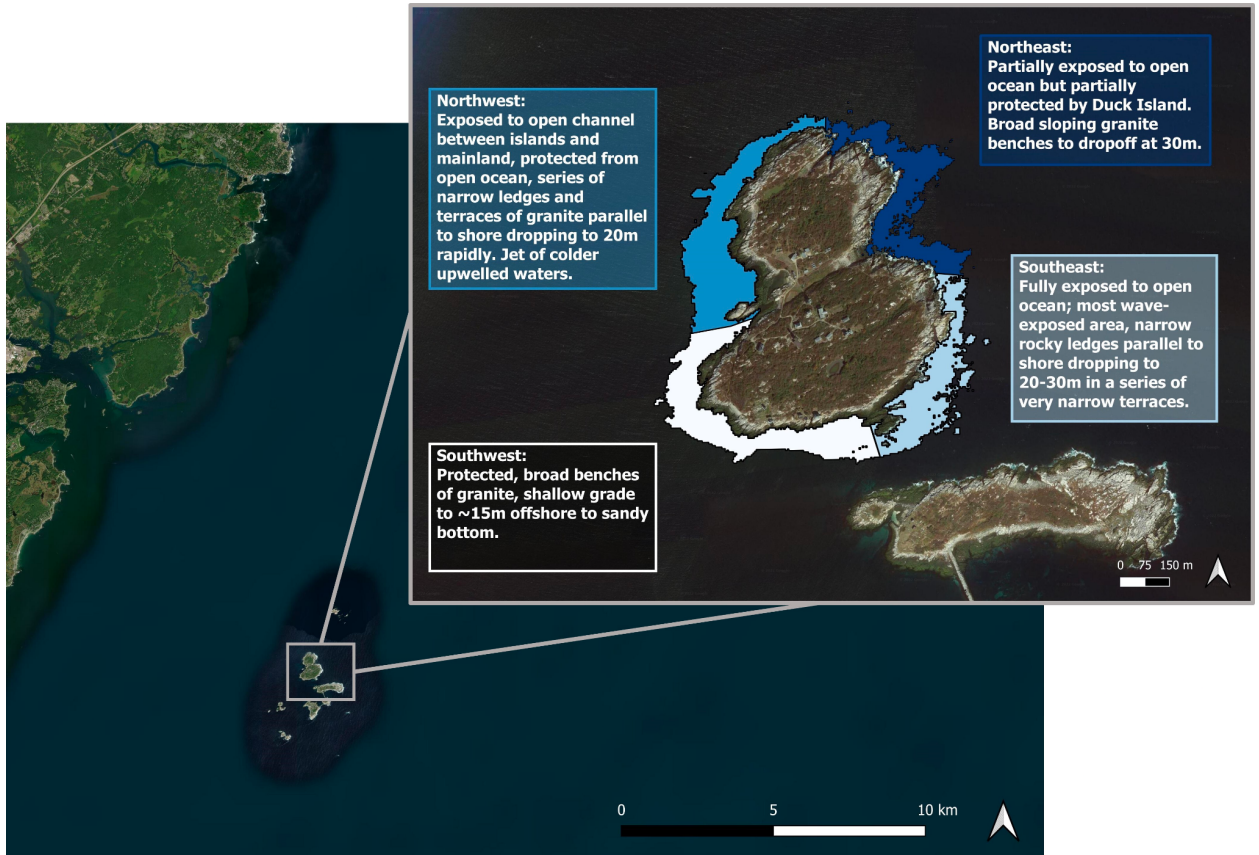
67 Ecologists and managers are constantly challenged to understand how global and regional
68 human change translates to changes at local scales (Wilbanks and Kates 1999; Knowlton and
69 Jackson 2008; Potter et al. 2013; De Boeck et al. 2015; Gonzalez et al. 2016; Blowes et al. 2019;
70 Chase et al. 2019). This ability to translate from the global to the local is crucial information, as
71 resilient and resistant communities can seed recovery and adaptation (Laborde et al. 2008;
72 Bongaerts et al. 2010; Reis et al. 2010; Rinde et al. 2014; Eger et al. 2022). As we confront the
73 changes to come, some of the most useful data on how local spatial variation in abiotic drivers
74 can modify the impacts of global and regional human-driven change come from the past. Yet,

75 these data are often rare — even within the past few decades — and typically are not taken at a
76 fine enough spatial grain to provide meaningful insights. Such data are particularly lacking for
77 temperate subtidal macroalgal communities where, until recently, one needed to be in the water
78 to see communities and colder waters limited access to even casual observers. Yet, the notebooks
79 and ephemera of great and passionate natural historians can provide a key to unlocking this
80 knowledge. Here we show that informal notes by faculty teaching at a marine lab can help us
81 understand how local-scale variation can reduce the effects of past runaway trophic cascades and
82 current-day bioinvasions.

83 Temperate macroalgal communities have experienced drastic changes both at the global
84 (Krumhansl et al. 2016) and regional (Steneck et al. 2013) scale over the past century. These
85 changes include radical shifts in abundance (e.g., Wernberg et al. 2012, 2016) as well as shifts in
86 species ranges and composition (Steneck et al. 2013; Dijkstra et al. 2017; Filbee-Dexter and
87 Wernberg 2018; Smale 2020). Macroalgal communities serve as the foundation for rocky
88 shallow-water benthic ecosystems; changes to these systems have immense implications for
89 associated species and their ability to provide ecosystem services, including harvesting of
90 commercial species. Local conditions, however, can alter the effects of global and regional
91 environmental change on these communities. Moreover, these local modifications to species
92 trajectories can even lead to improved trajectories of recovery after massive disturbances. When
93 kelps were subjected to massive overgrazing by sea urchins in Norway in the 1980s, for
94 example, local variation in wave exposure allowed for kelp persistence in some areas, which then
95 served as nuclei for recovery (Sivertsen 1997; Norderhaug and Christie 2009; Rinde et al. 2014).

96 The subtidal rocky reefs of the Gulf of Maine have experienced massive human-driven
97 changes over the past half-century. Aside from one of the fastest rates of warming in the ocean
98 (Pershing et al. 2015, 2021), we have seen a loss of predatory cod and other finfishes in the
99 1970s and 80s as a result of overfishing (Estes et al. 2013) creating runaway overgrazing of kelps
100 by sea urchins (Steneck and Wahle 2013; Steneck et al. 2013). This urchin boom was followed
101 by overfishing of urchins (Steneck et al. 2013), massive increases in mesopredatory crab and
102 lobster abundances (Steneck and Wahle 2013; Steneck et al. 2013), and some urchin disease
103 (Caraguel et al. 2007; Steneck et al. 2013), the latter of which was more prevalent in Nova Scotia
104 than the Gulf of Maine itself (Scheibling 1986; Scheibling and Lauzon-Guay 2010; Feehan and

105 Scheibling 2014). Alongside the resulting urchin declines, we have seen increases in crustacean
106 shell disease (Castro et al. 2012; Steneck and Wahle 2013), a rolling series of species invasions
107 (Harris and Tyrrell 2001; Mathieson et al. 2003; Bullard et al. 2007; Newton et al. 2013; Dijkstra
108 et al. 2017), changes in ocean color and pH due in part to increases in river runoff from strong
109 storms driven by climate change (Aiken et al. 2012; Balch et al. 2012; Huntington et al. 2016),
110 region-wide die-offs of mussels (Sorte et al. 2017), sea star wasting disease (Bucci et al. 2017;
111 Van Volkom et al. 2021), and likely more. The sequence of urchin overgrazing followed by
112 species invasions and increases in temperature, particularly in the southern Gulf of Maine (Harris
113 and Tyrrell 2001), has had profound influences on the composition and abundance of subtidal
114 habitat forming species (Steneck et al. 2013; Dijkstra et al. 2017, 2019). In particular, introduced
115 seaweed species have increased by 90% in the Gulf of Maine since the 1970's, reducing canopy
116 height and providing refuge for meso-invertebrate communities (Dijkstra et al. 2017). While we
117 have built up a wealth of knowledge looking at the consequences of regional changes in the
118 subtidal Gulf of Maine (see review in Steneck et al. 2013), few studies have examined how
119 small-scale environmental variability has moderated the impacts of regional anthropogenic
120 change across large spatial scales (but see Witman and Lamb 2018 for onshore-offshore
121 comparisons of fishing pressure and climate change). Without this information, we can only
122 begin to understand the factors that could impede, mitigate or facilitate adaptation to human-
123 driven ecological change in the Gulf of Maine subtidal zone.



124

125 **Figure 1.** The Isles of Shoals off the coast of New Hampshire and Maine with Appledore Island
 126 featured in the inset. In the inset, we highlight the four quadrants of the island considered in this
 127 manuscript and describe their broad differences in swell exposure and subtidal topography.

128 Starting in 1974, Dr. Arthur Borror taught a variety of courses in ornithology, zoology,
 129 and ecology at the Shoals Marine Lab on Appledore Island (Fig. 1). Borror, a phenomenal
 130 naturalist, recorded his observations each summer at the field station in a series of notebooks
 131 now archived at the University of New Hampshire (Borror 2016). As part of one class, students
 132 surveyed intertidal transects scattered around the whole island at low tide while Borror would
 133 circle the island by boat to check on them. Between 1982 and 1990, he also brought along a
 134 bathyscope, and would regularly lean over the side of the boat to observe the dominant subtidal
 135 habitat — either a species or functional group of algae or rocky urchin barren. He recorded five
 136 hand-drawn maps in his field notebooks of these habitats around the entire island. These maps
 137 span a huge gradient of wave exposure — from completely protected to fully exposed to the
 138 open ocean — as well as bottom topography. As a curiosity, along with Dr. James Coyer, one of

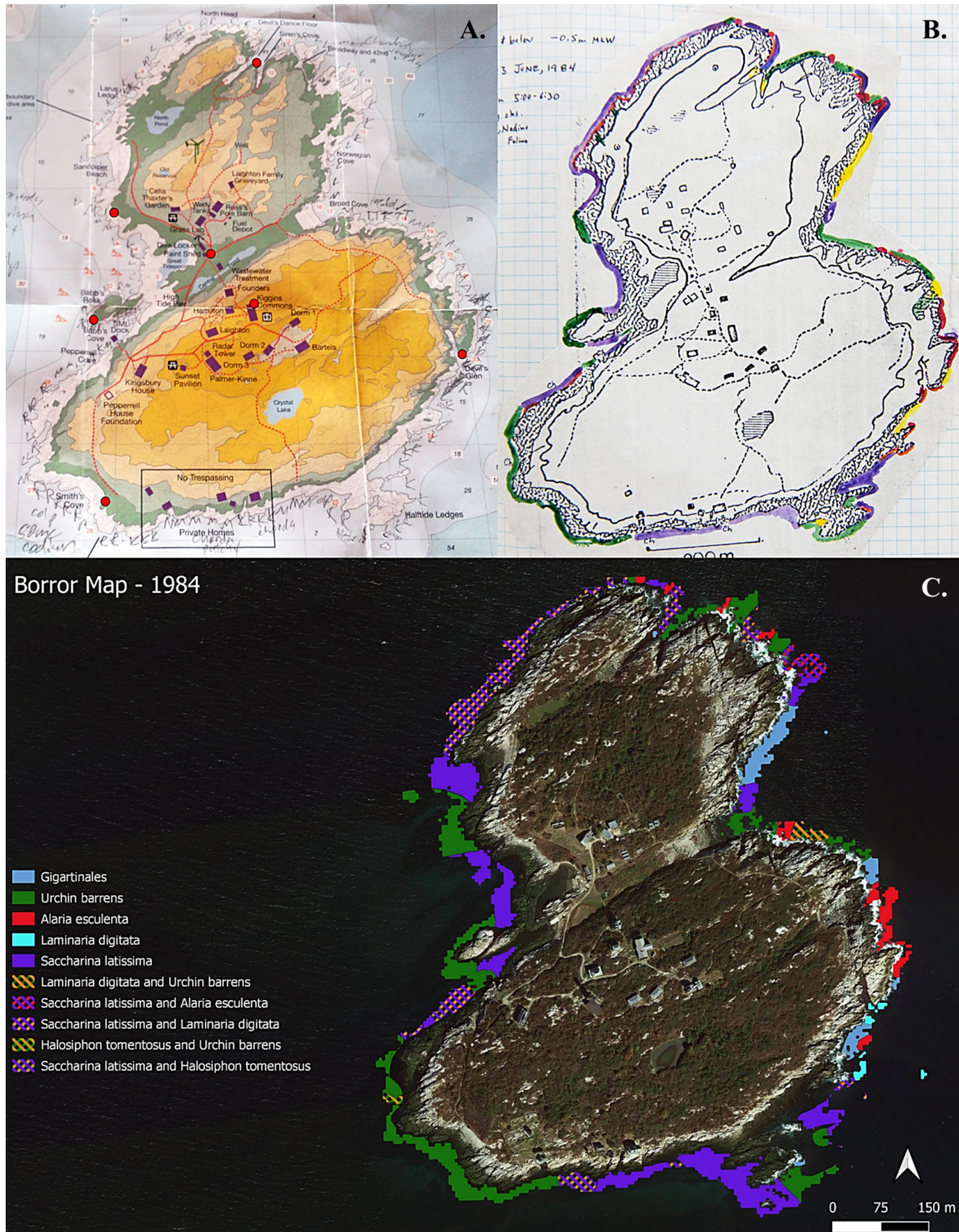
139 the authors of the present manuscript (Byrnes) repeated this observation in 2014, producing a
140 comparable map. While these are casual natural history observations, they provide an
141 unparalleled look at how the regional urchin boom of the 1980s and the rise of red algae in the
142 2010s played out against a backdrop of local environmental variability. Here we digitize these
143 maps and use the products to explore temporal and spatial patterns of macroalgae at Appledore
144 Island in order to understand how local variability can modify regional change within the Gulf of
145 Maine.

146
147

148 **Methods**

149 *Digitization of maps*

150 We recorded handwritten metadata and took digital photos of all maps and their legends
151 (Fig. 2, S1–S6, Supplementary Materials 1 for details of digitization), adjusted images with
152 Adobe Photoshop and then imported them into QGIS (QGIS Development Team 2022). In
153 QGIS, we georeferenced seven distinct points which were consistent across all maps based on
154 the more precise 2014 map (Fig. 2A). We overlaid the georeferenced photos on a Google
155 Satellite base map (obtained through QuickMapServices QGIS plugin Map data ©2015 Google)
156 with transparency at 50%. We manually added polygons matching maps and labeled them
157 corresponding to a single species or mix of species (Fig. 2B,C for 1984 map), which we will
158 refer to as communities or habitats. To account for changes in taxonomy across years and lack of
159 specificity for some groups, we identified communities based on a standardized taxonomy across
160 maps (Table S1). Using a bathymetry layer (Ward et al. 2021), we clipped polygons to areas
161 shallower than 5m below mean low low water. We then drew a perimeter line at 1.5m around the
162 island to create a gapless island perimeter from which to determine the percent cover of habitats.



163
 164 **Figure 2.** Appledore Island maps depicting the various habitats (often species) occupying the
 165 coastline. **A.** The 2014 map with seven red circles showing the points used for georeferencing all
 166 six maps and satellite maps in QGIS. Each habitat is represented by a different letter along the

167 coast. **B.** The original 1984 map where each habitat is represented by a different color along the
168 coast. **C.** The final 1984 digitized map showing habitats present between 0–5 meters depth.

169 *Percent cover of each habitat type*

170 To obtain the area covered by each habitat, we imported all six map shapefiles into R
171 (version 4.1.1, R Core Team 2020) and split polygons representing more than one habitat into
172 multiple overlapping polygons for each unique habitat. On the original Borrer maps, some labels
173 included details such as “kelp and sparse *Saccharina*”, but we were unable to quantify “sparse”
174 or other qualitative descriptors and therefore ignored these details for consistency. We
175 determined the intersection between the 1.5-meter perimeter around Appledore Island and
176 polygons for each habitat in each year and used the proportion of perimeter intersected as our
177 measure of cover. For overlapping polygons, we evenly divided the percentage of the perimeter
178 between them. We then repeated the process with habitats grouped into “pure kelp”, “mixed kelp
179 & reds”, “mixed red algae”, and “urchin barrens”.

180 *Assessing local modification of urchin barren formation and red algal dominance*

181 To evaluate how local environmental variation around the island might have impacted
182 urchin barren formation and the rise of red algae across Appledore, we split the island into four
183 quadrants due to substantial subtidal variation in these areas (see Fig. 1). Each quadrant had
184 unique properties of wave exposure and benthic topography (Supplementary Materials 2). Going
185 clockwise, these quadrants were: southwest, characterized by minimal wave exposure and wide
186 shallow sloping benches; northwest, characterized by exposure to swell coming from the
187 mainland and narrow fast-dropping ledges; northeast, characterized by moderate exposure to the
188 open ocean shielded by nearby Duck island and wide sloping benches, canyons; and the
189 southeast, characterized by direct exposure to the open ocean and fast-dropping ledges parallel to
190 shore.

191 To evaluate how quadrant affected urchin barren cover and kelp cover, we analyzed each
192 using beta regression with a logit link — ideal for bounded data (Cribari-Neto and Zeileis 2010;
193 Douma and Weedon 2019) — with quadrant, year (as a categorical variable), and their
194 interaction as predictors for data from 1980–1990. Based on the results, we ran *post-hoc*
195 contrasts between quadrants in each year, correcting p-values for False Discovery Rate

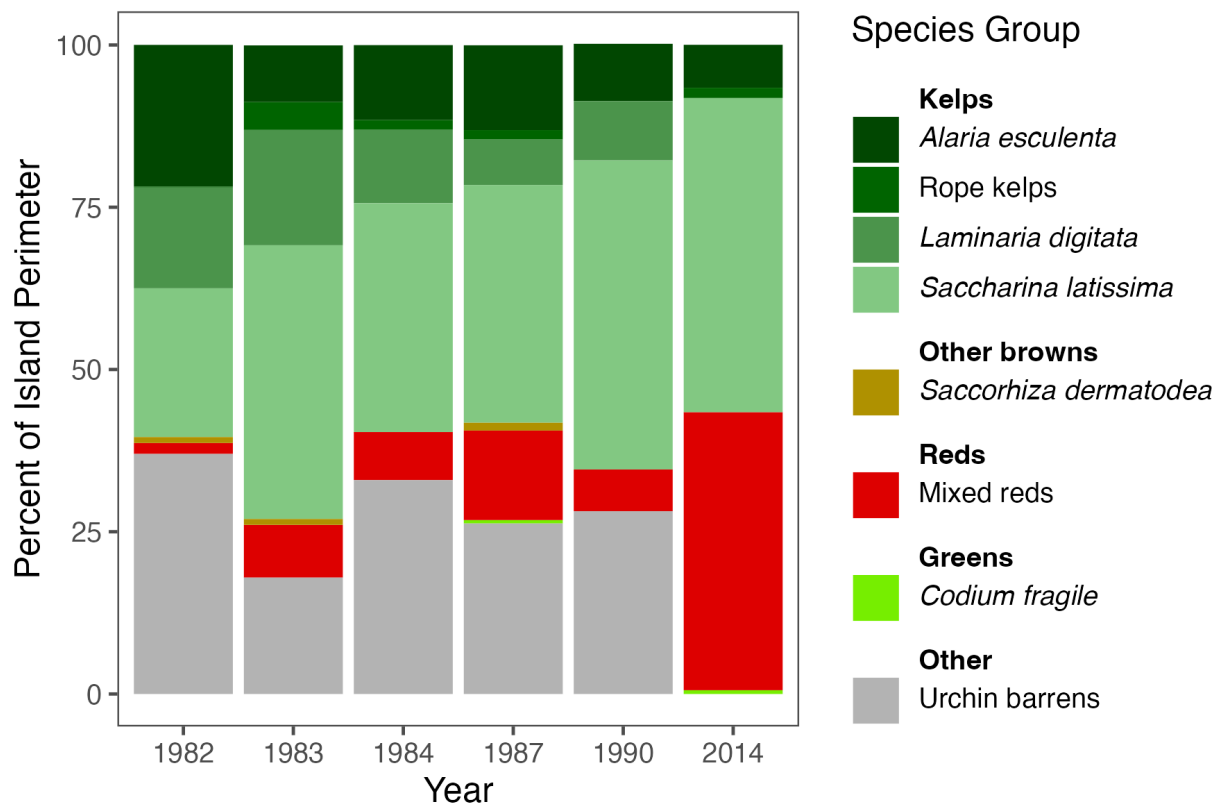
196 (Benjamini and Hochberg 2000). We did not use 2014 data for these analyses given the shift in
 197 the subtidal community from an urchin-dominated to non-urchin-dominated state. Instead, we
 198 used 2014 data to qualitatively compare the abundance of coarse taxonomic groups in different
 199 quadrants, as n=1.

200

201 **Results**

202

203 Digitized maps (Fig. 2, S7–S12, Supplementary Data 1,2) clearly show several trends in
 204 composition of dominant space holders over time (Fig. 3, Figure S13 for maps). First, urchin
 205 barrens were a dominant habitat type around Appledore in the 1980s (22.8–34.1% of total
 206 habitat), although kelps comprised the majority of habitat around the entire island (49.9–63.0%).
 207 Second, we see the expansion of *Saccharina latissima* between 1990 and 2014 and the absence
 208 of urchin barrens in 2014. Notably, in 2014 red algae composed 35% of the perimeter versus less
 209 than 12% in the 1980s. More subtly, *Laminaria digitata* is absent in 2014 and *Alaria esculenta*,
 210 while abundant in 1982, is greatly diminished in abundance (Fig. 3).



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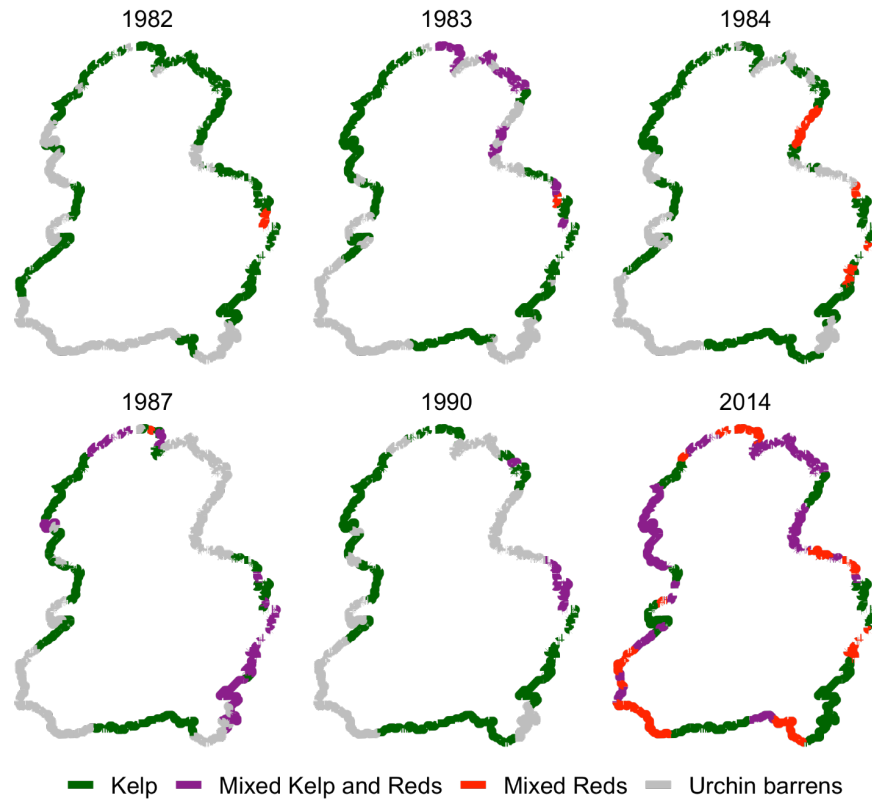
213 **Figure 3.** Change in percent of perimeter at 1.5m depth covered by each habitat or community
214 type over time.

215

216 Looking at these trends spatially and aggregating groups into kelps, red algae (or “reds”),
217 and barrens, we can see that the impact of urchins in the 1980s and putative impact of red algal
218 expansion in the 2010s was unevenly distributed over Appledore (Figure 4, Fig. S14), reflecting
219 local variability in abiotic conditions. In the 1980s, the southwest quadrant of the island was
220 characterized by an extensive urchin barren, which persisted into the early 2000s (Siddon and
221 Witman 2004, J. Byrnes pers. obs.). The northeast also appears to have developed two urchin
222 barrens — one in a cove known as Devil’s Dancing Floor at the north and the other at the back of
223 Babb’s Cove further to the south. These barrens eventually joined by 1987, although the most
224 exposed tip of the northeast had begun to revert back to kelp by 1990. Barrens were rare in the
225 northwest and southeast. This trend in urchin barrens is supported by an interaction between year
226 and quadrant ($df = 3$, $\chi^2 = 25.8$, $p < 0.001$ Supp. Table 2) and post-hoc test results showing the
227 trends described above (Fig. S15).

228 Curiously, 2014 looks similar to 1990, but red algae replaced barrens (Fig. 4). The
229 protected southwest was dominated by stands of reds, the partially-protected northwest and
230 partially-exposed northeast hosted a combination of kelps and reds, and the fully-exposed
231 southeast was largely dominated by kelps.

232



233
234

235 **Figure 4.** Maps of the perimeter of Appledore over time showing kelp, stands of mixed kelp and
236 red algae, red algae, and urchin barrens over time.

237

238 **Discussion**

239

240 Our analysis of these natural history observations supports long-term trends observed in
241 other studies (Harris and Tyrrell 2001; Steneck et al. 2013; Dijkstra et al. 2017). First, we can see
242 the major island-wide macroalgal community responses due to two important major regional
243 shifts in the Gulf of Maine, the explosion of urchins in the 1980s and the rise of — often invasive
244 — red algae in the 2010s. Yet, these two observations are by no means uniform, and the
245 substantial spatial variation suggests that local environments can play a strong role in mediating
246 the impacts of global or regional change. Second, informal natural history observations such as
247 these hand-drawn maps are an invaluable source of data that can contribute meaningful insight
248 into how the local variation of a region is shaping the response of biotic communities to global
249 patterns and even direct how we approach future management.

250 Borrer's maps from the 1980s show strong correlation with known regional trends. By
251 the 1980s, cod catches had declined due to overfishing (Sosebee and Cadrin 2006) and urchins
252 were likely already on the rise (Steneck et al. 2013). Urchin barrens increased notably on the
253 northeast and southwest of the island, where they were most abundant, while fluctuating
254 stochastically in other quadrants. In 1990, the last survey where barrens were observed, they had
255 notably decreased. The urchin fishery in Maine started in 1987 and peaked in 1993 (Johnson et
256 al. 2012). *Cancer* crab abundance — a current major predator of juvenile urchins — did not
257 begin to rise until the mid 1990s (Steneck et al. 2013). After urchin declines across the Gulf of
258 Maine, many former barren grounds turned over multiple times between different waves of
259 invasive algae (Harris and Tyrrell 2001). In particular, the last decade has witnessed the rise of
260 the invasive red turf alga *Dasysiphonia japonica* in New England (Newton et al. 2013; Dijkstra
261 et al. 2017, 2019; Ramsay-Newton et al. 2017). Indeed, much of the red algae (hereafter reds) in
262 2014 on the west side of the island are confirmed *Dasysiphonia*, while those in the northeast are
263 primarily other native reds mixed with some *Dasysiphonia* (J. Byrnes, pers. obs). This expansion
264 of red algae around Appledore Island matches both a regional and global turf-i-fication of
265 temperate rocky reefs (Dijkstra et al. 2017; Filbee-Dexter and Wernberg 2018) driven globally
266 by invasions, climate change, and more.

267

268 *The role of local environmental variation in temperate rocky reefs*

269

270 Within these broad temporal trends, however, we see substantial spatial variation. One of
271 the features that makes Appledore Island such an excellent living lab is the variation in the
272 abiotic environment around its rocky shores, from exposure to the open ocean to protected by the
273 natural harbor formed by the Isles of Shoals as well as substantial variation in benthic
274 topography. Island quadrants with narrow ledges and moderate to strong exposure to waves had
275 the fewest barrens (NW and SE Appledore). These trends follow what we know of the
276 biomechanical limits on urchins and their ability to form barrens under the stress of higher flows
277 from storms or even regular strong sublethal wave velocities (Siddon and Witman 2003; Rinde et
278 al. 2014). Curiously, the partially-exposed northeast also hosted a large barren, seeming to
279 contradict the exposure hypothesis. However, this area has relatively simple smooth descending
280 benches whose lack of complexity could have played a role in providing good habitat for barren

281 formation (Randell et al. 2022). Further, the barren in the northeast quadrant grew from two
282 protected embayments, which could have served as urchin refuges during periods of intense
283 wave action.

284 Variation by quadrant seems to also play a role in the expansion of red algae, seen on the
285 2014 map (Fig. S12). As urchins declined in the 1990s, a series of invasive algae moved into
286 former barren grounds (Harris and Tyrrell 2001; Levin et al. 2002; Mathieson et al. 2003;
287 Dijkstra et al. 2017). In 2014, the protected southwest quadrant — a former barren — is largely
288 covered with red algae that we verified in the field as the invasive *Dasysiphonia japonica*.
289 *Dasysiphonia* also has a strong presence in the more protected northwest, as verified by divers (J.
290 Byrnes, pers obs.). Red algae were also common in the shallow subtidal in the partially exposed
291 northeast, but field identification revealed a mix of native *Polysiphonia* and *Chondrus crispus*,
292 with *Dasysiphonia* composing only a small percentage thereof. The fully-exposed southeast
293 remained largely kelp-dominated, and, indeed, is the only place around the island to still hold the
294 high-wave energy tolerant *Alaria esculenta*. Aside from the southwest, red macroalgal
295 communities in all quadrants are typically mixed with kelp rather than being a large red shag-
296 carpet-like monoculture (J. Byrnes, pers. obs.).

297 Local variation appears to be key to understanding the ubiquity and composition of the
298 rise of reds around Appledore, as well as where kelps are able to persist. Many rocky reefs
299 around the globe are undergoing similar shifts from kelp forests to dominance by turf macroalgae
300 (Connell et al. 2014; Filbee-Dexter and Wernberg 2018). Our results suggest these regime shifts,
301 rather than being characterized by complete dominance, are more like patchworks determined by
302 local conditions at the seascape scale. Around Appledore, wave exposure and seafloor
303 topography create refuges for kelp from both sea urchins and red algal dominance. With respect
304 to urchins, the results are strikingly similar to results from Norway (Sivertsen 1997; Norderhaug
305 and Christie 2009; Rinde et al. 2014). The combination of exposure and benthic topography set
306 the stage for oceanographic conditions such as current speed, upwelling, and wave energy, all of
307 which could act to facilitate kelp persistence and dominance. For example, steep slopes around
308 islands in the Gulf of Maine, such as those seen at Appledore's north head, can facilitate local
309 upwelling (Townsend et al. 1983) bringing colder nutrient-rich waters to fast-growing kelps. We
310 see a similar example at Cashes Ledge, an underwater mountain range with steep slopes ~140km
311 from Appledore with a dense healthy kelp forest (Witman and Lamb 2018). Our work suggests

312 that there might be a suite of predictable characteristics that can strengthen kelp forests'
313 resistance to and resilience from ongoing trends of global change that warrant deeper
314 exploration.

315

316 *Natural history observations and global change*

317

318 These results, garnered from informal notebooks, provide key insights into the larger
319 field of global change ecology. Solid natural history observations and notes are an unparalleled
320 and largely untapped resource for the field. The old field notebooks and observations from
321 generations past floating around in archives, bookshelves, and file cabinets deserve preservation
322 and ought to be digitized to provide us with an ecological time-machine that could open new
323 chapters in our understanding of long-term change. Even informal large-scale observations can
324 provide incredible clarifying insight into the ability of the local environment to modify global
325 impacts.

326 Ultimately, our work shows a striking concordance with literature around the globe
327 attempting to grapple with the importance of local-scale drivers in modifying global and
328 regional-scale human-driven change (Wilbanks and Kates 1999; Knowlton and Jackson 2008;
329 Potter et al. 2013; De Boeck et al. 2015; Gonzalez et al. 2016; Blowes et al. 2019; Chase et al.
330 2019). Patterns in the spatial variability of urchin barrens over time echo patterns seen in Norway
331 (Sivertsen 1997; Norderhaug and Christie 2009; Rinde et al. 2014) and Southern California
332 (Harrold and Reed 1985; Randell et al. 2022), and show how small-scale observations in the
333 Gulf of Maine (Siddon and Witman 2003) scale up to whole coastlines. Further, large-scale
334 patterns in the rise of reds highlight that the same types of variation — high wave and current
335 energy — can mediate other forms of global change as well. We suggest that similar broad-scale
336 low-taxonomic resolution approaches — whether from formal or more informal sources —
337 might provide incredible insight as ecologists grapple with how global changes will manifest
338 locally. That, and it makes for some fun boat (or road) trips.

339

340

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350

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Supplementary Materials for Notes from the Past Show How Local Variability can Stymie Urchins and the Rise of the Reds in the Gulf of Maine

Supplementary Materials 1: Extended Methods

Maps and processing

Original Borrer maps consisted of digital photos of a photocopied map of Appledore Island glued into a field notebook. Species observations were annotated by outlining the coastline with colored markers. A key to the colors was hand drawn in the field notebook, alongside the date, time, and depths of the observation. Observations from 1990 were recorded on the map digitally, with letters instead of colors indicating the species, then printed. To prepare these photos for digitizing, we used Photoshop to crop, align, and adjust the contrast for each map so that the coastline was clear and shadows from creased paper minimized. All handwritten metadata and data was transferred into spreadsheets, including the associated color for each species.

Once each map was cropped and enhanced, they were imported into QGIS (QGIS Development Team 2022). Using the Georeferencing tool, we selected seven points (Fig. 2), which were consistent across all maps, to georeference the photocopied maps to the satellite maps available in QGIS. The 2014 map had the most precise coastline compared to the Borrer photocopies, so we used this map to select our reference points. We selected four distinct points around the coastline of Appledore Island, one on Babb's Rock, and two on distinctive manmade features within Appledore Island that appeared in all maps and the base tiles (Fig 2, S1-6). Each georeferenced photo was saved as a high resolution .tiff file and overlaid on the satellite map in QGIS. We set the transparency of the georeferenced .tiff map to 50%, or until we could see both the highlighted or lettered species and the QGIS map coastline. We created a SpatialLite Layer and manually added polygons, outlining each section (sections were depicted by letters or highlighted, see Fig 2) along the coast and identified each new polygon to the corresponding species or combination of species. We standardized a symbology protocol to assign each species a distinct color, as well as how to represent each section depending on how many species were present in that particular area of the coastline (Fig. 2, S1-6).

Using a bathymetry layer, obtained using the ImageServerConnector tool, we created a bathymetry vector from 0 to 5 meters using the following expression `"VALUE"<0 AND "VALUE">-5`, in the attributes table of the bathymetry .tiff file. This vector was then used to clip each polygon to the bathymetry that would have been surveyed to provide a digitized visualization of each historical map. Using a similar expression in the attribute's tables, a perimeter line was drawn at the 1.5-meter mark to create a layer with only a perimeter outline of Appledore island without any gaps in the bathymetry layer. Using the Field Calculator in the Attributes Table for each map, we calculated the perimeter that each polygon occupied along the coast of Appledore Island. This data was then exported as a .csv file, and the maps saved as images.

In order to maintain taxonomic consistency across years, we compiled all variants of taxonomic names from all six maps into a naming key. We use AlgaeBase (Guiry and Guiry 2022) to find the most recent taxonomic names for each species and expert knowledge from the Shoals Marine Laboratory for ambiguous entries on the maps and for creating general groupings of all the species present (Supplementary Table 1). Each species or grouping was assigned a color and symbol for better visual differentiation on the digitized maps.

Percent cover of each species

To obtain the area covered by each species or group, we imported all six map shapefiles with perimeter data into R (R Core Team 2020) and numbered all polygons for each year. Polygons representing more than a single species were divided into smaller polygons, with the number of “sub polygons” equal to the number of species present, with each species representing equal amounts of their coastline section. For example, a single-species polygon represented 100% of its polygon, whereas a polygon that has four shared species was separated in four, so that each species was attributed 25% of that polygon. On the original Borrer maps, some labels included specific details such as “kelp and sparse *Saccharina*”, however we were unable to quantify the percentage of the polygon “sparse” represented therefore we ignored such details for consistency. Using the 1.5-meter perimeter line around Appledore Island, we found how much each species’ polygons intersect with the perimeter line. The entire perimeter length was then divided by the lengths of perimeter covered by each species to obtain percent over of each species over time. To aid in analysis and visualization, in addition to the taxonomic standardization above, we also made maps with observations grouped into “pure kelp”, “mixed kelp & reds”, “mixed red algae”, and “urchin barrens”.

Supplementary Materials 2: Physical description of island quadrants

The southwest is characterized by broad benches of granite extending at a shallow grade to ~15m depth far offshore where they meet a sandy bottom. It is protected from the open ocean either by Smuttynose island, the other islands forming Gosport harbor, or by the body of the island itself. Northwest Appledore consists of a series of narrow ledges and terraces of granite parallel to shore dropping down to 20m rapidly. The northwest is exposed to the open channel between the islands and the mainland, although it is protected from the open ocean by Appledore itself. It also features upwelling coming from the island’s north head that dissipates as it goes further south along the shoreline. The northeast consists of broad sloping exposed granite benches extending perpendicular to shore with small canyons in between. Benches gradually slope down to 30m where they then drop into deeper water rocky canyons, gullies, and sand. While the northeast is somewhat exposed to the open ocean, some northern and northeastern swell is blocked by nearby Duck Island. The southwest of Appledore consists of narrow rocky ledges parallel to shore that swiftly drop to 20-30m in a series of very narrow terraces. The southeast is fully exposed to the open ocean - the most wave exposed area on the island. It is the only area that consistently has areas dominated by the kelp *Alaria esculenta* to this day - an indicator of very high wave exposure.

Supplementary References

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Supplementary Tables

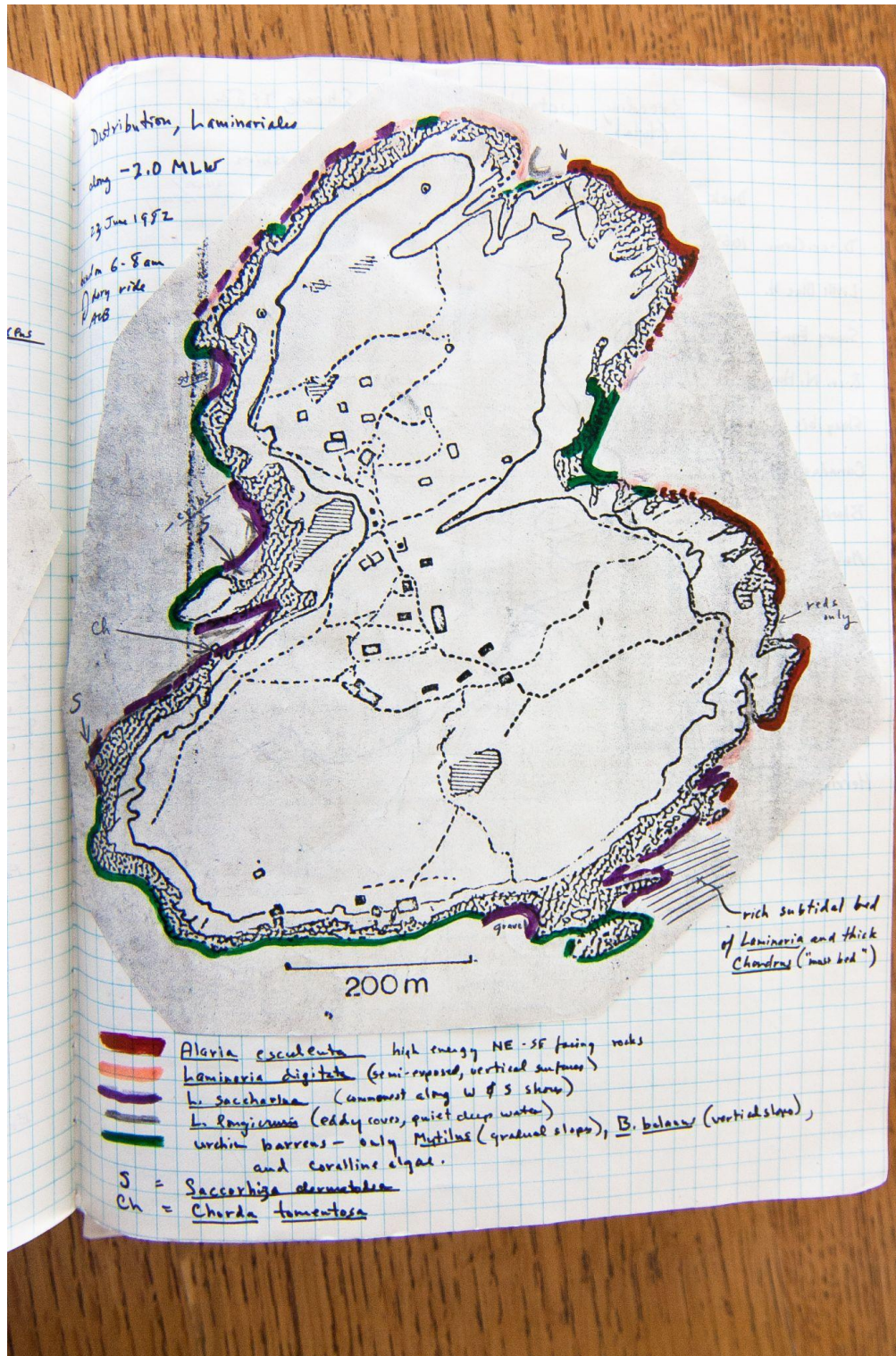
Supplementary Table 1. Key to how species names were translated from hand-drawn maps to current taxonomy to species/group names used in maps.

Species on maps (1982 - 2014)	To date Taxonomic name	Species name or species group on digitized maps
<i>Alaria esculenta</i>	<i>Alaria esculenta</i>	<i>Alaria esculenta</i>
<i>Laminaria saccharina</i>	<i>Saccharina latissima</i>	<i>Saccharina</i>
<i>Laminaria digitata</i>	<i>Laminaria digitata</i>	<i>Laminaria digitata</i>
<i>Laminaria longicuris</i>	<i>Saccharina longicuris</i>	<i>Saccharina</i>
Urchin barrens	Urchin barrens	Urchin barrens
<i>Codium fragile</i>	<i>Codium fragile</i>	<i>Codium fragile</i>
Gigartinales	Gigartinales	Mixed reds
<i>Chondrus</i>	Gigartinales	Mixed reds
Red mix	Mixed red algae	Mixed reds
Light kelp	<i>Saccharina</i>	<i>Saccharina</i>
<i>Chorda tomentosa</i>	<i>Halosiphon tomentosus</i>	Rope kelps
<i>Saccorhiza dermatodea</i>	<i>Saccorhiza dermatodea</i>	<i>Saccorhiza dermatodea</i>
Tough, coralline reds	Tough, coralline red algae	Mixed reds

Supplementary Table 2: Chi-squared likelihood ratio tests for the urchin barren beta regression model.

	df	LR	P
quadrant	3	44.75	0.00
year	1	0.57	0.45
quadrant:year	3	25.80	0.00

Supplementary Figures



Supplementary Figure 1. Borror Map from 1982.

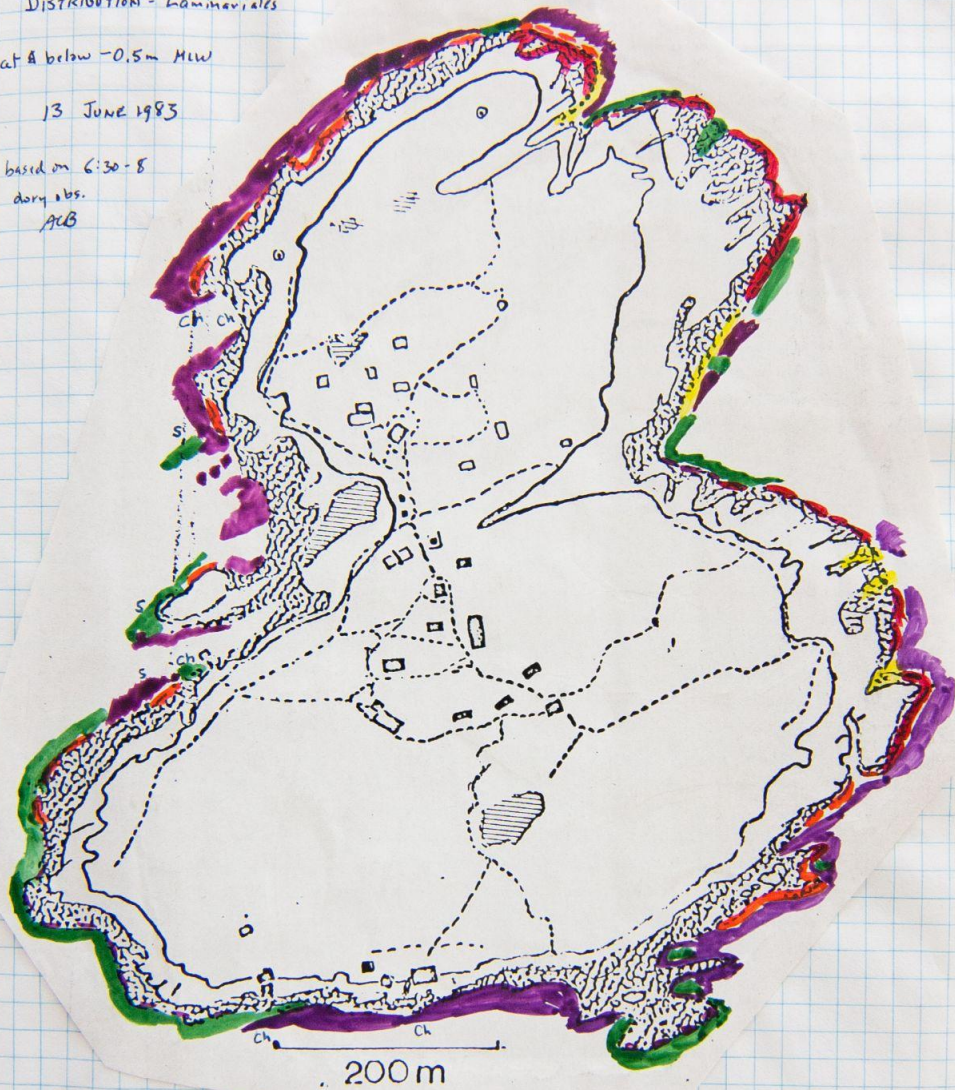
DISTRIBUTION - Laminariales






at A below -0.5m MLLW

13 JUNE 1983

based on 6:30-8

dory obs.
ACB



- | | | | |
|---|--|---|--|
|  | <u>Alaria esculenta</u> |  | only <u>Chondrus</u> (# <u>Gigartina</u>) |
|  | <u>Laminaria digitata</u> | S = | <u>Saccorhiza</u> & <u>Armatodes</u> |
|  | <u>Laminaria saccharina</u> | Ch = | <u>Chorda</u> <u>tomentosa</u> |
|  | urchin barrens (<u>Mutulus</u> , <u>Balanus</u>) | | |

Supplementary Figure 2. Borror map from 1983

Distribution - Laminariales

at # below -0.5m MLW

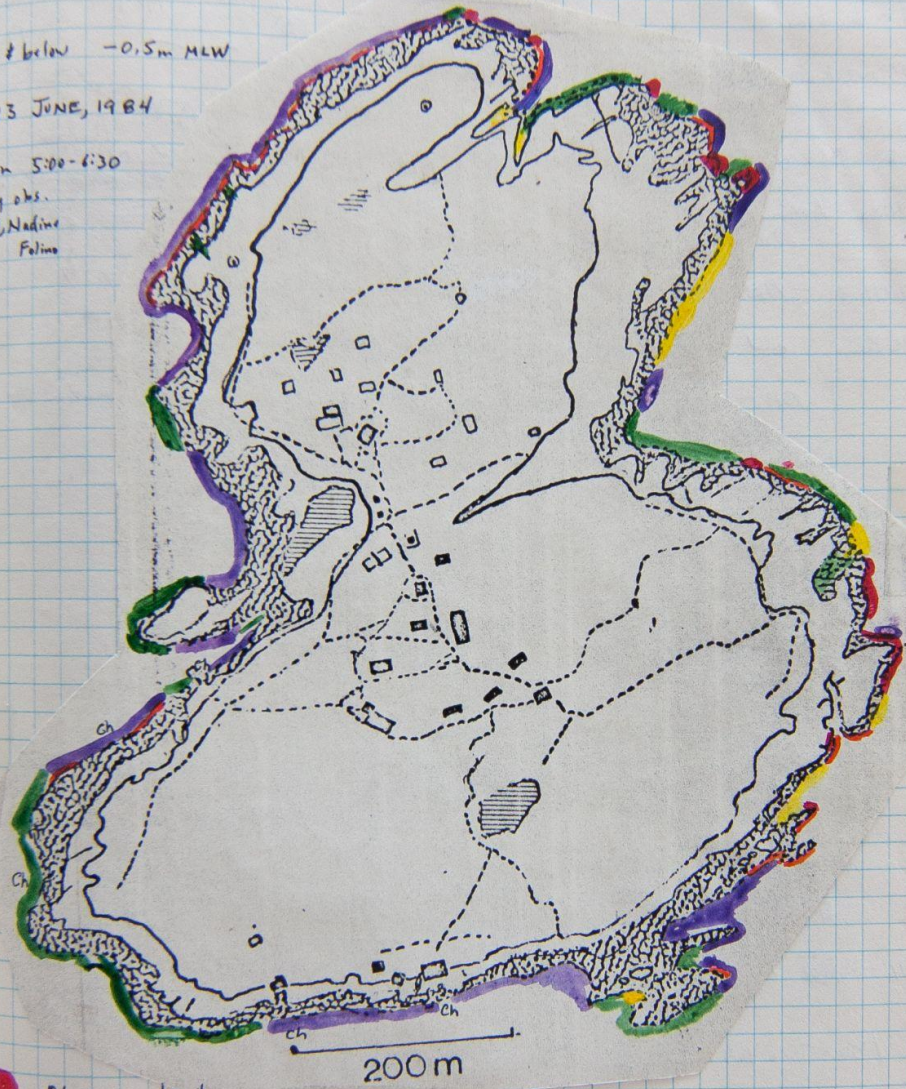
13 JUNE, 1984


bandon 5:00-6:30


dory obs.


ACB, Nadine


Felino




 *Aleria reticulata*

 *Laminaria digitata*

 *Laminaria saccharina*

 urchin barren

 only *Gigartinales*

S *Saccorhiza dermatodea*

ch *Chorda tomentosa*

200 m

Supplementary Figure 3. Borror map from 1984.

Distribution - laminariales

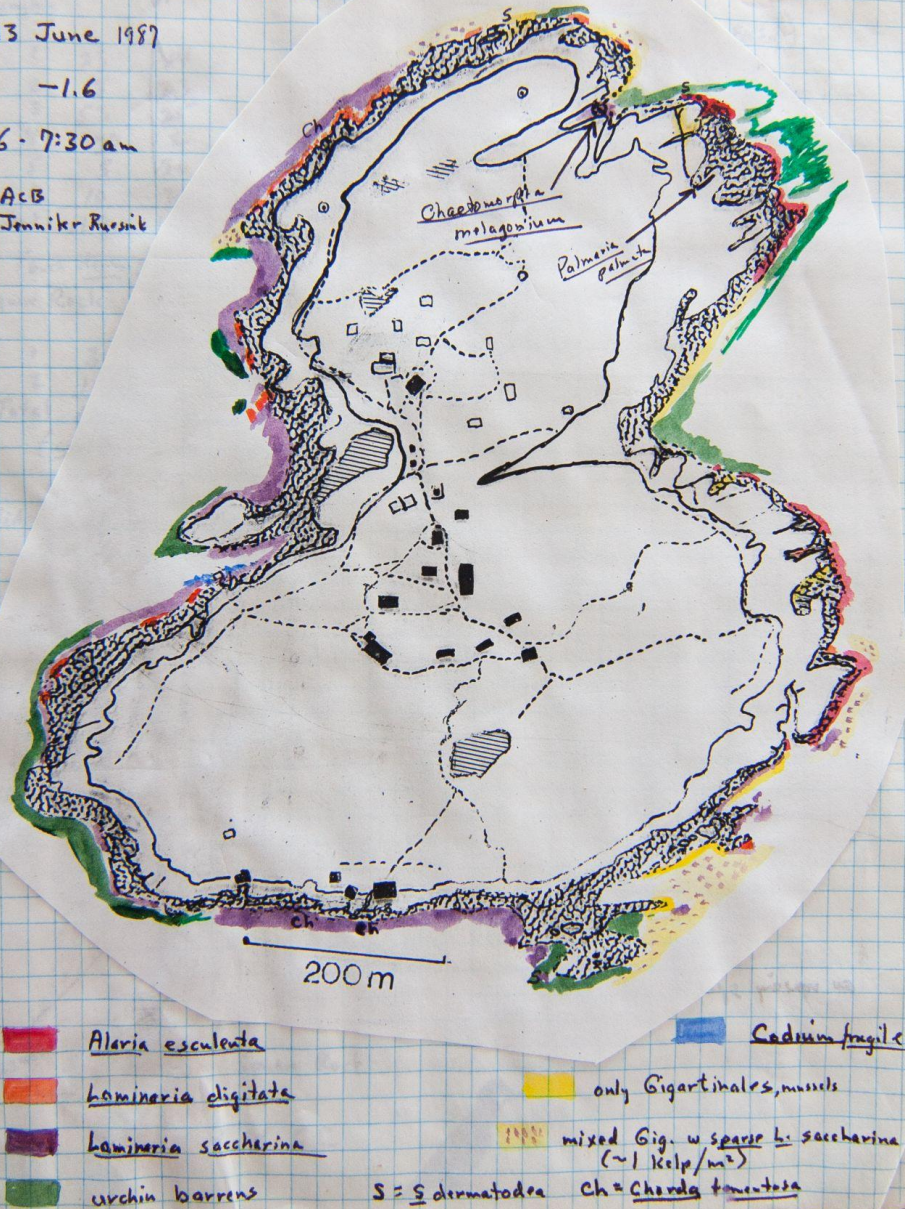
13 June 1987

-1.6

6 - 7:30 am

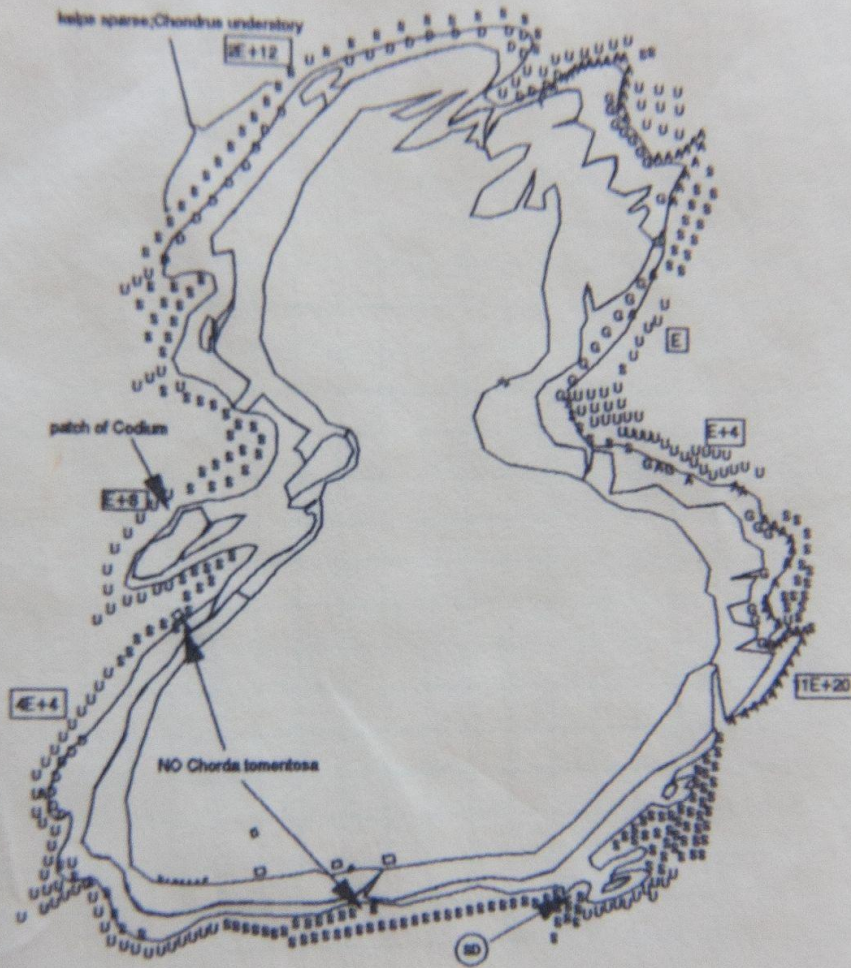
A & B

Jennifer Ruesink



Supplementary Figure 4. Borror map from 1987.

1990 CENSUS OF KELPS, APPLIEDORE ISLAND
A. C. Borror



LEGEND

2E+6: two female Common Eiders with six downy young

U: urchin barrens with no kelps

S: *Laminaria saccharina*

D: *Laminaria digitata*

A: *Alaria esculenta*

SD: *Saccorhiza dermatodea*

C: *Chorda tomentosa*

G: a complete covering of gigartinales

CONDITIONS:

5:30-6:45 am -1.3 MLW

wind light, rain, fog, 1' seas

23 June

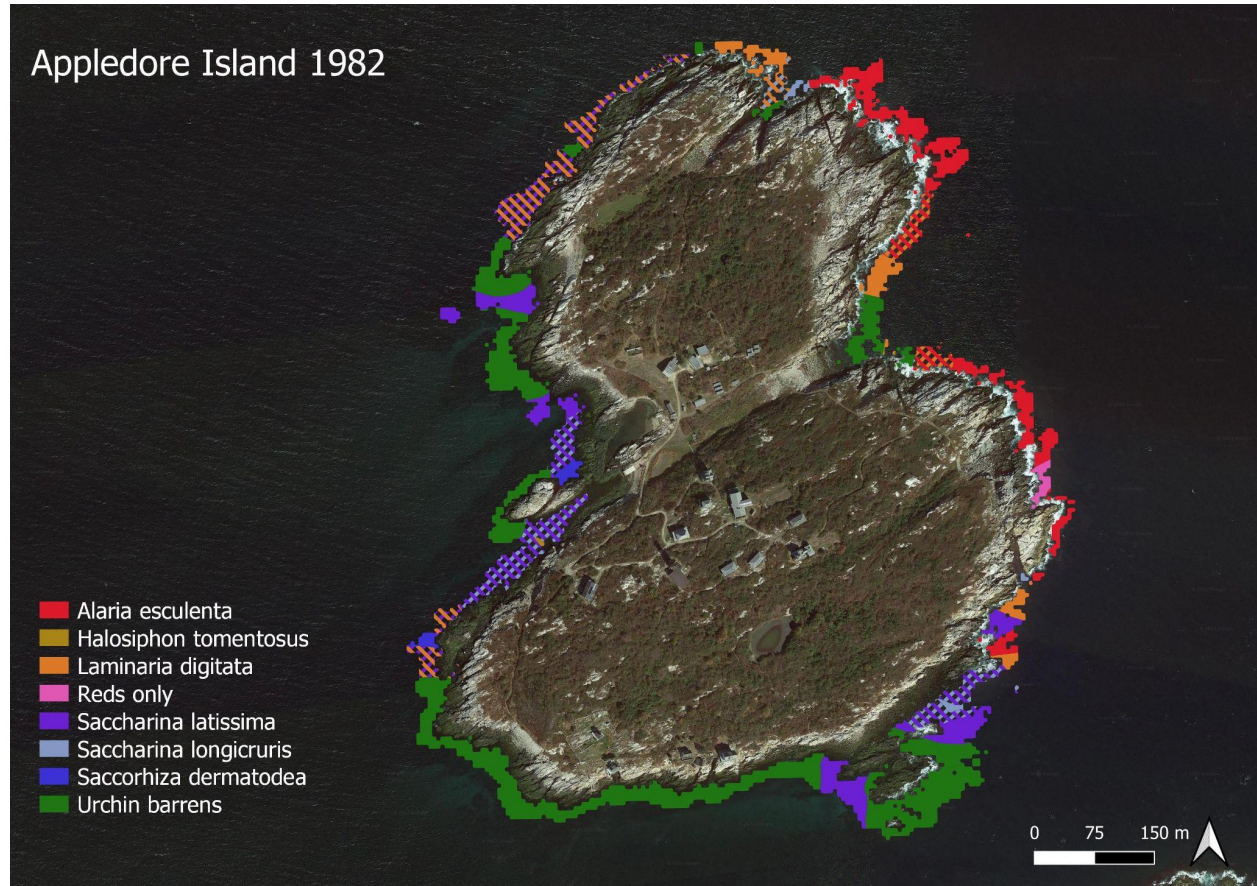
from Zodiac, ACB only

Supplementary Figure 5. Borror map from 1990



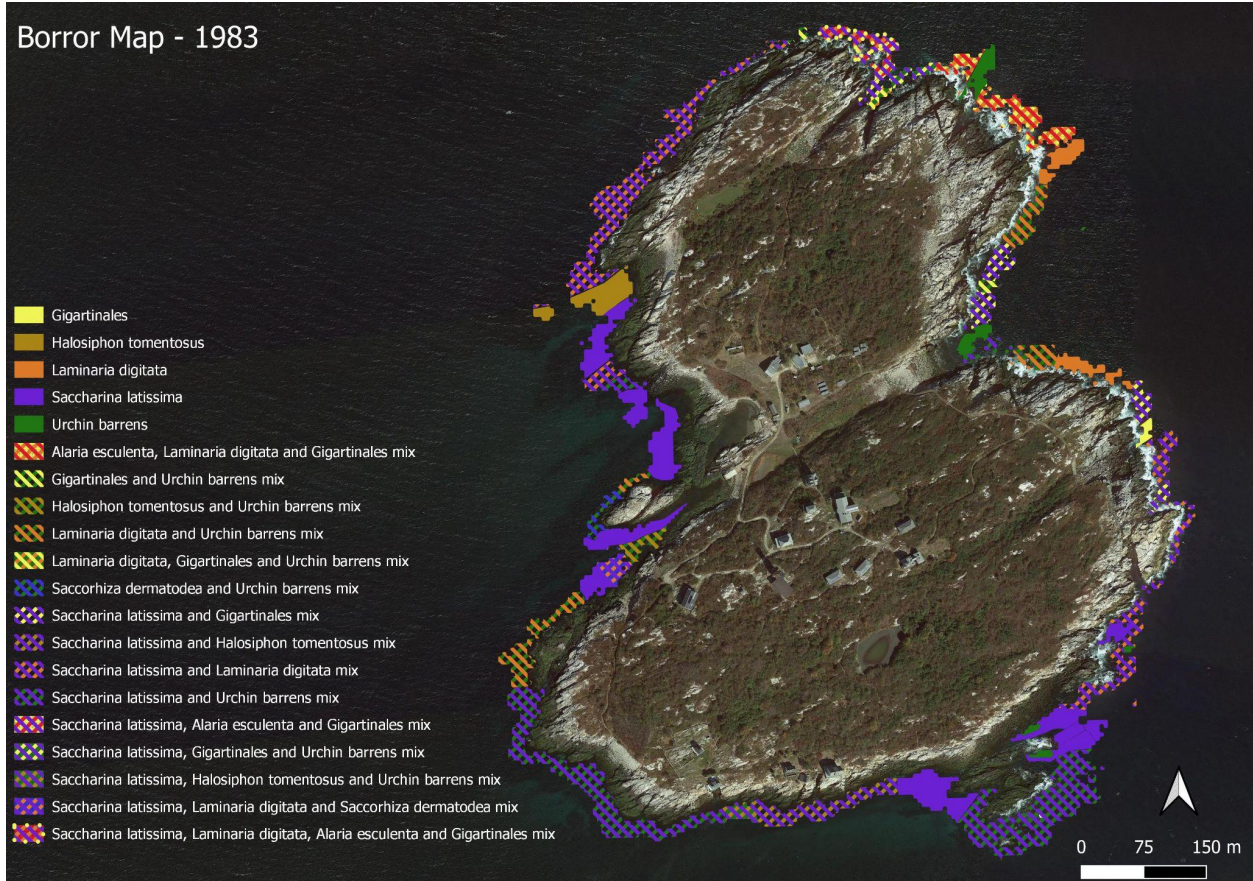
Supplementary Figure 6. Byrnes and Coyer map from 2014.

Appledore Island 1982



Supplementary Figure 7. Digitized map of Appledore subtidal habitats from 1982.

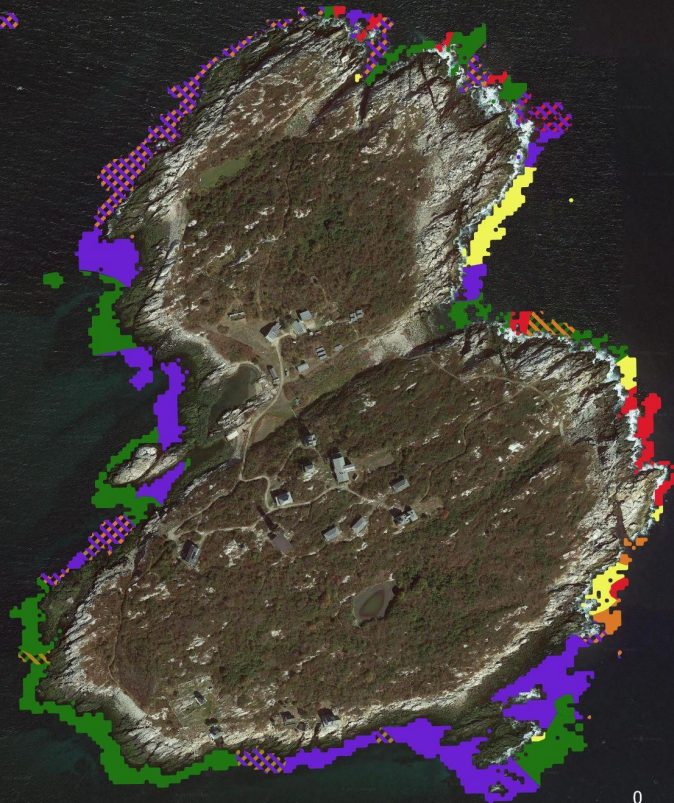
Borrer Map - 1983



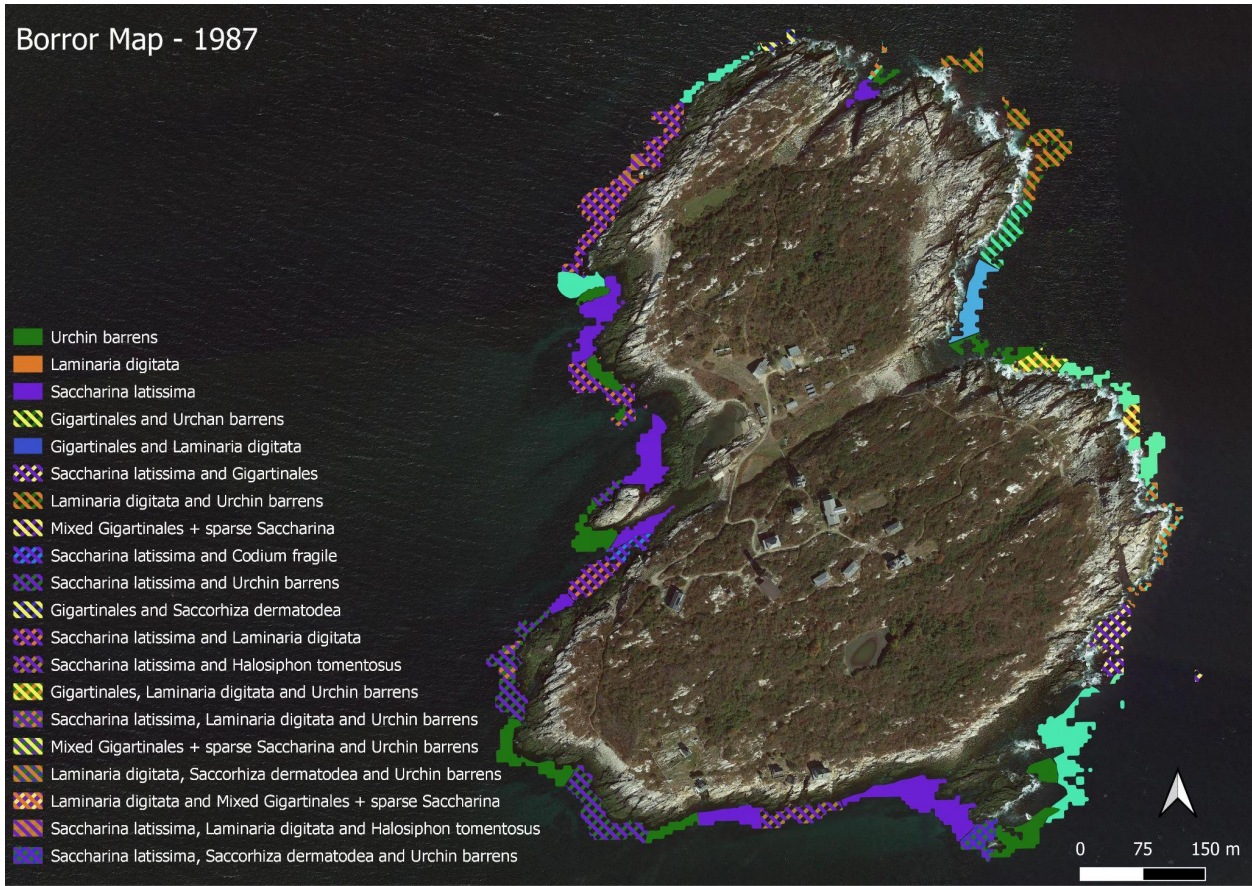
Supplementary Figure 8. Digitized map of Appledore subtidal habitats from 1982.

Appledore Island 1984

- Alaria esculenta
- Gigartinales
- Laminaria digitata
- Urchin barrens
- Saccharina latissima
- Saccorhiza dermatodea
- Halosiphon tomentosus



Supplementary Figure 9. Digitized map of Appledore subtidal habitats from 1984.



Supplementary Figure 10. Digitized map of Appledore subtidal habitats from 1987.

Borrer Map - 1990



Supplementary Figure 11. Digitized map of Appledore subtidal habitats from 1990.

2014



Supplementary Figure 12. Digitized map of Appledore subtidal habitats from 2014.

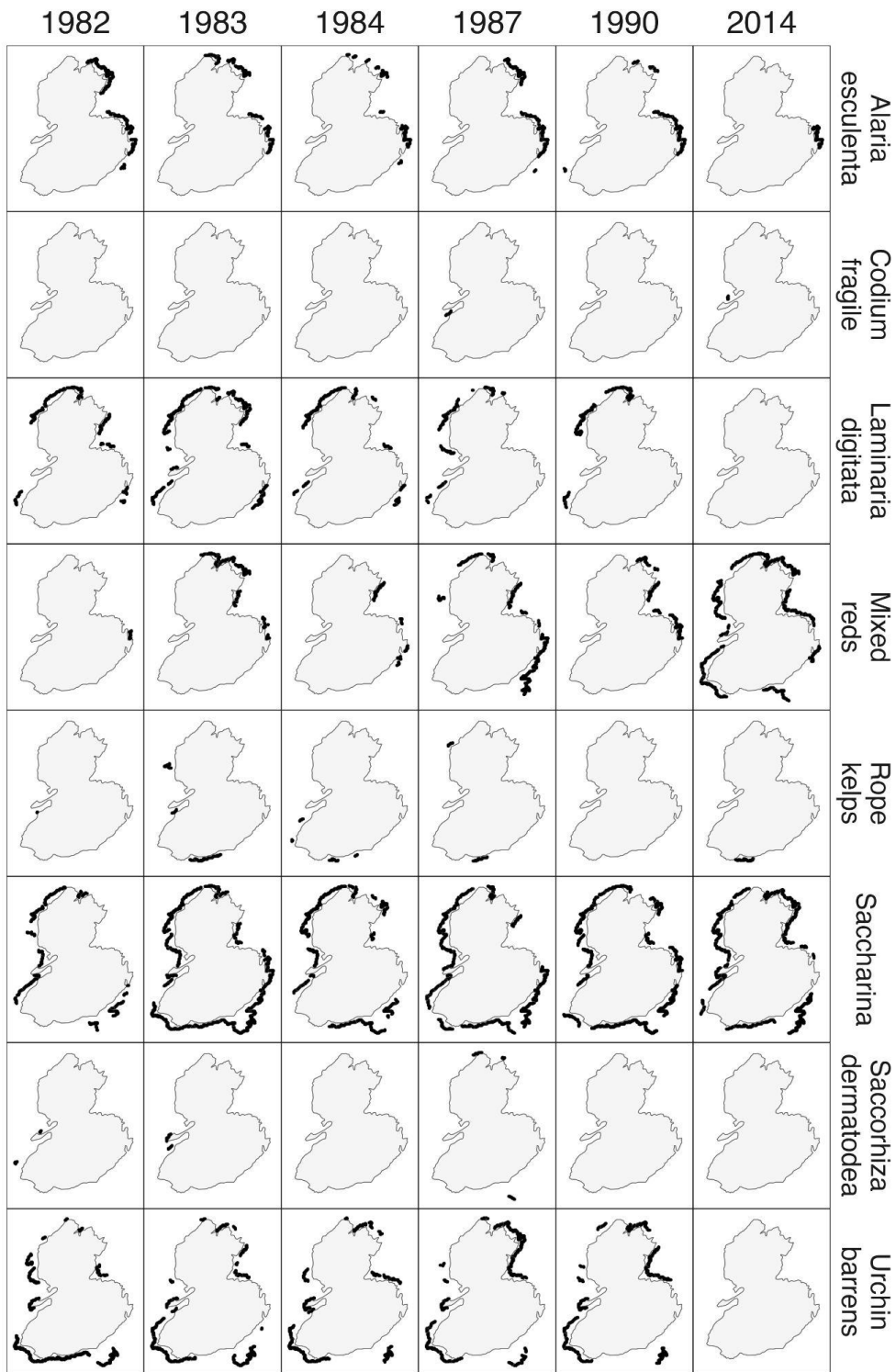
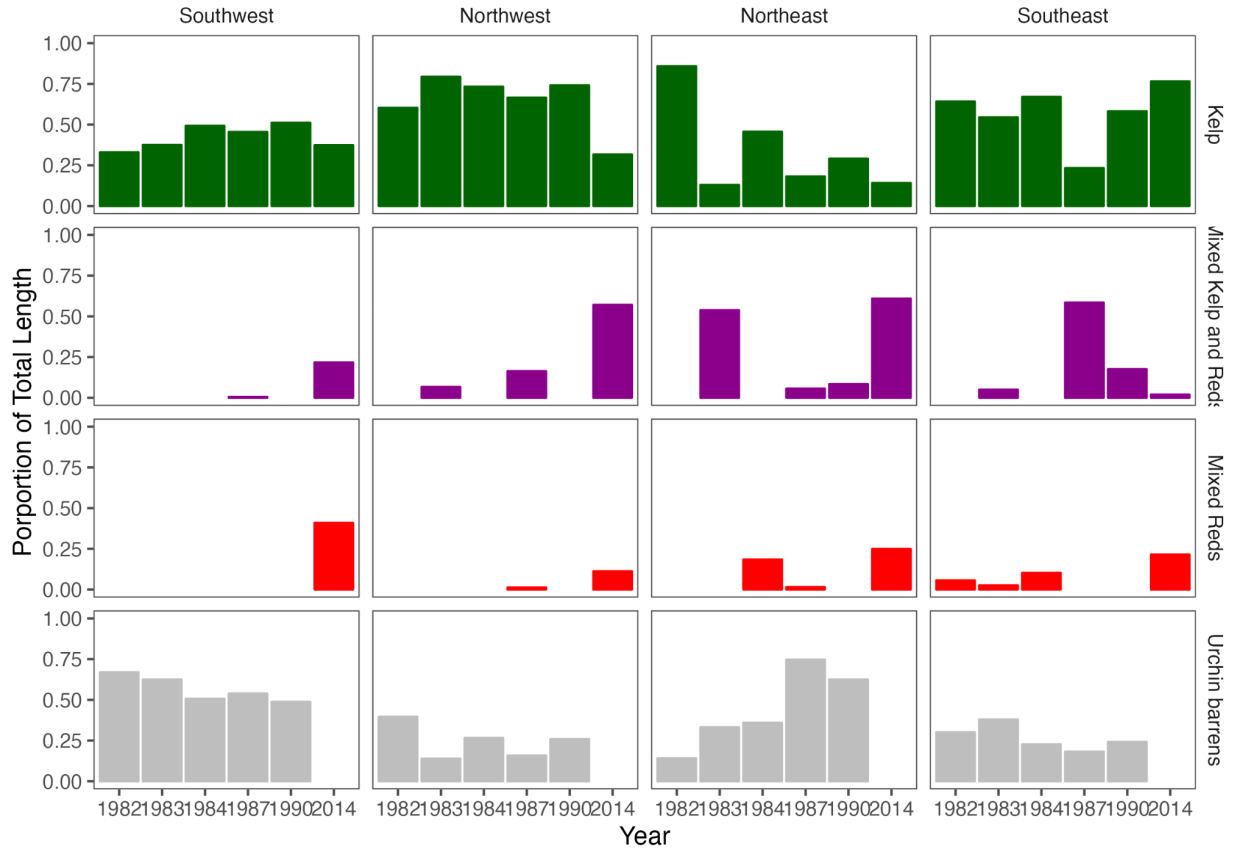
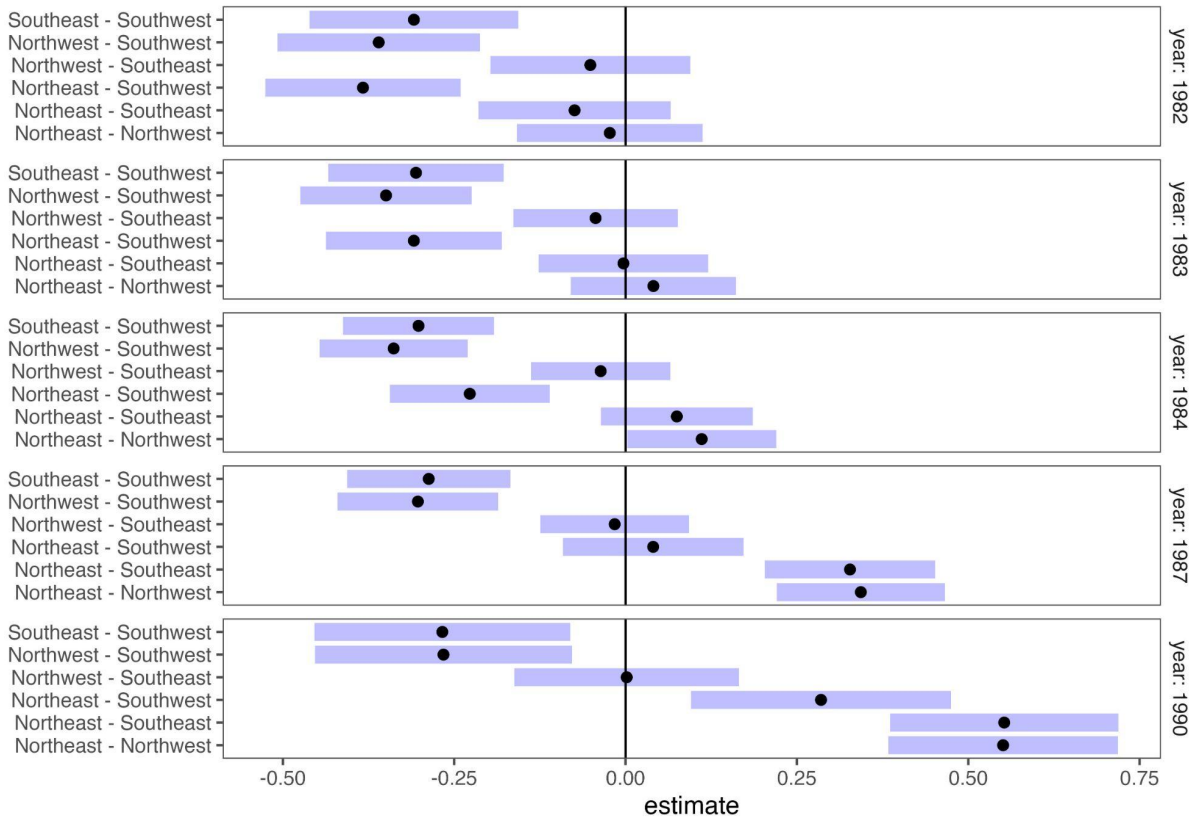


Figure S13. Species plotted along the 1.5m depth contour over time.



Supplementary Figure 14. Time series of different aggregated habitat groups in different quadrats of the island.

Posthoc with fdr for Barrens



Supplementary Figure 15. Mean and upper and lower confidence interval for post-hoc contrasts using the False Discovery Rate from urchin barren model.