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Journal:	<i>Journal of Ecology</i>
Manuscript ID	JEcol-2017-0424
Manuscript Type:	Standard Paper
Date Submitted by the Author:	24-Jun-2017
Complete List of Authors:	Pfister, Catherine; Chicago University, Berry, Helen; Washington Department of Natural Resources Mumford, Thomas; Marine Agronomics
Key-words:	Plant-climate interactions, Pacific Decadal Oscillation, <i>Macrocystis pyrifera</i> , <i>Nereocystis luetkeana</i> , California Current Large Marine Ecosystem (CCLME), sea surface temperature, temporal autocorrelation, ARIMA

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The dynamics of Kelp Forests in the Northeast Pacific Ocean and the relationship with
environmental drivers

5 Running head: long-term kelp forest dynamics

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Keywords: Pacific Decadal Oscillation, *Macrocystis pyrifera*, *Nereocystis luetkeana*, California

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ARIMA

Submitted as a Standard Paper to *Journal of Ecology*, word count 6693

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ABSTRACT

- 25 1. The dynamics of foundation species in ecosystems are key to the fate of many species. Kelp forests are foundation species in temperate ocean ecosystems and contribute to carbon storage, macronutrient dynamics, primary production, and biodiversity of myriad associated species. Downward trends in their abundance globally have been of concern.
- 30 2. We analyzed 26 years of aerial censuses (1989-2015) of 2 canopy kelp species in Washington State (USA) waters. We compared these modern censuses with censuses in 1911 and 1912 to determine how persistent over the past century. Using Auto-regressive Integrated Moving Average (ARIMA) models, we compared kelp dynamics with likely environmental drivers, including local environmental variables and ocean indices for this region.
- 35 3. Kelp remains at historic levels in many areas, though some eastern populations in proximity to greater human populations are the exception to this pattern. The abundance of kelp through time showed high spatial autocorrelation in western areas of Straits of Juan de Fuca, with more variable populations in the annual species and eastward toward Puget Sound. Further, both species covaried positively in their abundance throughout most of the study area. The population dynamics of these kelp species showed that the abundance one year previous was an important predictor, and cyclic dynamics were not indicated using Auto-regressive
- 40 Integrated Moving Average (ARIMA) models. Kelp abundance correlated inversely with the Pacific Decadal Oscillation and the Oceanic Nino Index, and positively with the North Pacific Gyre Oscillation, indicating that large-scale processes associated with colder seawater temperatures were associated with greater relative abundance of kelp.
- 45 4. *Synthesis.* While kelp beds in this area of the California Current Large Marine Ecosystem have mostly remained persistent over the past century and over many km, some areas may

have decreased in abundance. The sensitivity of these populations to indices of ocean climate, our demonstration that a historic 93-year SST record (Race Rocks, Canada) showed a 0.72°C increase, and the classification of some areas as high variability-low abundance, suggest that 50 kelp bed viability merits continued attention into the future.

INTRODUCTION

55 Foundational species provide habitat and food resources and alter the physical environment. It is imperative that we understand their dynamics and links to environmental variables. In coastal marine systems, many foundational species provide essential ecosystem services (Barbier *et al.*, 2011), yet are affected by the stressors that are associated with increasing human populations near coasts (Small and Nichols 2003, Lotze *et al.* 2006). Canopy kelp species are 60 foundation species that provide an important natural feature in temperate oceans globally. Their primary productivity is unsurpassed (Mann 1973), and their tissues enhance productivity *in situ* and in adjacent ecosystems ((Dayton *et al.*, 1998) (Krumhansl & Scheibling, 2012) (Hansell, 2013). Kelp provide habitat and food for myriad invertebrates and fishes (Bodkin 1986, Duggins et al. 1989, Teagle *et al.*, 2017); their biogenic structure means that any changes in their 65 abundance will have cascading effects (Sunday *et al.*, 2016). Their abundance is determined by sea surface temperature, salinity and nutrient provisioning, possibly generated by large-scale climate drivers (Wernberg *et al.* 2013, 2016). Local interactions that include herbivory (Graham, 2002)(Sala & Graham, 2002)(Vergés *et al.*, 2016), and microbial interactions (Michelou *et al.* 2013) are also important. Compilations of kelp populations globally showed a diversity of trends 70 in kelp species abundances, with some populations and species increasing, while others are

decreasing (Steneck *et al.*, 2002) (Krumhansl *et al.* 2016). Understanding these foundation species requires an analysis of local versus regional factors on kelp dynamics.

A key challenge for predicting the fate of ocean primary producers is linking current and past dynamics to large-scale climate factors, where large-scale factors associated with harmful effects
75 on kelp include warmer sea surface temperatures (Wernberg *et al.*, 2010)(Krumhansl *et al.*, 2017) and increased urban runoff and pollution (Antrim *et al.*, 1995). Thus, climate drivers that affect sea surface temperature (SST) and nutrient supply have been shown to correlate with kelp fitness ((Dayton *et al.*, 1999) (Edwards, 2004)(Pfister & Wang, 2005)(Parnell, 2010)(Cavanaugh *et al.*, 2011)). Globally, kelp abundance is positively related to colder SSTs and upwelling
80 regimes where nitrate is supplied to surface waters (Schiel & Foster, 2015). Kelp growth may also benefit from increased carbon dioxide inputs to the surface ocean (Sunday *et al.*, 2016), though some stages of the kelp life cycle are sensitive to ocean acidification (Gaitán-Espitia *et al.*, 2014). In addition to large-scale climate drivers, local scale factors and their interaction with large-scale factors may be important. Changes to food web structure negatively affect kelp if
85 they result in increased grazing pressure (Vergés *et al.*, 2016), as in the iconic example of sea urchin increases following sea otter extirpation (Estes & Palmisano, 1974). Local disturbance, including pollutants, also negatively affect kelp (Antrim *et al.*, 1995)(Schiel & Foster, 2015).

A recurrent theme in the study of kelp forest communities is the dynamic nature of abundance and thus the need for long-term data to interpret temporal pattern. In the northern
90 California Current Large Marine Ecosystem (CCLME), there are 2 species of floating canopy forming kelp: the bull kelp, *Nereocystis luetkeana* (Mertnes) Postels *et* Ruprecht, and the giant kelp *Macrocystis pyrifera* (Linnaeus) C. Agardh. While we understand some of the factors important to *Macrocystis* in the southern CCLME, *Nereocystis* is absent south of Pt Conception,

and relatively little is known about either *Macrocystis* or *Nereocystis* in the northern region.

95 *Macrocystis* in the southern California region shows a relationship with SST, with demonstrated positive responses to lower sea surface temperatures (SST) (Parnell, 2010) (Wernberg *et al.*, 2016). Cavannaugh *et al.* (2011) found that annual *Macrocystis* biomass was inversely related to SST and waves. Induced local warming caused by a power plant outfall was associated with the virtual disappearance of *Nereocystis* and replacement by *Macrocystis* over an 18 year period
100 (Schiel *et al.*, 2004). However, the response of *Macrocystis* to a recent warming event in southern California was modest enough that investigators suggested this species is not a ‘sentinel’ species for warming effects (Reed *et al.*, 2016).

The identification of climate cycles such as the Pacific Decadal Oscillation (PDO) and the North Pacific Gyre Oscillation (NPGO) provide motivation to determine whether these climate
105 patterns are reflected in biological data. The PDO is a decadal or greater pattern of sea surface temperature variation in the north Pacific related to the strength of the Aleutian low-pressure cell (Mantua *et al.*, 1997)(Hare & Mantua, 2000). Sea surface temperatures are warmer and productivity is reduced throughout the California Current Large Marine Ecosystem (CCLME) during a positive PDO, while the opposite occurs during a negative phase of the PDO. The
110 NPGO index has roughly the opposite features, and is thought to be associated with sea level pressure changes in the region (Di Lorenzo *et al.*, 2008). Both the PDO and the NPGO are often characterized as long-term events lasting 10-20 years. Further, variability in upwelling and the association of episodic events such as ENSO with decreased kelp abundance (Dayton, 1999) provide further value for querying biological data with the greatest length possible.

115 Here, we use a 26 year span of annual aerial survey data from 1989-2015 for the two co-occurring canopy kelp species *Macrocystis* and *Nereocystis* in coastal Washington state to test

whether these species show a trend in abundance through time, linkages to climate indicators, and spatial coherence in response over the 445 km of coastline that we censused. Because experimental manipulation of kelp abundance was not feasible over this time scale and spatial 120 expanse, we used time series models to test whether there is evidence of density dependence or species interactions, focusing on quantitative approaches that provide maximum inference (Brown *et al.*, 2011). We tested whether both species responded similarly or distinctly to environmental variables in light of their divergent life histories; *Nereocystis* is primarily annual, whereas *Macrocystis* has a perennial life history. Although a 26-year time frame can be 125 restrictive for estimating dynamic properties of species, time series for environmental variables ranged from 70-115 years. We thus tested 1) the 70-116 year time span of environmental variables for pattern, and 2) used the timescale of pattern from 1) to test for trends in kelp abundance and correlates with environmental variables. In addition to testing for temporal patterns, we used the 66 spatially delineated areas of the coast to test patterns of spatial 130 abundance in kelp forests. We tested 3) whether there is coherence in outer coast populations with populations in the western versus eastern portions of the Strait of Juan de Fuca, and 4) whether the 66 areas differ in how correlated their abundance is through time. We performed all the above analyses on the conspicuous sporophyte stage of both species, though we recognize that both species have a microscopic gametophyte stage for which little is known.

135 We complement this 26 year pattern of abundance with a census of these same kelp populations in 1911 and 1912 (Cameron & United States., 1915). Comparison of 1989 to 2015 to these historic 1911-1912 surveys suggested local extirpation of kelp beds in some areas, with inherently high variability in the abundance of some kelp beds in particular locales.

140

STUDY SYSTEM & METHODS

Nereocystis luetkeana occurs from the Aleutian Islands to Point Conception, CA, while *Macrocystis pyrifera* extends further south to Baja California, Mexico (Druehl, 1970). *Nereocystis* is primarily an annual, with a long stipe and a terminal bulb with blades that proliferate on the surface. Individual *Macrocystis* can live for 2-3 years and have similar-sized 145 alternating fronds along 1 or more stipes. Both species occur singly and together, with *Macrocystis* often slightly closer to shore than *Nereocystis*. Since 1989, the aerial cover of both kelp species (*Macrocystis* and *Nereocystis*) has been estimated from low-flying aircraft every August when canopy cover is near a maximum, allowing both the canopy area and estimates of discrete kelp beds to be measured. The Washington Department of Natural Resources has led 150 these efforts and data are archived ([http://www.dnr.wa.gov/programs-and-
services/aquatics/aquatic-science/kelp-monitoring](http://www.dnr.wa.gov/programs-and-services/aquatics/aquatic-science/kelp-monitoring)). To optimize visualizing kelp, flights were made at late season low tide (between MLLW and +0.9 m) every year when the kelp canopy was maximally concentrated. The distinct morphological traits of each species make them 155 distinguishable from aerial photography. Through 2008, color-infrared film was used; following that, digital images were used. In 2008, both methods were used to standardize the methodology. Aircraft altitude was maintained at approximately 2300 m with a photographic scale of 1:30,000 and a base mapping scale of 1:12,000 over the 177 km from Port Townsend to Destruction Island, WA. The digital files were high resolution 12-bit files of 15.4 MB each. Throughout the 26-year censusing period, images have been quantified by the same individual. Although tidal 160 currents can affect estimated bed size from aerial photography (Britton-Simmons *et al.*, 2008), the timing of the photos during low, slack tides reduced this effect. Further, aerial photography

correlated well with *in situ* biomass of harvested *Nereocystis* in British Columbia (Foreman, 1984). Finally, the spatial and temporal extent of the data reduced these local effects.

To test whether canopy kelp population dynamics showed pattern through time, we used an
165 Auto Regressive Integrated Moving Average (ARIMA) modelling framework (Jassby & Powell, 1990) (Legendre & Legendre, 2012)(Ives *et al.*, 2010), to test whether the previous abundance values determined the abundance at time t (auto-regressive), suggesting autocorrelation. We further tested whether variability in the data at each time t was caused by species interactions, the environment, or measurement error (moving average). We also explored whether using a
170 differencing method, where each data point is instead a difference of two observations to reduce variance (termed ‘integrated’ form of the data), revealed pattern. The advantage of ARIMA models for these kelp populations is there are few parameters needed and it provides a robust method for inferring internal dynamics and possible species interactions (Ives *et al.*, 2010) (Ziebarth *et al.*, 2010). Comparing ARIMA models for environmental data to the kelp data
175 allowed us to see if there was similar underlying pattern between environmental variables and the abundance of kelp. Although specific interactions cannot be inferred from ARIMA, significant AR and MA terms give an indication that biotic interactions may be important. To aid in ARIMA model selection, we first tested the degree of autocorrelation through time in each species abundance, followed by a partial autocorrelation analysis to assess the autoregressive
180 component of an ARIMA model and any possible MA term (Crawley, 2007)(Ives *et al.*, 2010). We then used this estimate as a starting point to systematically test a number of ARIMA models with the form (p, d, q) , where p is the AR term, d is the differencing, and q is the MA term. All models were compared with an AIC. All analyses were done with R 3.3.0, and modules ‘Forecast’ for the ARIMA modeling.

185 To determine whether there are environmental or climate drivers that correlate with kelp abundance, we also examined the patterns in these variables. We focused our analyses on measures directly related to SST and nutrient supply, including the PDO, the NPGO, the Upwelling Index (UI), and the SST. We used annual means based on monthly averages. The UI is a metric based on wind shear values (<https://www.pfeg.noaa.gov/>). Positive values of the
190 upwelling index are associated with the increased supply of nitrate and occur seasonally in spring and summer months in the CCLME ((Pfister *et al.*, 2007)(Capone & Hutchins, 2013). Remotely measured SST was sparse in the coastal areas of Washington state until the establishment of the Neah Bay Buoy (#46087) in 2004. Race Rocks, Canada, in the eastern Strait of Juan de Fuca (48.299 N, 123.531 W, www.pac.dfo-mpo.gc.ca, Figure 1), has a 93-year record initiated in
195 1921, and mean monthly sea surface temperature at Race Rocks correlates strongly with the Neah Bay Buoy between 2004-2015 when the 2 buoys have simultaneously recording ($r=0.903$, $df=118$, $p<0.001$). We thus used Race Rocks sea surface temperature data to look for temperature correlates with kelp forest abundance. The PDO and NPGO extend much further back in time compared with the kelp species data; the PDO is from 1900 and the NPGO from
200 1950. The UI began in 1946. The Race Rocks SST record has a hiatus for months in 1940 and 1941, requiring us to use data after 1941 for analysis of cycles. We used ARIMA and spectral analyses on monthly means to reveal any inherent cycles. By comparing the dynamics of environmental data with the dynamics of kelp forests, we tested whether dynamic components of environmental data correlate to patterns in kelp abundance.
205 The documentation that sea surface temperature has increased at other coastal locales (Wernberg *et al.*, 2011) (Lima & Wethey, 2012)(Tanaka *et al.*, 2012) prompted us to test whether the extensive Race Rocks record showed a long-term temperature increase. To

decompose the seasonal pattern from the annual data, we used the post-1942 data portion of the time series that had no missing data to extract the annual means after we accounted for a
210 seasonal cycle. We further used a linear regression on annual means for 93 years to test for a significant slope through time. We used “STL” (Seasonal and Trend Analysis using Loess in the ‘stats’ module in R.

Spatial Patterns of Abundance

215 We analyzed the kelp forest data at two spatial scales. We first grouped the kelp forests on the outer coast and Strait of Juan de Fuca into 3 broad spatial areas and asked whether abundance was correlated across these 3 areas (Figure 1). The populations on the outer coastal areas of Washington State that are exposed to open ocean conditions are ‘outer coast’ and extend from the northeast corner of the state at Cape Flattery to the southern extent at Destruction Island. We
220 excluded the southern outer coast from Destruction Island south to the Columbia River from further analysis because floating kelp was never recorded along these shorelines in the historical or modern dataset. Populations on the western end of the Strait of Juan de Fuca extended from the westernmost Cape Flattery to Crescent Bay in the east, an area over which open ocean influence diminishes. The third area continued eastward from Crescent Bay to Port Townsend, at
225 the entrance of Admiralty Inlet and the more protected areas of Puget Sound. Shoreline length within the 3 areas ranged from 113 to 203 km.

The second scale of spatial analysis further divided the kelp forest into 66 spatial regions that were bounded by geomorphological features, such as headlands, and encompassing on average 8 km of shoreline per unit (Figure 1). Using these 66 areas and all t years of data, we estimated 1-
230 year autocorrelations in abundance for each species in each of these areas from 1989-2015; thus,

a correlation of t versus $t+1$ for all t , excepting the missing 1993 data. We interpreted a high autocorrelation estimate to indicate relatively high predictability in abundance through time, whereas a low autocorrelation indicated that abundance fluctuated independently in year $t+1$ compared to year t .

235

A Century-scale Comparison

The potential to harvest kelp for fertilizer and potash resulted in an ambitious sampling of kelp populations from Alaska south to California in 1911-1912 (Cameron 1915). Washington State coastal areas were censused in 1911 and 1912 from a fifty-foot vessel with a 40 hp motor.

240 The areal cover of both canopy kelp species combined was drawn on bathymetric nautical maps that were digitized to estimate the extent in area of kelp beds. The mapping, the depth contours that the kelp beds follow, and the descriptions in accompanying reports seem especially carefully done by G. B. Rigg (then a Professor of Botany at the University of Washington) for the regions of Puget Sound and the Strait of Juan de Fuca, with extensive documented survey effort (Rigg 245 1912, Cameron 1915). Although the (Cameron & United States., 1915) study recognized the two species, they were combined for areal analyses and we thus combined both canopy species in the modern estimates in our comparisons.

We compared these 1911 and 1912 estimates of area in the Strait of Juan de Fuca to all aerial estimates from 1989-2015. We also noted any populations that existed in 1911-1912 that are no longer present. We recognize that the censuses in 1911-1912 could be incomplete, resulting in a bias such that kelp beds might have been present, but were not recorded by Rigg if conditions prevented their modest boat operations from maneuvering in an area. We thus did not assume kelp present in 1989-2015 but absent in 1911-1912 were new beds. If, however, an area was

identified as containing a kelp bed in 1911-1912, we were able to test whether a kelp bed was
255 still present and compare it with the range of modern areas. If Rigg and colleagues identified a
bed in 1911-1912 that had no record of occupancy since 1989, we concluded local extirpation.
On the outer coast of Washington in the Cape Alava region, W. C. Crandall, not G.B. Rigg
continued the survey, and these seemed less reliable, indicating kelp beds extending into depths
that could be unrealistic (Figure S4). There was also less field survey documentation and effort
260 compared with areas in the Strait, perhaps reflecting the challenging nature of surveying these
outer coast areas. We have thus excluded a quantitative analysis of these outer coast areas from
our analysis.

We compared the modern to the historical kelp beds by generalizing modern kelp extent,
where the modern kelp bed area was defined as an entity that included any identifiable kelp
265 canopy with a surrounding 25 m buffer, and any buffered canopy features that overlapped. By
thus defining a bed, we had an analogous measure to that defined by Rigg (Cameron & United
States., 1915).

RESULTS

270 *Patterns of Kelp Abundance over the Past 26 years*

Kelp abundance varied by almost a factor of 3.6 along Washington State's Strait of Juan de
Fuca and outer coast, with a low of 722 hectares to a high of 2574. Maximum extent was
measured in the middle of the time series (2000), while low values were measured early (1989,
1997) and late (2014) in the time series. Since 1989, *Macrocystis* and *Nereocystis* contributed
275 equally on average (Figure 2), with *Macrocystis* varying from 439 to 1042 hectares, while
Nereocystis showed more extreme variation from 198 to 1532 hectares, although there were

distinct geographic differences. The abundance of these two species was significantly correlated through time ($r=0.845$, $p<0.001$, $df=23$) and there were no lag terms that had greater significance than the contemporaneous term. Thus, where they co-occur *Macrocystis* at time t is most
280 correlated with *Nereocystis* at time t (Table 1). The abundance of canopy kelp increased through the study if 1989 was included ($p=0.030$), but the linear trend was not significant if 1989 was excluded ($p= 0.076$). In either analysis, the r^2 value was small ($r^2=0.147$ and 0.093) and 2014 was a year of relatively low kelp, suggesting any increasing linear trend was slight.

The autocorrelation function for both species showed a gradual decay expected if an AR
285 component equals 1.0 (Figure S1). The partial autocorrelation function showed relatively weak terms beyond $t=1$. Because the kelp species show little evidence of stationarity, we also fit difference terms of 1 or 2. The ARIMA models that best described the dynamics of each species separately or together were similar, suggesting an autoregressive and moving average term of 1 time step with a difference of 2 time steps. Thus, even though *Macrocystis* can live a year or two
290 longer than *Nereocystis*, their dynamics were similar and density-dependent effects were suggested for one time step only. Although the partial autocorrelation function for *Nereocystis* had a suggestion of a positive two-year lag and a negative lag at year 3, the 1-year lag dominated and ARIMA models with an AR term of 1 were consistently the best fit to the data (Table 2), indicating that *Nereocystis* abundance at time t was best predicted by the previous time step and
295 longer lags were unimportant. We ignored any correlations at $t>6$ to follow the general recommendation that we do not extend tests of lags more than approximately one-fourth of our data series (Jassby & Powell, 1990). We fit ARIMA models with varying differencing terms as well as different moving average values. Both species separately or together showed the best model fit was a differencing of 1 or 2 years with a moving average for only a single time step

300 (Table 2). In all cases, residuals were independent and normally distributed. Consistent with the ARIMA modeling, neither kelp species showed a long-term trend through time when we plotted abundance with a number of moving averages from 1 to 6 time intervals. A spectral analysis (R, ‘spec.pgram’) of abundance for each also did not indicate the presence of cycles over the current range of the data. (Figure S2)

305 *Environmental data*

Environmental data for the region, including the large-scale ocean climate variables (PDO, NPGO and UI) and local sea surface temperatures all showed variability over the time span where kelp were censused (Figure 2). All environmental data also showed a similar autocorrelation function to both canopy kelp species with autocorrelation terms steadily 310 declining after 1 year (Figure S1). The yearly mean PDO, SST at Race Rocks, and the Upwelling Index at 48 degrees North latitude all show a similar partial autocorrelation function to the kelp: a lag of only 1 time step was the most significant outcome, although a partial autocorrelation term >1 was suggested for the PDO and the ONI, with a lag of 4 for the NPGO (Figure S1).

Because the environmental data occur over a much larger time span than the kelp data, we 315 asked if there was any evidence of periodicity in the environmental data that may not yet be detectable in the kelp data. A spectral analysis ('spec.pgram' in the stats module of R) of multiple environmental variables suggested some periodicity (Figure S2). The time series for the mean annual PDO and NPGO suggested a 10-year cycle. The indices for upwelling as well as the ONI were similar and both indicated short cycles of ~3-4 years and long cycles of ~10-11 years.

320 No long-term cycles were suggested in the Race Rocks SST data.

The ARIMA model that best fit the environmental variables was similar to that of the kelp. An autoregressive term of 1 was always the best fit. Either zero or one differencing and either no

moving average or a single order term had the lowest AIC (Table 2). When we increased the autoregressive term, it did not improve model fit, even though we had a much longer time series
325 in environmental data over which to test a greater range of parameter combinations.

A decomposition of the Race Rocks SST data indicated a long-term increasing trend since 1942, though it was slight (Figure S3). Linear regression on annual mean SST revealed a 0.0076°C (0.0015SE) since 1921, an increase of ~0.72°C between 1921-2015 ($r^2=0.0209$, $p<0.001$). If the temperature is divided into the upwelling season from April to August versus the
330 winter months of September to March, the trends are different, with a coefficient that indicated decreasing temperature through time (-0.00456, $r^2=0.067$, $p=0.007$) in the summer versus increasing in the winter (0.00855, $r^2=0.270$, $p<0.001$). Thus, the overall temperature increase that is being recorded at Race Rocks seems to be due to an increase during the winter period, when upwelling is weakest. During the Apr to Aug period of seasonal upwelling, and the greatest kelp
335 growth, the temperature decrease may indicate a slight strengthening of upwelling through time, bringing down summer water temperature.

When we tested whether environmental variables could be predictors of total kelp canopy area, cross-correlation analyses indicated that the PDO and the ONI correlated negatively with total kelp canopy area within the same year, with positive values of the PDO and the ONI
340 indicating lower abundance of kelp (Table 3). While the ONI, the PDO, and especially the NPGO showed significant correlations as leading variables one or more years previously, the SST and UI showed little correlation, except that values of the UI two to three years previous was correlated with *Macrocystis* abundance. While Table 3 reports correlations with the annual mean of an environmental variable, the results were similar when we used Apr to Aug values

345 only. Overall, the NPGO and PDO explained the most variance in kelp abundance, accounting for 10-57% of the variance in kelp abundance.

Spatial Patterns of Abundance

When the kelp distribution was divided into three broad areas, *Macrocystis* correlated 350 positively with *Nereocystis* within the outer coast and Western Juan de Fuca regions (Table 1), while they were uncorrelated in the Eastern area where *Macrocystis* is rare (Table 1, Figure 2). *Nereocystis* abundance was strongly correlated across all 3 broad regions, and *Macrocystis* was strongly correlated in the two regions (outer coast and Western Juan de Fuca) where it is common (Table 1). For every comparison between regions, the correlation between the spatially 355 disjunct regions (East-Coast) was lower than between adjacent areas (East-West and West-Coast).

When we analyzed the 66 regions individually, there were distinct patterns of abundance and temporal variation in the kelp forest. Some areas were consistently low abundance and highly variable, particularly at either end of the study area near Destruction Island and areas around 360 Protection Island (Figure 1), while the Western Strait showed relatively high areal abundance and persistence through time. Only one area (Cape Flattery) showed generally high abundance in *Nereocystis* with high variability. Overall, *Macrocystis* showed generally lower variability than *Nereocystis* as indicated by low autocorrelation estimates; the CV in abundance for *Macrocystis* also was approximately half of that of *Nereocystis* (39.8 versus 81.6).

365 Kelp beds in the Strait of Juan de Fuca have been persistent features for at least 100 years, though there is evidence of decreased abundance in the most easterly regions (Figure 3). Most of the beds recorded in the Straits by G.B. Rigg (Cameron & United States., 1915) are still present

today, with some notable exceptions (Figure S4). The location of the Neah Bay kelp bed (index area 15.4) currently differs from 1911-12, likely following the construction of the breakwater
370 during WWII. Protection Island (index area 2.5) had abundant kelp in 1911, then Cameron (1915) reported that “only scattering plants were found” in 1912. When we examined the range of sizes of kelp beds in each area from 1989-2015, most of the 1911-12 censuses fall within those ranges, excepting five kelp beds eastward in the Strait of Juan de Fuca in the vicinity of Port Angeles and Port Townsend that appear to have decreased in size, including sites at Port
375 Townsend (index area 1.1), Gray’s Marsh (index area 3.2), and Sequim (index area 4.1). In the central and western Straits, Freshwater Bay (index area 7.3), Crescent Bay (index area 8.3) and 1 of the 3 areas at Cape Flattery (index area 16.3) also have not had a kelp bed with the aerial extent of those identified by Rigg in 1911-1912 (Figure 3), though their populations have been persistent (Figure 1).

380

DISCUSSION

These two kelp forest species showed similar dynamics through time with strong correlation in the abundance of each species despite somewhat different life histories and longevities.
Although there was little evidence for cycles in each species, kelp were correlated with some
385 environmental parameters, suggesting that the data series may need to be longer to detect population cycles in excess of a decade. Although there is evidence of ecological differences between the two species (Schiel *et al.*, 2004) (Watson & Estes, 2011), the similarity of response in this study suggests that both species occupy a similar niche and have similar resource requirements. There was no evidence of negatively correlated dynamics that are associated with
390 competition (Rees *et al.*, 1996). Instead, both species appeared to covary through time,

suggesting that conditions favorable to one species were also favorable to the other. The positive covariance in the abundance of these two canopy forming species revealed that kelp forests in the Northern CCLME potentially have no complementarity in their abundance; a poor year for one species is a poor year for both and low canopy cover results. Spatially, both species also
395 showed positive covariation with outer coast and Strait of Juan de Fuca regions showing similar trends. The only exception to this was *Macrocystis* in east Strait of Juan de Fuca, likely due to its virtual absence in this area. The fitness and fate of myriad invertebrates and fishes that use this habitat (Bodkin, 1988)(Duggins *et al.*, 1989)(Teagle *et al.*, 2017) are thus likely connected to the temporal and spatial coherence in canopy kelp dynamics.

400 The spatial coherence of the overall dynamics of canopy kelp suggests that large-scale environmental drivers are important. Indeed, our tests of environmental data for the region showed similar dynamics to kelp. Specifically, the PDO, the UI, and SST all had an autoregressive term of 1 in ARIMA models, as did kelp, suggesting spatial coherence. Although the PDO and UI additionally had evidence of 10-year cycles in a spectral analysis (Figure S3),
405 detecting that signal in kelp is not yet possible given the length of the data. Thus, the kelp data through 2015 indicate that kelp abundance in the previous year has the greatest explanatory power for abundance in year t . Kelp abundance was also negatively correlated with the PDO and ONI, with the PDO and UI being leading indicators of kelp abundance (Table 3). The correlation between kelp abundance and temperature was not significant within the same year (Table 3). It
410 may be that indices such as the PDO, NPGO, ONI, and UI, though averaged over large scales, are a better correlate of kelp abundance throughout the region compared with a temperature in a single locale.

Previous studies with kelp suggest sensitivity to both increased temperature and decreased salinity. *Nereocystis* in British Columbia, Canada showed warmer SST at time t is associated 415 with lower kelp abundance in that same year (Foreman 1984). An 18-year study by Schiel et al. (2004) concluded that increased temperature was associated with a decrease in *Nereocystis* abundance and an increase in *Macrocystis* abundance. *Macrocystis* distribution was also negatively affected by increased temperature, which also corresponds with decreased salinity in British Columbia; transplant studies suggested low salinity during summer may limit its 420 distribution (Druehl, 1978). However, Reed et al. (2016) argued that canopy kelp were poor sentinel species for sea surface warming, and did not respond disproportionately negatively in Southern California during a 2014-2015 warm water event. Although the ‘sentinel species’ label (sensu Reed *et al.*, 2016) may not apply, canopy kelp abundance repeatedly shows an inverse relationship to temperature in the Northern and the Southern Hemispheres, and in the Pacific and 425 Atlantic Oceans (Foreman, 1984)(Wernberg *et al.*, 2012) (Wernberg *et al.*, 2016)(Filbee-Dexter *et al.*, 2016)(Cavanaugh *et al.*, 2011). Despite the slight SST increase shown in Race Rocks over 93 years (Figure S3), there were only 9 days when the SST was 14.0°C or higher, a value used as a benchmark in the Southern CCLME for compromised kelp performance (Tegner & Dayton, 1987). Whether decreased kelp with positive PDO and negative NPGO indices is a direct result 430 of temperature is unknown. Higher SSTs can be associated with lower salinity and nutrients, both of which are associated with decreased kelp fitness (Druehl, 1967)(Druehl, 1978)(Schiel & Foster, 2015). While Race Rocks provides regional information in an area with complex circulation (e.g. Newton *et al.*, 2003), its placement away from the shore means that it will not record the temperature fluctuations of sites immediately at the shore and may not indicate the 435 temperature events important to kelp. Long-term temperature records in close proximity to

Washington kelp forests is thus lacking and prevents a rigorous test the direct effect of temperature.

As with other studies of kelp, we also found relationships between climate indices and kelp performance. This study found a significant cross correlation between total Washington kelp
440 canopy and PDO (0-2 year lag), NPGO (0-3 year lag), and ONI (0,1 year lag). Additionally, the UI was a leading indicator for *Macrocystis* abundance at 2 and 3 years (Table 3). Although *Macrocystis* in Southern California was not correlated with the PDO at 0 to 6 year lags, the NPGO and SST were significant explanatory variables (Cavanaugh *et al.*, 2011). Thus, despite the close anti-correlated relationship between the PDO and NPGO, they have slightly different
445 relationships with kelp populations in the different parts of the CCLME.

Our analysis of the 66 map indices showed that high variability in kelp abundance at the scale of approximately 8 km of shoreline, (range 0.9 – 25.0), while the 2 kelp species were persistent over an entire scale of 650 km of shoreline (Figure 1). Some areas showed continual abundance of either *Macrocystis* or *Nereocystis* thorough time (a high autocorrelation), while
450 others were characterized by high variability. An area of *Nereocystis* west of Neah Bay (index area 16.2) was typically highly abundant, while variable in abundance through time (Figure 1, Figure S4). Those populations that are variable and low abundance are at particular risk of extinction (Lande *et al.*, 2003), and these tended to be concentrated in the eastern areas of the Strait of Juan de Fuca where only *Nereocystis* occurs and the southern areas of the outer coast,
455 especially for *Macrocystis*. The eastern areas lay at one end of a strong gradient in environmental conditions along the Strait of Juan de Fuca due to natural (i.e. wave energy) and anthropogenic (i.e. development) causes. The southern areas of the outer coast are at a habitat transition from predominantly rocky shorelines to sandy ones where kelp attachment is prevented. Why

populations are variable from one time to the next is unknown and may be related to localized
460 effects. It is also unknown whether these patches of kelp have autonomy or are linked genetically, factors that will be key to determining any future risk of extirpation (Wootton & Pfister, 2013).

Although we show an increasing trend in seawater temperature at the Race Rocks locale in the Strait of Juan de Fuca, the overall change since 1921 is small (+0.72°C) (Figure S3). This
465 SST increase using daily values was less than that of the Rogers-Bennett *et al.* (2011) estimate of 1°C annually based on yearly data from 1969-2006, perhaps reflecting both our use of the entire time series and the elimination of any seasonal cycles. Because this is a region dominated by upwelling, the documentation of a warming trend is unexpected and potentially significant. When we divided the year into the upwelling season versus the winter months of downwelling,
470 the downwelling period is the one that showed increasing temperature. Thus, the downwelling winter period, when the intrusion of deeper cold water is less pronounced, may be an interval when surface temperature changes are best detected, although its importance relative to spring/summer values is unknown. Although currently a small increase in an annual mean, increasing changes could have important effects in these coastal ecosystems. Kelp distributions
475 are generally associated with higher latitudes and colder water (Steneck *et al.*, 2002). There is evidence of episodes of increased sea surface temperatures in the California Current in recent years (Di Lorenzo & Mantua, 2016), (Reed *et al.*, 2016), and analysis of the Race Rocks data suggested an ongoing trend (Figure S3, Rogers-Bennett *et al.*, 2011), that is seasonally divergent (Figure S3). Whether increasing SST trends are occurring elsewhere in the northeast Pacific
480 Ocean is unknown.

Coherence between large-scale environmental drivers and the fitness of primary producers breaks down when local-scale factors are important. One notable pattern in kelp abundance is a striking threefold increase followed by a decrease that occurs in the middle of the time series and creates two periods of relative stability, separated by rapid change. Although we cannot explain 485 this pattern, we recognize that a number of local factors have been shown to be important to kelp bed abundance in North Pacific Ocean kelp beds. Trophic cascades via sea otter consumption of sea urchins (Estes & Palmisano, 1974), have been shown to be a key driver. Sea otter predation on sea urchins following their reintroduction in 1969 and 1970 (Kvitek *et al.*, 1989)(Laidre & Jameson, 2006), as well as an extensive sea urchin fishery that started in the 1980s (Pfister & 490 Bradbury, 1996), has likely resulted in low sea urchin populations and thus reduced herbivory on kelp. This suggests that the area has generally been in an algal-dominated, rather than urchin-dominated, phase state (Watson & Estes, 2011). In some subareas during the study period, changes in urchin abundance may be associated with observed changes in kelp abundance. On the outer coast, sea otters expanded their numbers and range to the north and south between 1987 495 and 1995, and then farther to the north in 1999, and urchin abundance decreased rapidly in the newly occupied territories (Kvitek *et al.*, 1998) (Laidre & Jameson, 2006). Along the Strait of Juan de Fuca, intensive harvest in the early 1990s substantially decreased urchin abundance throughout the Strait of Juan de Fuca. While red urchin population densities were higher during the end of the study period (2013-2014) along the Strait of Juan de Fuca relative to levels in the 500 early 2000s, they remain generally low with many areas containing a fraction of an urchin per m² with a high of only 1.4 urchins per m² (WDFW unpublished data). The historic Rigg study in 1911 and 1912, however, occurred during a period of likely relatively increased sea urchin abundance due to local sea otter extirpation and no subtidal urchin harvest. Yet, this era did not

differ greatly from the modern era in the western Strait where urchin harvest has increased. Thus,
505 the extent to which variation in sea urchin density has controlled kelp forest abundance in this study is unclear.

The kelp beds that were censused over a century ago provide insight into kelp dynamics in the northeast Pacific (Figure 4, Figure S4), showing overall persistence of kelp beds over the entire scale of the study. Kelp beds that may be reduced in abundance relative to 1911-12 in the
510 Strait of Juan de Fuca are those eastward toward Puget Sound and include sites between Dungeness and Port Townsend. Modern censuses indicate these are beds have low and variable cover. This pattern of reduced kelp abundance eastward is coupled with the loss of some populations further eastward into Puget Sound that were recorded in Cameron (1915), but have been absent for more than a decade (e.g. Bainbridge Island, WDNR unpublished data). The
515 possible reasons for declines in these two kelp species in the eastern Strait of Juan de Fuca and Puget Sound locales could be varied and include increased turbidity (Schiel & Foster, 2015), increased point source pollution, and numerous other anthropogenic stressors associated with increasing human population size over the last century. Compared with outer coast kelp beds and those in the western areas of the Strait, the beds to the east show possible declines in abundance.
520 Assuming all three regions experience the same ocean climate drivers, the declines in the eastern region suggest that climate may play a secondary role where direct anthropogenic effects are enhanced due to a human population size greater than 4 million surrounding Puget Sound (e.g. Shelton *et al.*, 2016), a possibility that deserves greater attention. The differences in the trends seen in Washington kelp beds may mirror the diversity of trends reported in kelp species, with
525 some populations and species increasing, while others are decreasing (Krumhansl *et al.*, 2016), likely due to a difference in the factors that drive kelp populations depending upon their

proximity to concentrated anthropogenic effects. Throughout the range of the study, we find that kelp beds are relatively persistent throughout the Strait of Juan de Fuca and exposed coast of Washington state, but they are subject to high variation at smaller spatial scales.

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ACKNOWLEDGEMENTS

Funding from NOAA CPO #NA16OAR4310155 to CAP and HB made this synthesis possible. Washington State DNR funded the data collection from 1989-2015, with assistance from the
535 NOAA Olympic Coast National Marine Sanctuary in 3 years. We thank Robert Van Wagenen and EcoScan for providing the aerial data. We thank Alison Bailey and Sound GIS for help with the spatial geodatabase. We thank the P. Dowty and the librarians at U of Chicago (A. Mantrone, S. Byrne) for digitizing the Cameron (1915) maps. Comments from S. McCoy, JT Wootton, and P. Dowty improved the manuscript. The authors have no conflicts of interest to declare.

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AUTHOR CONTRIBUTIONS

CAP: Wrote the manuscript, analyzed the data; HB: contributed to writing the manuscript, collecting and analyzing the data; TM contributed to collecting the data and editing the manuscript.

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DATA ACCESSIBILITY

Data will be made accessible via Dryad. Archival maps are now accessible via the The University of Chicago Library.

550 Table 1. The relationships in abundance of *Macrocystis* and *Nereocystis* among years. The blue diagonal represents the correlation coefficients between the 2 species. Above the diagonal are the spatial correlations with *Macrocystis* abundance; below the diagonal is *Nereocystis*. All bold values are statistically significant at p<0.001.

		<i>Macrocystis</i>		
<i>Nereocystis</i>	locale	Eastern Strait	Western Strait	Outer Coast
	Eastern Strait	0.192	0.159	0.123
	Western Strait	0.864	0.842	0.786
	Outer Coast	0.576	0.629	0.689

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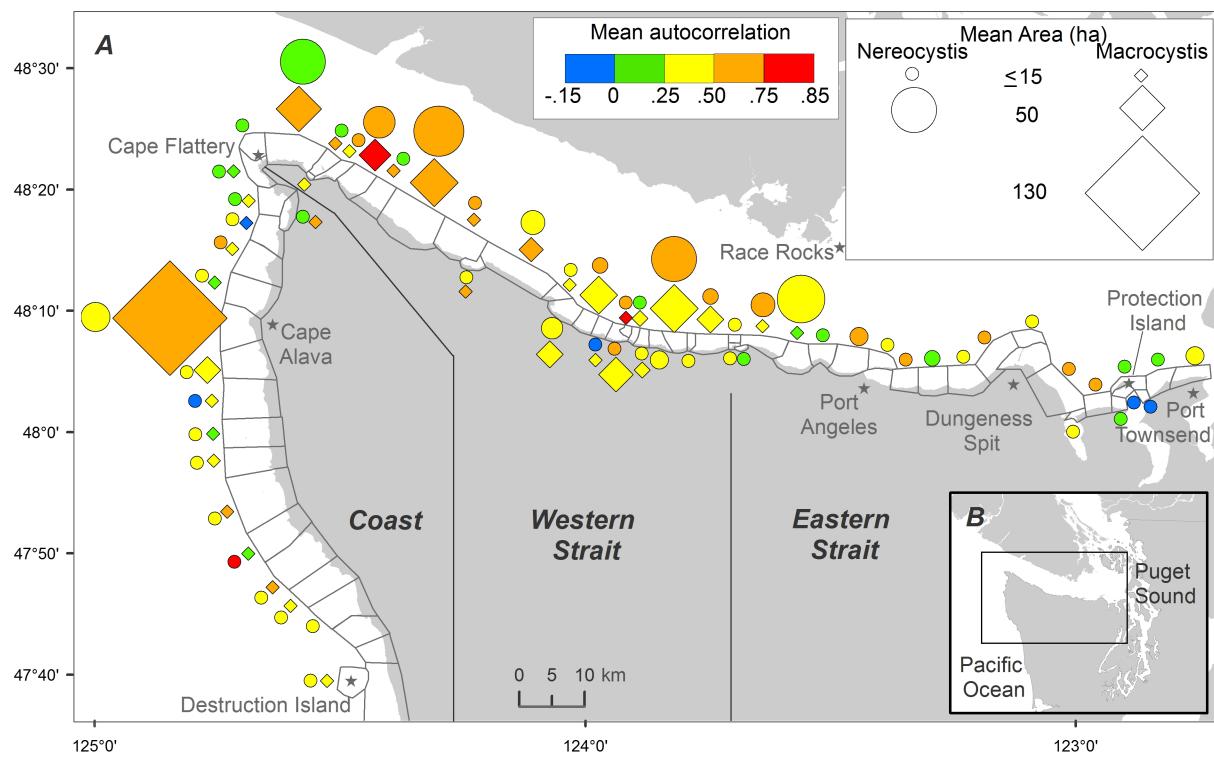
Table 2. The AIC values for ARIMA models fit to the kelp and environmental data. The model is designated as (auto regressive term, difference, moving average term). The best fitting model is shaded green. Not all model combinations are shown. The best-fitting ARIMA model for
 560 *Nereocystis* and *Macrocystis* showed an AR coefficient of -398, -.358 and MA coefficient of -1.00 and -.912, respectively.

ARIMA Model	<i>Macrocystis</i>	<i>Nereocystis</i>	Total canopy	Race Rocks SST	PDO	UI	ONI	NPGO
(1,0,0)	314.90	359.35	389.46	52.70	146.00	568.58	120.62	183.60
(1,0,1)	315.83	360.39	389.86	53.24	145.60	569.52	118.52	185.35
(1,1,1)	300.11	346.75	373.81	48.26	145.92	565.47	123.83	184.68
(1,2,0)	300.66	343.56	369.90	101.94	188.17	613.60	193.25	222.59
(1,2,1)	294.19	337.62	364.24	63.97	157.87	572.35	154.61	198.40
(1,0,2)	317.08	359.95	389.16	50.61	146.61	569.55	112.15	187.35
(1,0,4)	319.45	365.27	393.17	56.02	151.73	541.36	117.77	182.33
(2,0,0)	315.44	359.64	388.95	54.24	146.26	567.69	114.99	185.32
(5,0,0)	320.82	364.27	393.63	53.08	149.94	571.39	120.64	186.88
(10,0,0)	---	---		62.06	155.15	572.68	122.29	193.02

565 Table 3. The cross correlation between the total kelp canopy cover and environmental variables with the same year and 1, 2 and 3 years previous. Bold values are significant at $p < 0.05$.

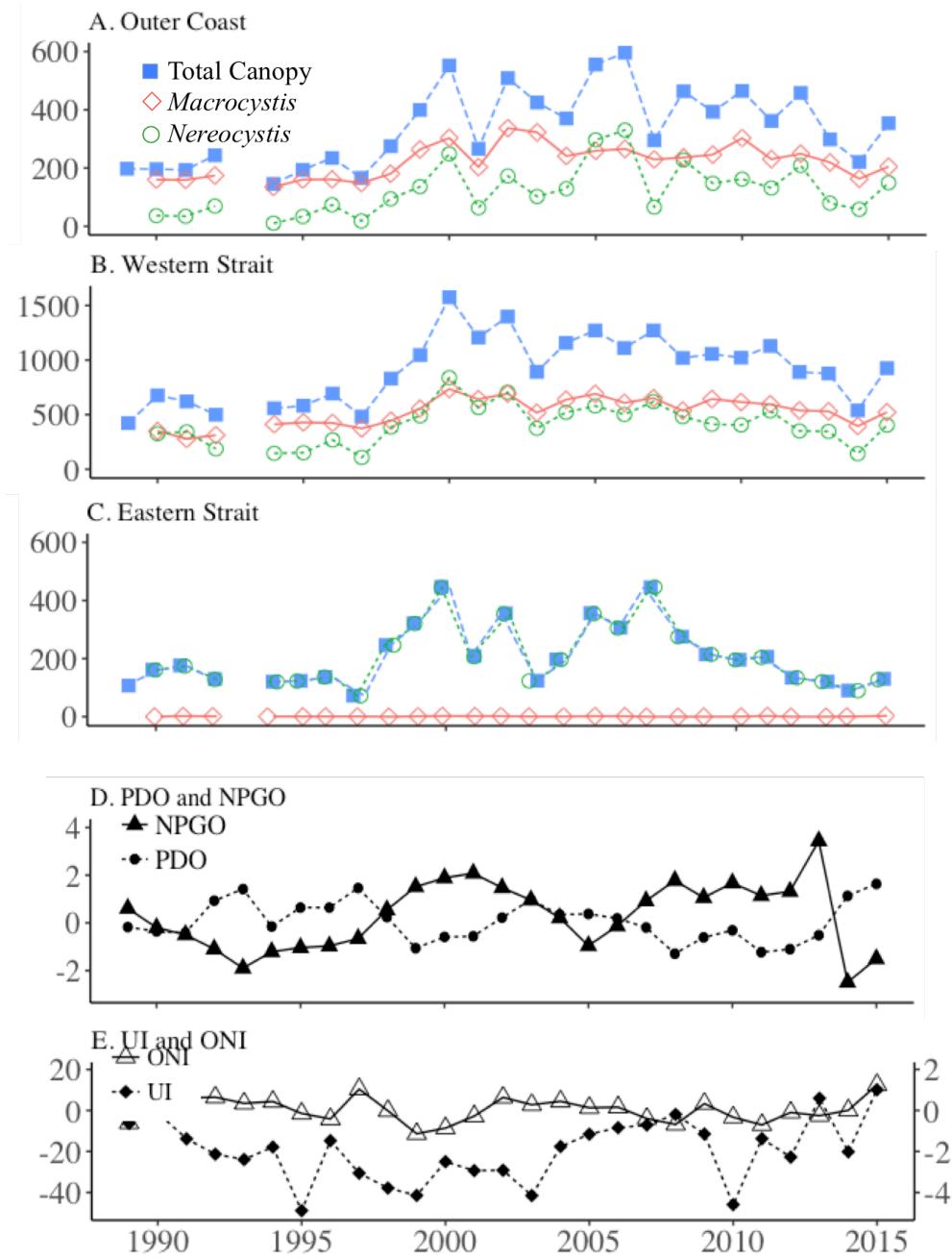
Environmental Variable	Canopy Species	time 0	1 year previous	2 years previous	3 years previous
PDO	<i>Macrocystis</i>	-0.321	-0.477	-0.319	-0.143
	<i>Nereocystis</i>	-0.440	-0.517	-0.258	-0.140
	Total Canopy	-0.376	-0.467	-0.263	-0.209
ONI	<i>Macrocystis</i>	-0.326	-0.330	-0.002	-0.012
	<i>Nereocystis</i>	-0.384	-0.312	0.004	0.043
	Total Canopy	-0.305	-0.329	-0.062	-0.058
UI	<i>Macrocystis</i>	-0.054	0.063	0.265	0.405
	<i>Nereocystis</i>	0.089	0.124	0.116	0.229
	Total Canopy	-0.008	-0.009	0.162	0.251
Race Rocks SST	<i>Macrocystis</i>	-0.095	-0.126	-0.091	-0.126
	<i>Nereocystis</i>	-0.088	-0.199	-0.114	-0.082
	Total Canopy	-0.014	-0.205	-0.079	-0.124
NPGO	<i>Macrocystis</i>	0.753	0.746	0.551	0.363
	<i>Nereocystis</i>	0.650	0.797	0.503	0.287
	Total Canopy	0.651	0.760	0.624	0.371

570 Figure 1. The abundance of each species of canopy kelp is shown by the size of the circle (*Nereocystis*) and diamond (*Macrocystis*), while the color indicates the autocorrelation through time for each locale from 1989 to 2015; increased consistency in abundance through time leads to a greater autocorrelation. Each coastal polygon delineates an index area. Detailed maps of kelp abundance and index area boundaries are shown in Figure S4.



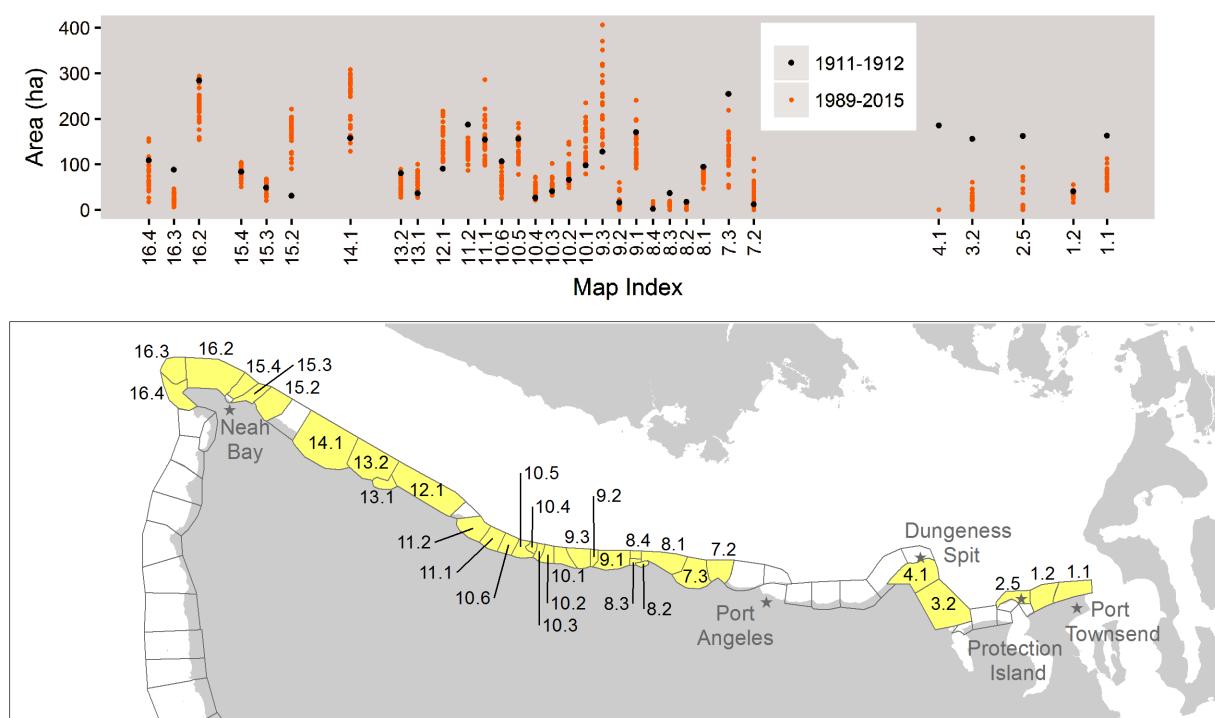
575

580 Figure 2. The relative abundance (in hectares) of the total canopy, *Nereocystis* and *Macrocystis* from 1989-2015 based on aerial surveys in the A. outer Coast region, B. Western Strait, and C. Eastern Strait. There was no census in 1993. The environmental variables over the same time period for the region include D. the PDO and the NPGO and E. the UI and ONI. Correlations between kelp abundance and environmental variables are shown in Table 3.



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590 Figure 3. The kelp bed area in hectares in 1911-1912 (black circles) compared with annual surveys from 1989 to 2015 (red circles), from areas along the Strait of Juan de Fuca where Rigg (Cameron 1915) identified kelp beds. Yellow highlighting indicates the modern Index Areas where kelp beds were noted in 1911-1912. Detailed maps of historical and modern kelp abundance are presented in Figure S4.



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Figure S1. The partial autocorrelation function for a. *Nereocystis*, b. *Macrocystis*, and annual means values of c. PDO, d. NPGO, e. SST, and f. UI. Lagged terms tended to not be significant.

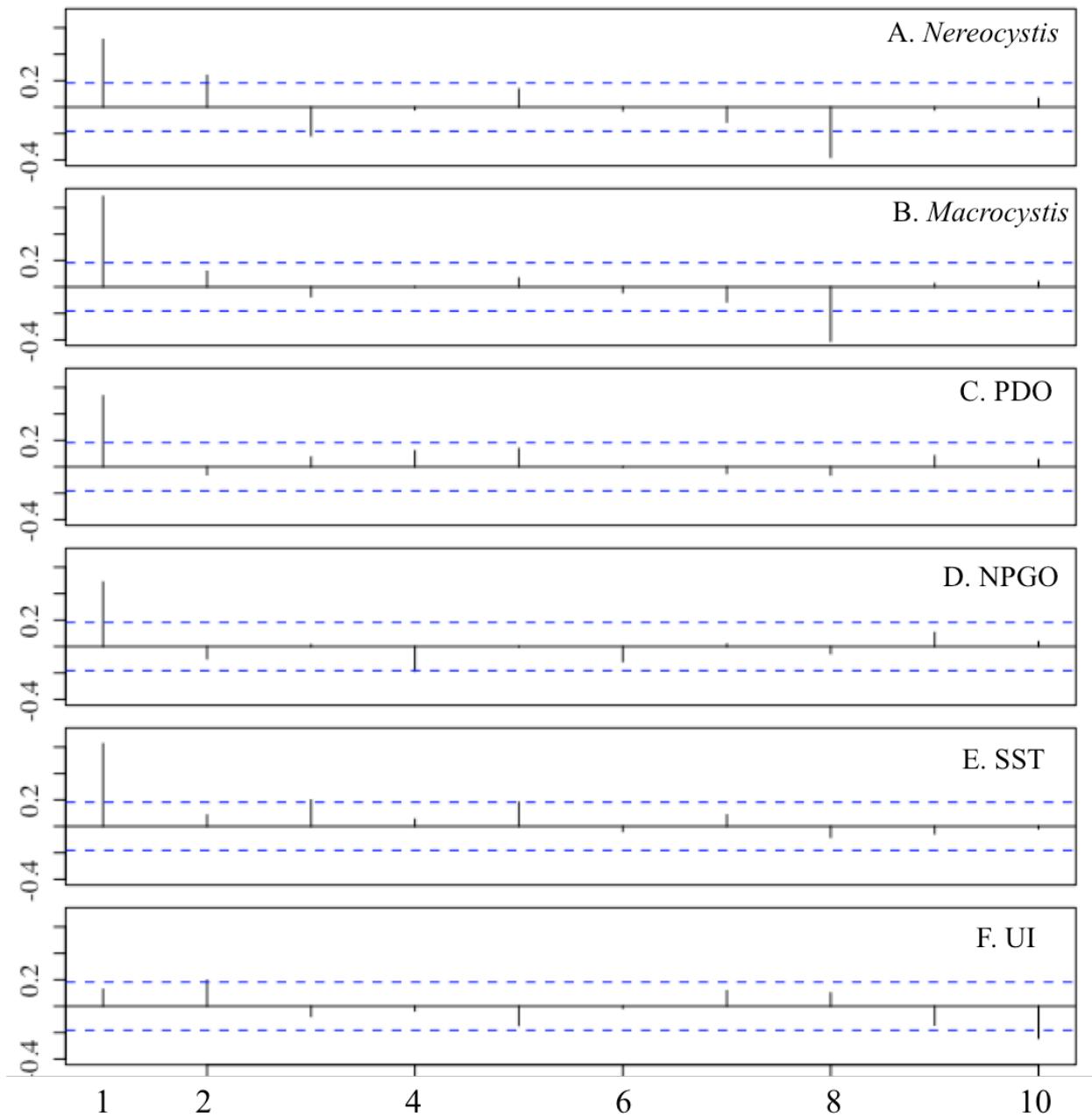
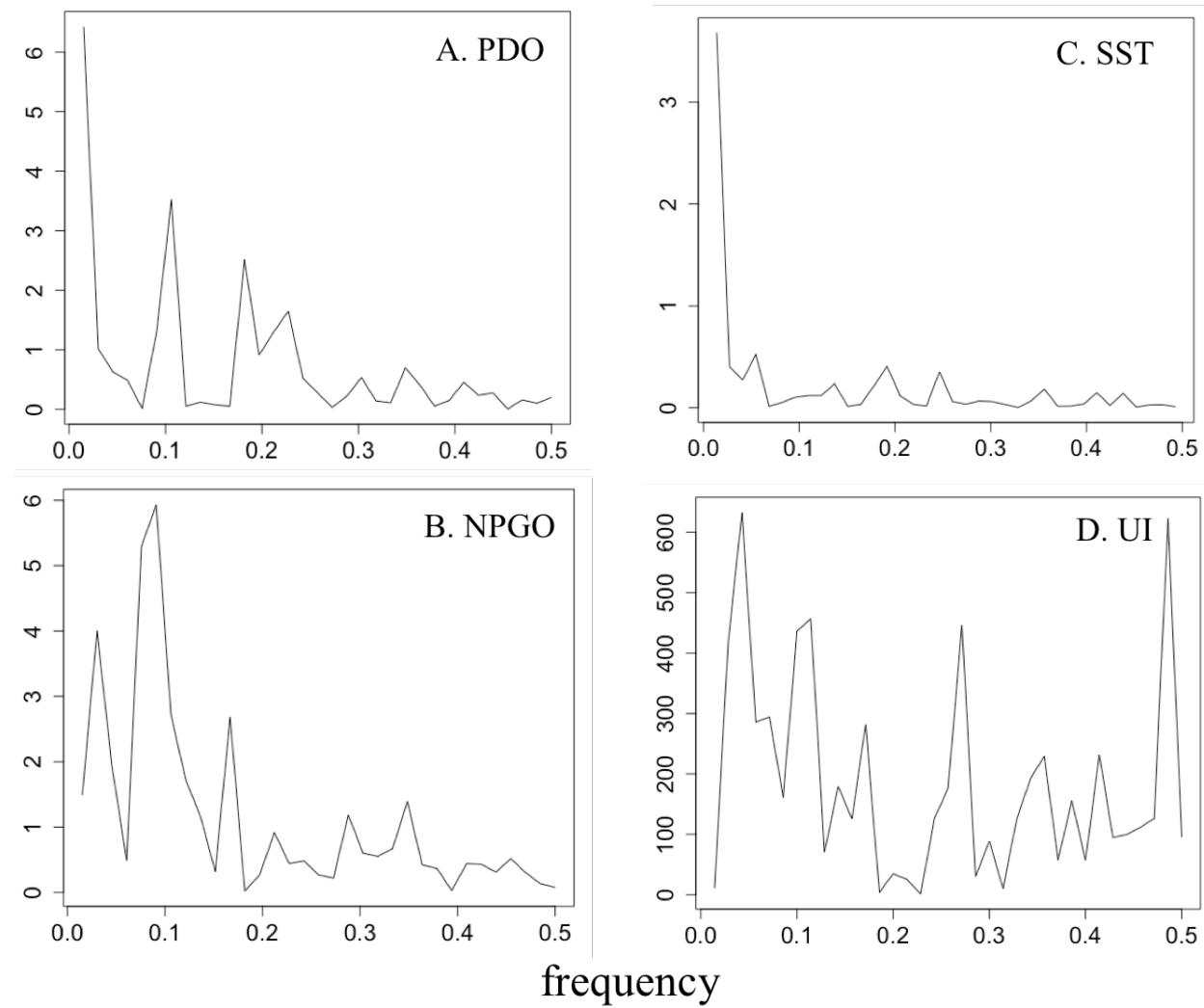
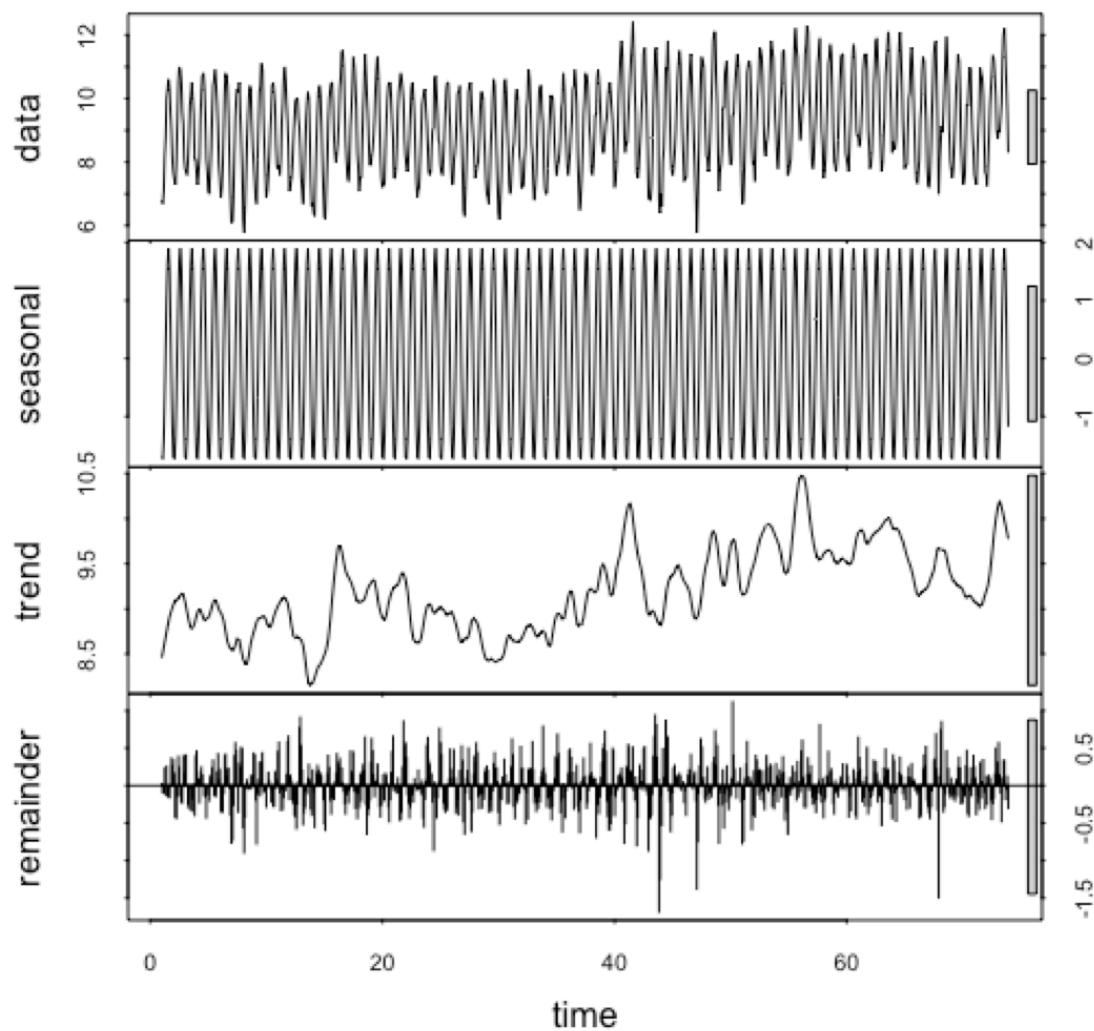


Figure S2. The spectrum for four environmental variables, showing the periodic components of each of the A. annual PDO, B. NPGO, C. SST, and D. UI. Cycles are estimated as the inverse of the frequency, indicating 10-year cycles in the PDO the UI, and the NPGO, as well as 20 year cycles in the UI.



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Figure S3. The trend in monthly mean SST at Race Rocks since 1942. The top panel represents the raw data, the second panel shows the underlying 12 month seasonal cycle, while the third panel extracts trend data. The bottom panel plots the remaining variability as residuals after the seasonal and trend components have been removed. All analyses based on “STL” in the ‘stats’ module in R. The bar at the right shows the relative magnitude of change for each component. The trend line visually appears to be increasing, and linear regression on annual mean SST revealed a 0.0076°C (0.0015SE) since 1921, an increase of $\sim 0.72^{\circ}\text{C}$ between 1921-2015 (r²=0.0209, p<0.001). If the temperature is divided into the upwelling season from April to August versus the winter months of September to March, the trends are different, with a coefficient that indicated decreasing surface temperature through time (-0.00456) in the summer versus increasing in the winter (0.00855).



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Figure S4. Historical and modern floating kelp surveys from a. eastern to the h. southwestern shoreline of Washington state. Index areas are delineated in gray and identified by number. The 1911-1912 survey was completed by Rigg and delineated bed extent and density category (Cameron 1915). The 1989-2015 surveys were completed by Washington DNR and summarize the number of years that floating canopy was present, based on annual late-summer mapping of the canopy. Basemap: ESRI World Ocean Database.

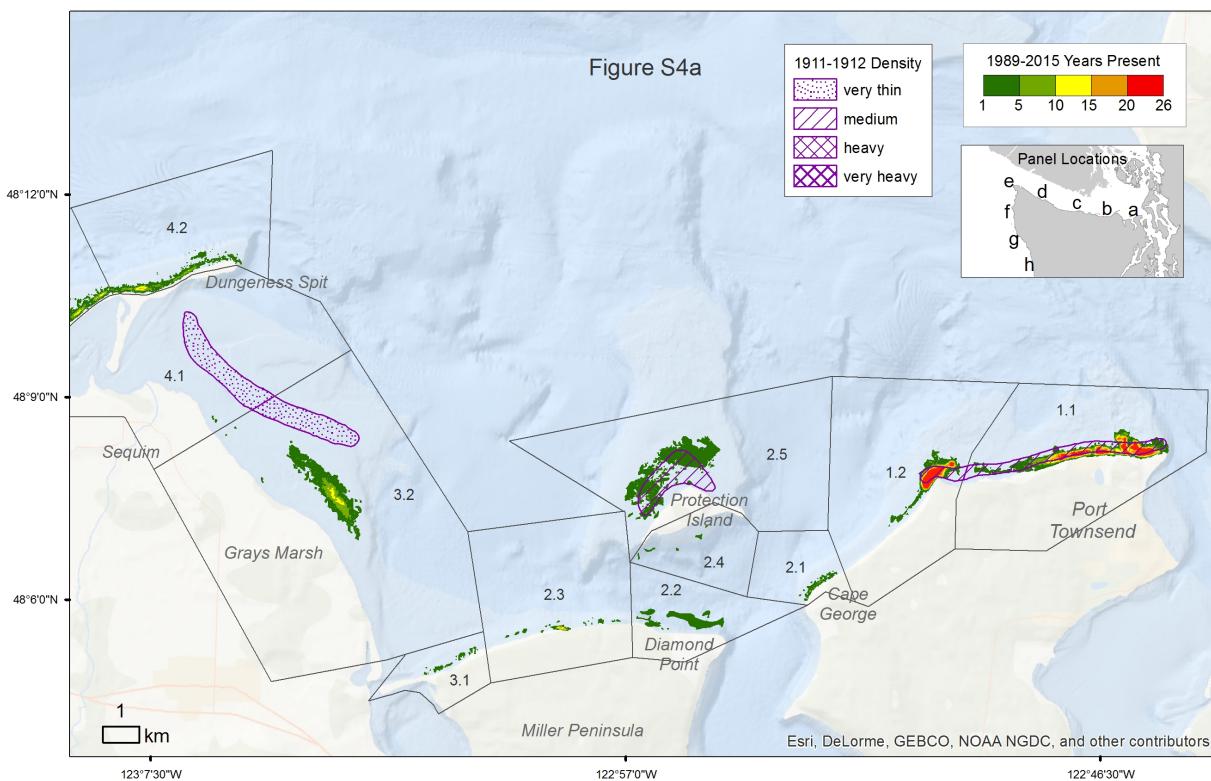


Figure S4. Historical and modern floating kelp surveys, from (a) eastern to (h) southwestern shoreline. Index areas are delineated in grey and identified by number. 1911-1912 survey was completed by Rigg and delineated bed extent and density category (Cameron 1915). 1989-2015 surveys were completed by DNR and summarize the number of years that floating canopy was present, based on annual late-summer mapping of canopy. Basemap: ESRI World Ocean Basemap.

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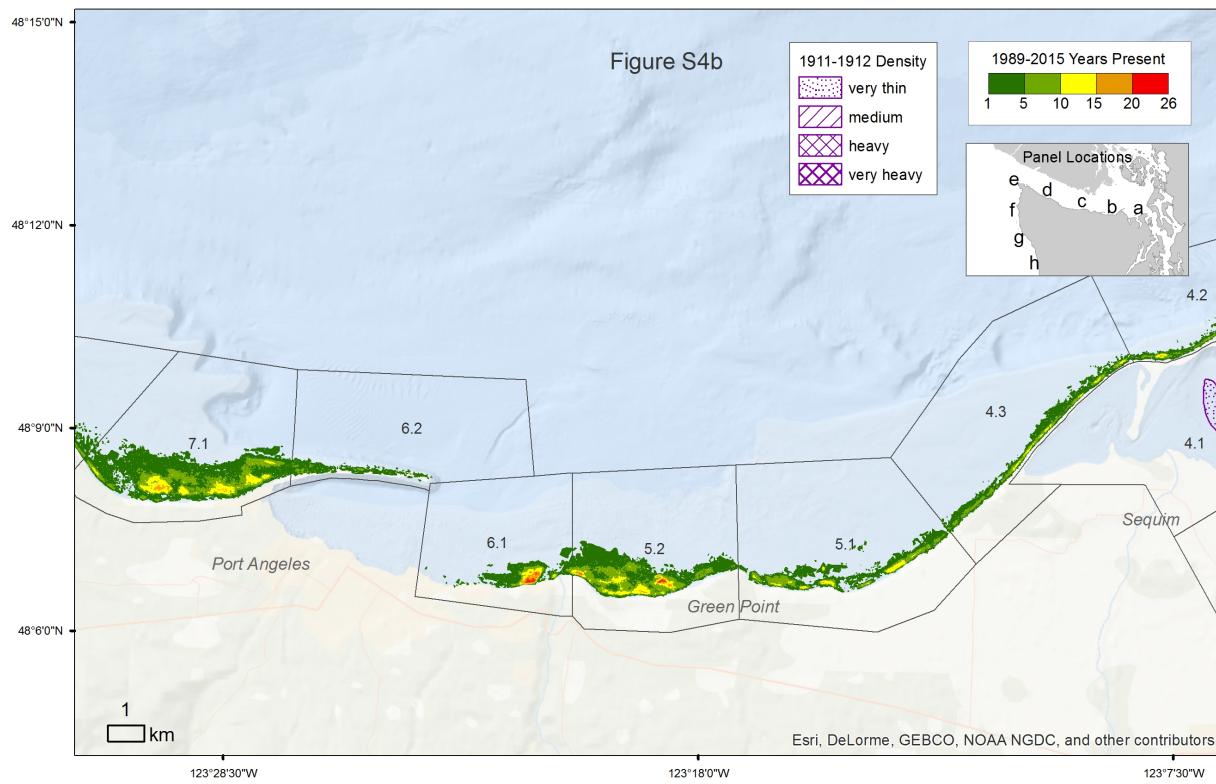


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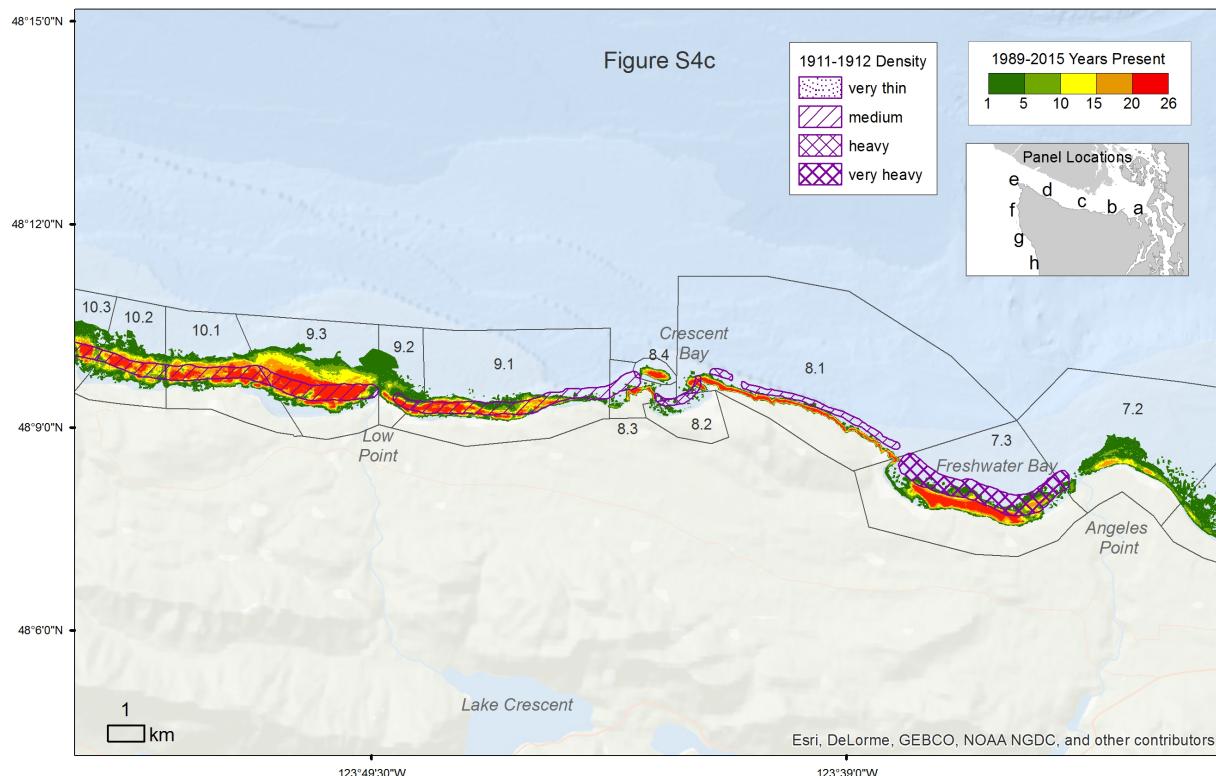


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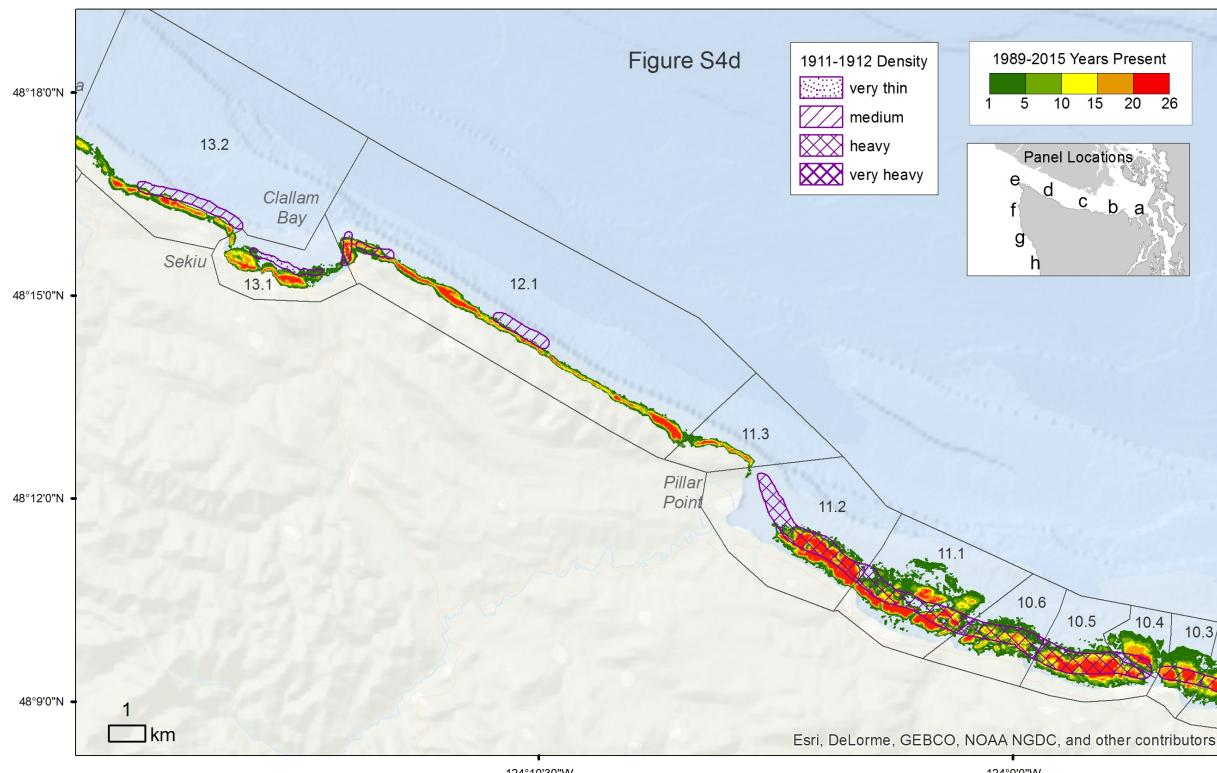


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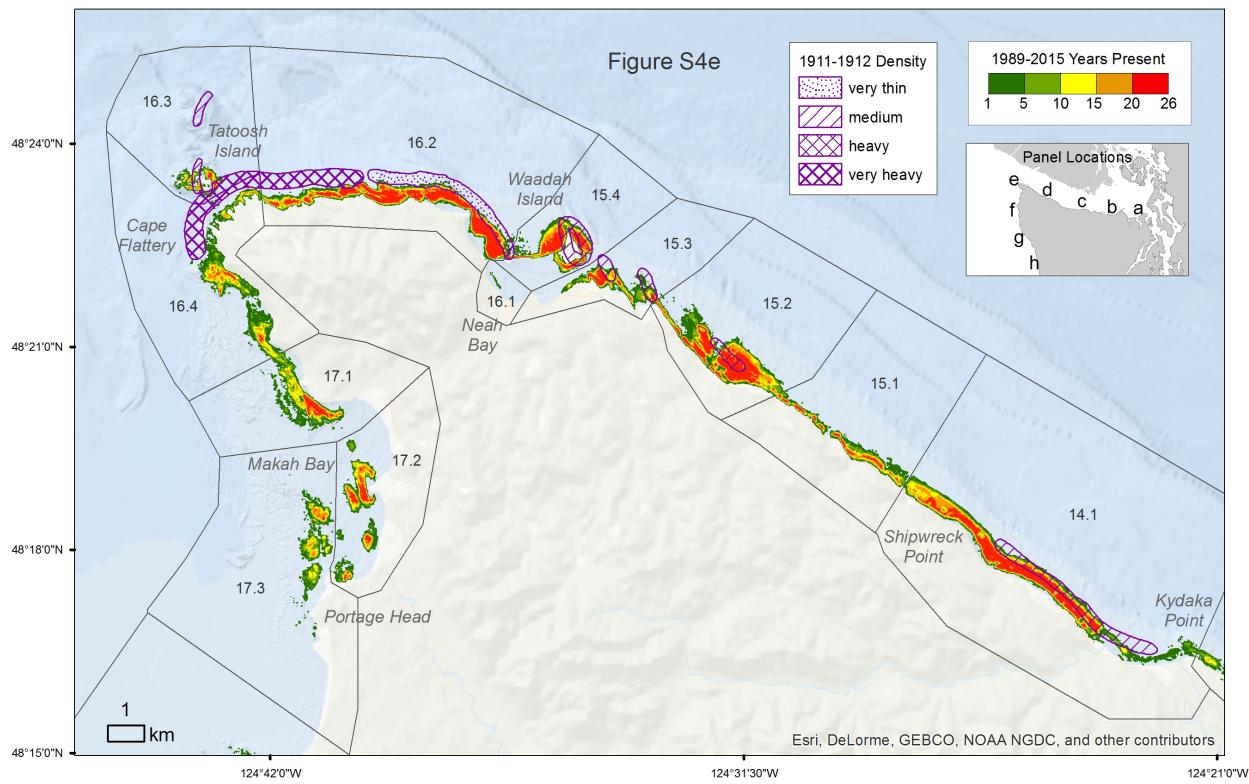


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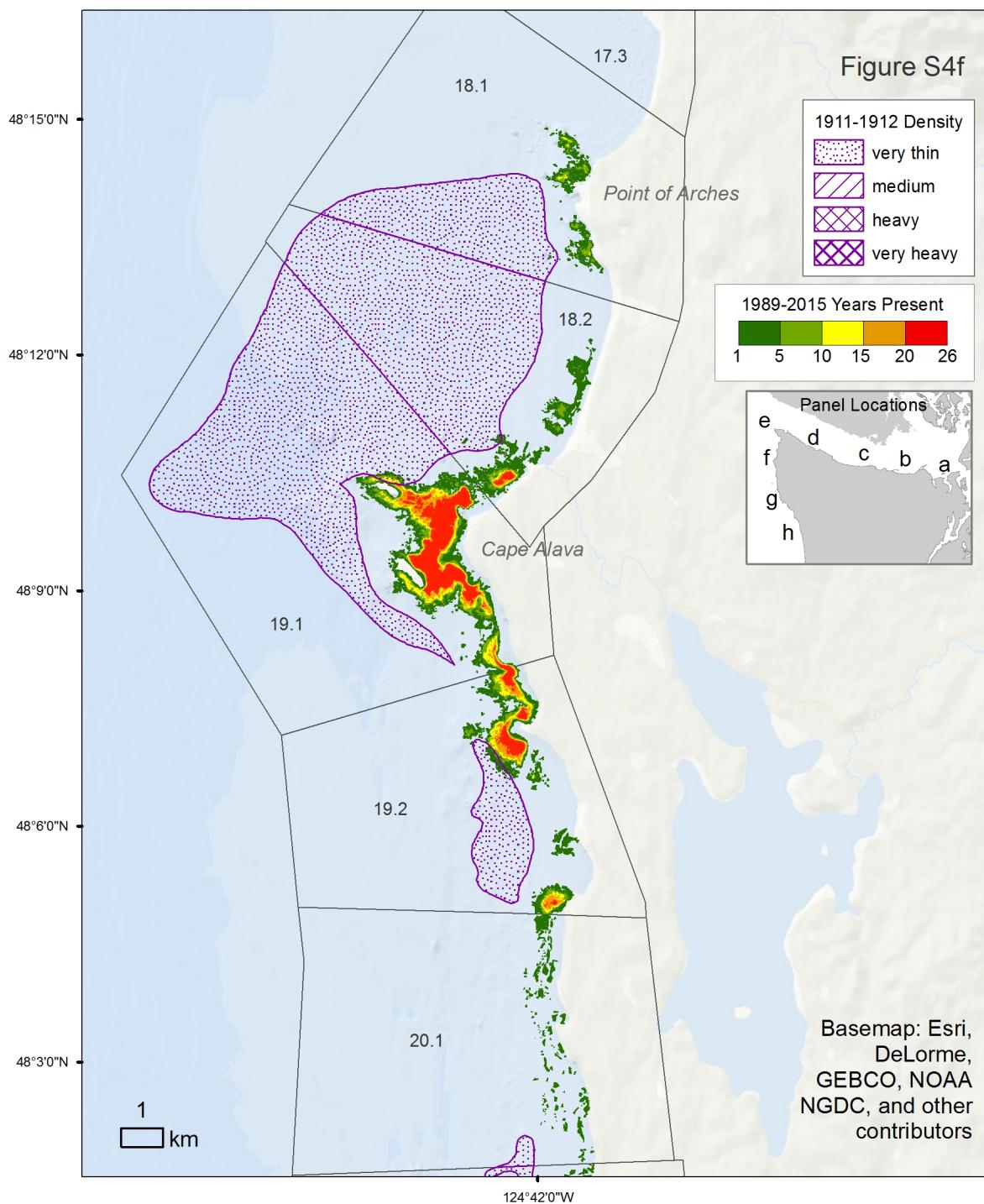


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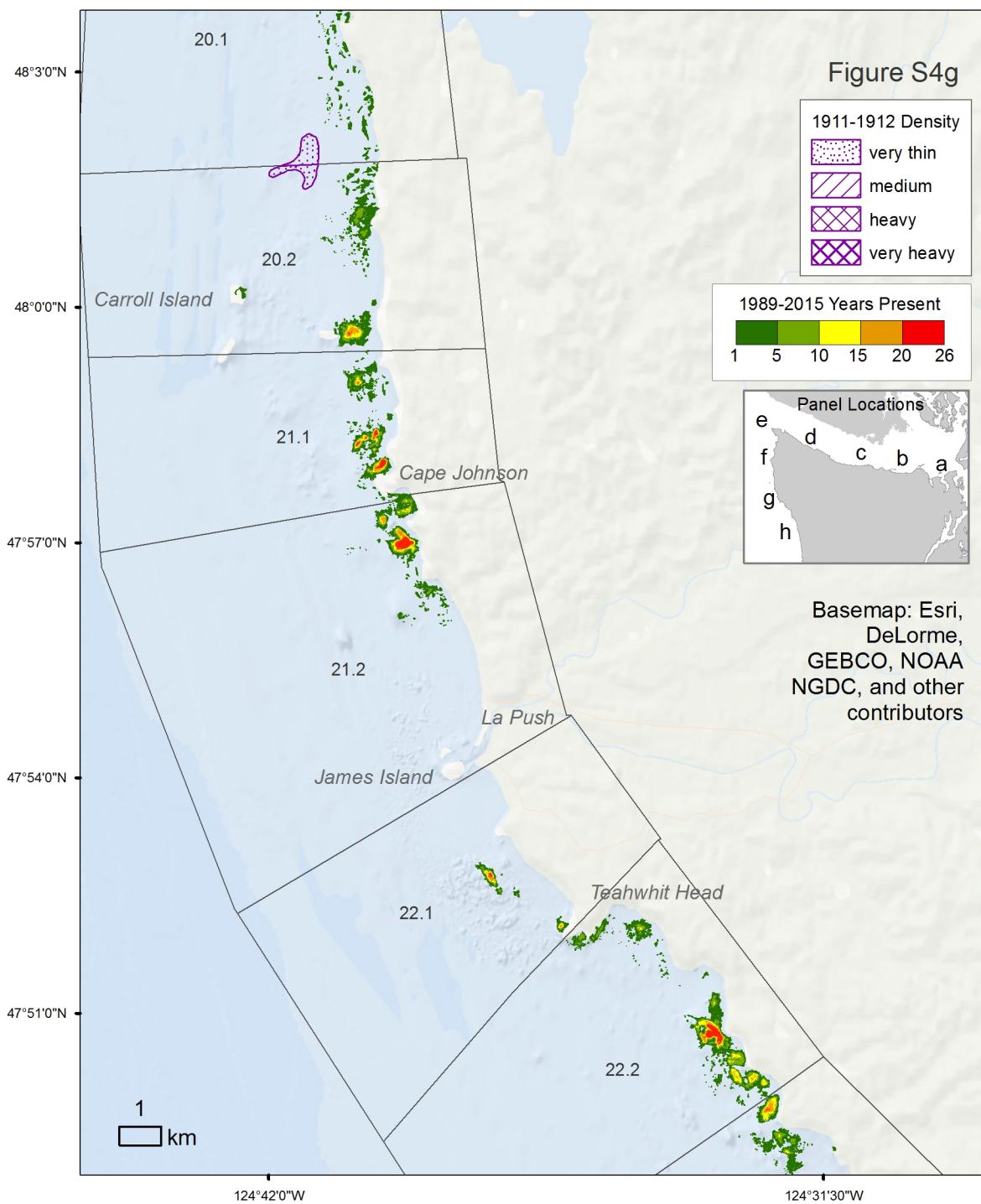


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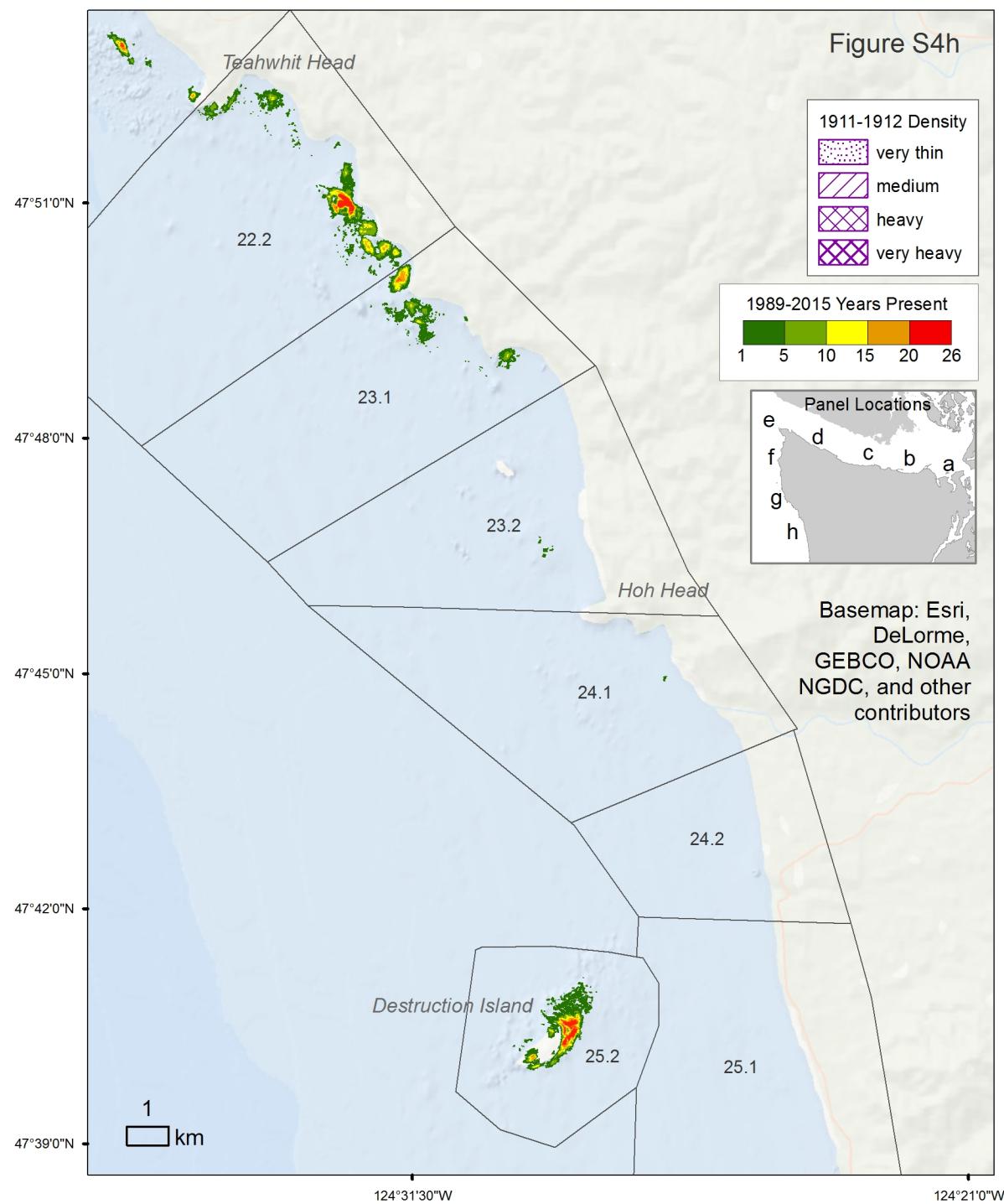


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