Appendix A

Differential responses of eelgrass and macroalgae in Pacific Northwest estuaries following an unprecedented NE Pacific Ocean marine heatwave

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Table S1. Physiographic characteristics of the four study estuaries (Figure 1) located on the Pacific Northwest coast of the US, including Willapa Bay (46.69 ºN, 124.08 ºW), Washington, and Netarts Bay (45.44 ºN, 123.96 ºW), Coos Bay (45.44 ºN, 123.96 ºW), and Yaquina Bay (44.62 ºN, 124.07 ºW), Oregon. Variable abbreviations used in the Partial Least Squares Regression radar plots are in italics below the factors included in that analysis. Population estimates for 2010 were obtained from the U.S. Census Bureau for Pacific (Willapa Bay), Tillamook (Netarts Bay), Lincoln (Yaquina Bay), and Coos (Coos Bay) counties. County population density (people per km^2) was multiplied by the watershed area (km^2) and then divided by the estuary area (km^2) to estimate population normalized to estuary area for each watershed.

Estuary	**Normalized Human Population** (number per estuary area km^{-2})	**Total freshwater nitrogen load per estuary area** (kg km^{-2} yr^{-1})†	**Total freshwater phosphorus load per estuary area** (kg km^{-2} yr^{-1})†	**Catchment (km^2) per estuary area** (km^2)†	**Tidal Volume per day** (m^3 d^{-1})† *VolExch*	**Freshwater inflow (volume normalized)*** *FWFlow*
Willapa Bay	66.03	10×10^6	14×10^4	6.8	161.9×10^7	6.0
Netarts Bay	42.12	9.3×10^6	9.3×10^4	3.1	3.0×10^7	8.0
Yaquina Bay	641.66	75×10^6	130×10^4	45.3	5.1×10^7	42.0
Coos Bay	447.65	99×10^6	180×10^4	33.6	14.0×10^7	14.0

Data sources: †Hessing-Lewis and Hacker 2013; *Lee and Brown 2009

Table S2. Summary of annual (July or August) macrophyte (eelgrass, macroalgae, and epiphyte) data and other estuary and ocean environmental factors compiled for the four US Pacific Northwest estuaries (Figure 1; Willapa Bay, WA, Netarts Bay, OR, Yaquina Bay, OR, and Coos Bay, OR) from 2006-2010 and 2015-2019. Data sources are given in Appendix A: Table S3. Italicized values indicate missing data that were imputed with an estuary-specific average. Abbreviations for factors used in the Partial Least Squares Regression radar plots are given in italics below each factor title.

		Macrophyte Biomass			**Estuary Conditions**			**Ocean Conditions**		
Estuary	**Year**	**Macroalgae biomass (g dry wt 0.25 m^{-2})** *macroalgae*	**Eelgrass biomass (g dry wt 0.25 m^{-2})** *eelgrass*	**Epiphyte load (g dry wt per g eelgrass)** *epiphyte*	**Water Temperature (°C)** *Water Temp*	**Estuarine Heat Wave Cumulative Intensity (°C x days)** *EHW*	**Salinity** *Salinity*	**Offshore Current (cm s^{-1} west)** *Offshore*	**Alongshore Current (cm s^{-1} south)** *Alongshore*	**Upwelling Index (m^3 s^{-1} 100 m^{-1})** *Upwelling*
Willapa	2007	0.41	61.19	*0.03*	18.30	103.0	*28.43*	-0.493	9.390	18
Willapa	2008	1.96	51.54	*0.03*	14.40	0	*28.43*	3.276	15.048	28.7
Willapa	2009	7.49	41.57	*0.03*	15.70	0	*28.43*	3.888	12.802	22.9
Willapa	2010	4.30	42.10	*0.03*	14.60	0	*28.43*	6.402	16.316	20.9
Willapa	2016	0.11	31.48	0.01	16.40	116.8	28.8	6.910	16.334	28.7
Willapa	2017	0.20	27.57	0.06	15.70	0	26.8	5.696	16.990	32
Willapa	2018	6.54	18.65	0.01	15.90	0	28.6	0.831	11.446	24.4
Willapa	2019	3.43	16.12	0.03	16.60	23.3	29.5	1.105	14.513	25
Netarts	2006	1.70	58.70	*0.19*	13.30	0	*32.4*	*5.625*	*21.143*	57.6
Netarts	2008	0.70	53.30	*0.19*	12.40	0	*32.4*	6.198	22.359	41.4
Netarts	2010	1.10	40.10	*0.19*	12.50	0	*32.4*	9.120	24.971	32.2
Netarts	2015	0.79	42.37	*0.19*	14.10	233.5	32.8	7.054	22.020	63.3
Netarts	2016	0.11	28.86	0.04	14.50	102.2	32.4	3.916	22.294	46.8
Netarts	2017	0.43	18.32	0.10	14.10	0	30.7	5.315	22.597	52.4

Netarts	2018	0.35	24.05	0.34	14.50	28.1	32.6	3.515	21.183	41.6
Netarts	2019	3.25	22.13	0.27	14.30	34.2	33.5	7.280	13.119	41.7
Yaquina	2006	24.40	22.90	*0.35*	11.88	116.5	*32.17*	*9.853*	*18.755*	78.6
Yaquina	2007	29.20	21.70	*0.35*	13.10	59.3	*32.17*	8.649	17.939	36.7
Yaquina	2008	65.80	16.80	*0.35*	11.10	0	*32.17*	8.293	20.365	55.1
Yaquina	2009	46.40	12.90	*0.35*	11.60	0	32.50	8.558	16.302	38.5
Yaquina	2010	49.40	15.70	*0.35*	11.70	17.6	31.00	13.911	20.416	46.8
Yaquina	2015	10.1	20.13	*0.35*	12.40	185.3	33.00	10.336	15.750	79.8
Yaquina	2016	29.26	15.25	0.16	*12.40*	376.2	*32.17*	11.583	18.342	67.5
Yaquina	2017	15.46	19.29	0.25	12.20	14.6	*32.17*	11.685	16.219	73.6
Yaquina	2018	37.43	11.50	0.45	*12.40*	0	*32.17*	10.193	16.805	62.4
Yaquina	2019	39.60	11.15	0.52	12.60	28.7	*32.17*	12.063	15.031	60.8
Coos	2006	24.50	22.50	*0.23*	13.70	21.2	31.4	*9.883*	*19.865*	103
Coos	2007	45.20	17.20	*0.23*	14.30	58.8	33.8	8.161	18.170	48.7
Coos	2008	62.60	15.10	*0.23*	12.30	0	31.6	11.535	21.335	78.9
Coos	2009	42.70	8.50	*0.23*	13.10	0	33	10.166	17.658	53.2
Coos	2010	12.30	13.70	*0.23*	12.70	0	29.8	9.671	22.299	68.1
Coos	2015	7.77	42.59	*0.23*	13.50	111.4	31.8	14.382	10.931	91.8
Coos	2016	6.75	45.32	0.04	13.90	113.6	33	4.963	19.438	80.5
Coos	2017	7.53	21.31	0.15	13.60	13.0	31.5	6.224	20.979	76.4
Coos	2018	3.61	23.77	0.30	13.40	0	32.7	4.518	17.683	71.8
Coos	2019	5.78	18.51	0.44	13.90	28.3	31.7	8.317	14.073	69.5

Table S3. Years, locations, and sources for the macrophyte (eelgrass and ulvoid macroalgae), epiphyte, and environmental data for the four US Pacific Northwest estuaries (Figure 1; Willapa Bay, WA, Netarts Bay, OR, Yaquina Bay, OR, and Coos Bay, OR) used in the analyses.

Parameter(s)	**Years used**	**Location(s), Latitude & Longitude**	**Source/Contact**
Macrophyte (eelgrass and ulvoid macroalgae) surveys	2006-2010 & 2015-2019	Willapa Bay (46.600 ºN, 124.033 ºW), Netarts Bay (45.416 ºN, 123.936 ºW), Yaquina Bay (44.619 ºN, 124.029 ºW), Coos Bay (43.347 ºN, 124.317 ºW)	This Study, Hessing-Lewis and Hacker 2013, and Hayduk et al. 2019
Epiphyte surveys	2016-2019	Same as above.	This Study
Water temperature (Ocean)	1979-2019	Offshore Buoy near Cape Blanco (42.5890 ºN, 130.4740 ºW)	NANOOS, http://nvs.nanoos.org/Climatology Asset ID: NDBC_46002_site
Water temperature (Willapa Bay)	1995-2019	Toke Point, WA (46.7075 ºN, 123.9669 ºW)	NANOOS, http://nvs.nanoos.org/Climatology Asset ID: NOS_9440910_site
Water temperature & salinity (Willapa Bay)	2011-2019	Tokeland, WA (46.7075 ºN, 123.9669 ºW)	Pacific Shellfish Institute, Olympia, WA (contact: Andy Suhrbier)
Water temperature (Netarts Bay)	2006-2019	Garibaldi, OR (45.5545 ºN, 123.9189 ºW)	NANOOS, http://nvs.nanoos.org/Climatology Asset ID: NOS_9437540_site
Water temperature & salinity (Netarts Bay)	2014-2019	Netarts Bay, OR (45.3949 ºN, 123.9376 ºW)	Whiskey Creek Shellfish Hatchery, Netarts, OR (contact: Dr. Burke Hales)
Water temperature (Yaquina Bay)	1992-2019	South Beach, OR (44.6248 ºN, 124.0455 ºW)	NANOOS, http://nvs.nanoos.org/Climatology Asset ID: NOS_9435380_site
Water temperature & salinity (Yaquina Bay)	2009-2015	Yaquina Bay, OR (44.6252 ºN, 124.0452 ºW)	US EPA Pacific Coastal Ecology Branch, Newport, OR (contact: T. Chris Mochon Collura)

Water temperature (Coos Bay)	1993-2019	Charleston, OR (43.3450 ºN, 124.3220 ºW)	NANOOS, http://nvs.nanoos.org/Climatology Asset ID: NOS_9432780_site
Water temperature & salinity (Coos Bay)	2002-2019	Charleston, OR (43.3377 ºN, 124.3205 ºW)	NOAA, Office of Ocean and Coastal Resource Management, CDMO, Baruch Marine Field Lab, University of South Carolina: http://cdmo.baruch.sc.edu
Upwelling Index (Bakun)	2006-2010 & 2015-2019	0.5º radius of each estuary mouth: Willapa Bay (46.69 ºN, 124.08 ºW), Netarts Bay (45.44 ºN, 123.96 ºW), Coos Bay (45.44 ºN, 123.96 ºW), Yaquina Bay (44.62 ºN, 124.07 ºW)	Pacific Fisheries Environmental Laboratory (NOAA) https://coastwatch.pfeg.noaa.gov
Offshore & alongshore ocean currents	2007-2010 & 2015-2019	0.6 º radius of each estuary mouth: Willapa Bay (46.69 ºN, 124.08 ºW), Netarts Bay (45.44 ºN, 123.96 ºW), Coos Bay (45.44 ºN, 123.96 ºW), Yaquina Bay (44.62 ºN, 124.07 ºW)	CODAR dataset, M. Kosro, Oregon State University http://bragg.coas.oregonstate.edu
Land cover	2006 & 2010	Coos Bay, Yaquina Bay, & Willapa Bay watersheds	NOAA Coastal Change Analysis Program, https://coast.noaa.gov/ccapatlas
Land cover (Netarts Bay)	2011	Netarts Bay watershed	https://www.tbnep.org/reports-publications/netarts-bay-habitat-study-restoration-plan.pdf
Population density (by County)	2000 & 2011	Pacific County, WA, Tillamook County, OR, Lincoln County, OR, Coos County, OR	US Census Bureau, www.census.gov/quickfacts

Table S4. Average (standard error) of eelgrass abundance metrics (biomass, shoot density, and per shoot biomass), eelgrass epiphyte load, and macroalgae biomass in four US Pacific Northwest coast estuaries (Figure 1) for three periods: before (2006-2010), during (2015-2016), and after (2017-2019) the 2013-2016 northeast Pacific Ocean marine heat wave. Epiphyte load was not available across all estuaries and time periods for this study, but data are compiled from other sources (indicated by footnotes) for comparison. n/a = data not available.

Estuary	**Period**	**Eelgrass biomass** (g dry wt $0.25m^{-2}$)	**Eelgrass shoot density** (shoots $0.25m^{-2}$)	**Eelgrass per shoot biomass** (g dry wt $shoot^{-1}$)	**Epiphyte load** (g dry wt per g eelgrass)	**Macroalgae biomass** (g dry wt $0.25m^{-2}$)
Willapa Bay	Before	51.1 (1.35)	39.5 (1.05)	1.29 (0.06)	0.025 (0.044)[1] 0.03 (n/a)[2]	2.94 (0.58)
	During	31.5 (1.61)	40.2 (2.05)	1.01 (0.08)	0.008 (0.003)[3]	0.11 (0.06)
	After	20.9 (1.20)	26.8 (1.53)	0.66 (0.05)	0.04 (0.005)	3.39 (0.88)
Netarts Bay	Before	50.7 (1.76)	89.4 (3.19)	0.58 (0.04)	0.52 (n/a)[4]	1.18 (0.30)
	During	39.0 (1.61)	73.5 (1.86)	0.53 (0.02)	0.04 (0.01)[3]	0.62 (0.19)
	After	21.6 (0.90)	52.1 (2.18)	0.43 (0.04)	0.24 (0.03)	1.35 (0.64)
Yaquina Bay	Before	17.9 (0.96)	23.1 (1.16)	0.85 (0.06)	1.42 (n/a)[5]	42.3 (2.30)
	During	19.2 (1.28)	8.99 (1.28)	0.88 (0.04)	0.16 (0.02)[3]	13.9 (1.11)

	After	14.3 (1.13)	23.3 (1.83)	0.66 (0.04)	0.39 (0.04)	29.9 (2.68)
Coos Bay	Before	15.4 (0.98)	29.5 (1.76)	0.55 (0.03)	0.022 (0.015)[1]	37.4 (2.43)
	During	43.1 (2.40)	22.4 (3.60)	1.22 (0.05)	0.04 (0.01)[3]	7.57 (0.42)
	After	23.2 (1.38)	41.6 (2.48)	0.51 (0.03)	0.27 (0.03)	7.12 (0.76)

[1]July – August 1998-2001 (Thom et al. 2003)
[2]June 2012 (Ruesink 2016)
[3] Early August 2016 only (this study)
[4]April 1980 – May 1981 (Kentula 1982)
[5]August 2000 – November 2004 (Nelson 2018)

Table S5. Summary of the partial least squares regression (PLSR) analysis between the response block (Y), including two response variables, and the explanatory block (X), including 8 explanatory variables (see Appendix A: Tables S1 and S2 for variable abbreviations) for four US Pacific Northwest estuaries (Figure 1) from before the marine heat wave (2006-2010). Load indicates the sign of the relationship of each variable with Axis 1 and weight^2 indicates the proportion of Axis 1 explained by each explanatory variable. Variable importance (VIP) measures the explanatory power of each variable for the Y block. VIP > 1 are considered most important (indicated with asterisk and bold text). Cross-correlation is the coefficient for the correlation between each variable and the opposing block. Correlation is the coefficient for the correlation between each variable and its own block. n/a = metric not applicable to variable.

PLSR Compo-nent	**Variable**	**Load**	**Weight^2**	**VIP**	**Cross-Correlation**	**Correlation**
X	**Tidal Exchange Volume**	+	0.13	1.04*	0.53	0.93
	Freshwater Flow	–	0.19	1.22*	-0.62	-0.66
	Water Temperature	+	0.15	1.10*	0.56	0.91
	Offshore Current	–	0.28	1.50*	-0.77	-0.90
	Estuarine Heat Wave	+	0.00	0.12	0.06	0.10
	Salinity	–	0.10	0.91	-0.46	-0.78
	Upwelling Index	–	0.12	0.98	-0.50	-0.67
	Alongshore Current	–	0.02	0.42	-0.21	-0.74
Y	Eelgrass	+	*n/a*	*n/a*	0.69	0.97
	Macroalgae	–	*n/a*	*n/a*	-0.68	-0.97

Table S6. Summary of the partial least squares regression (PLSR) analysis between the response block (Y), including three response variables, and the explanatory block (X), including 8 explanatory variables (see Appendix A: Table S1 and Table S2 for variable abbreviations) for four US Pacific Northwest estuaries (Figure 1) from during and after the marine heat wave (2015-2019). Load indicates the sign of the relationship of each variable with Axis 1 and weight^2 indicates the proportion of Axis 1 explained by each explanatory variable. Variable importance (VIP) measures the explanatory power of each variable for the Y block. VIP > 1 are considered most important (indicated with asterisk and bold text). Cross-correlation is the coefficient for the correlation between each variable and the opposing block. Correlation is the coefficient for the correlation between each variable and its own block. n/a = metric not applicable to variable.

PLSR Compo-nent	**Variable**	**Load**	**Weight^2**	**VIP**	**Cross-Correlation**	**Correlation**
X	Tidal Exchange Volume	+	0.10	0.90	0.48	0.79
	Freshwater Flow	–	0.27	1.46*	-0.78	-0.83
	Water Temperature	+	0.24	1.38*	0.74	0.97
	Offshore Current	–	0.15	1.08*	-0.57	-0.83
	Estuarine Heat Wave	–	0.00	0.11	0.06	-0.29
	Salinity	–	0.09	0.87	-0.46	-0.73
	Upwelling Index	–	0.10	0.89	-0.47	-0.83
	Alongshore Current	+	0.06	0.66	0.35	0.08
Y	Eelgrass	+	*n/a*	*n/a*	0.25	0.68
	Macroalgae	–	*n/a*	*n/a*	-0.71	-0.87
	Epiphytes	–	*n/a*	*n/a*	-0.71	-0.86

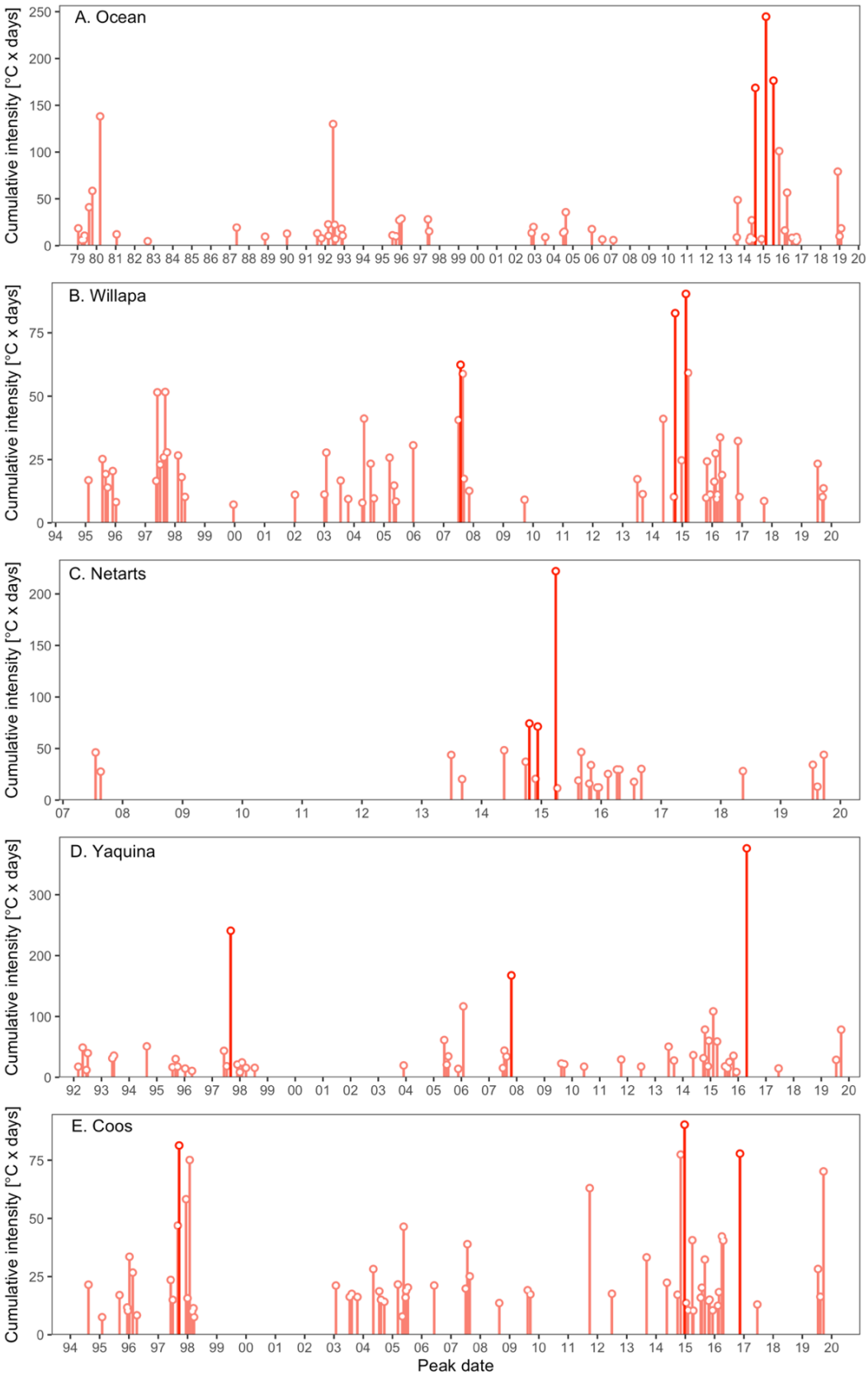
A. Ocean
B. Willapa
C. Netarts
D. Yaquina
E. Coos
Cumulative intensity [°C x days]
Peak date

Fig. S1 Cumulative intensity (°C x days) of detected heatwave events (centered on peak date) in the northeast Pacific Ocean (A) and four US Pacific Northwest estuaries (Figure 1): Willapa Bay, WA (B), Netarts Bay, OR (C), Yaquina Bay, OR (D), and Coos Bay, OR (E) during the full timeseries of the available water temperature data for each site. For clarity, the x and y axes differ among plots. The top three events (highest cumulative intensity) in each location are emphasized with a red line. Graphs were produced using definitions and functions contained in the 'heatwaveR' R package (Schlegel and Smit 2018).

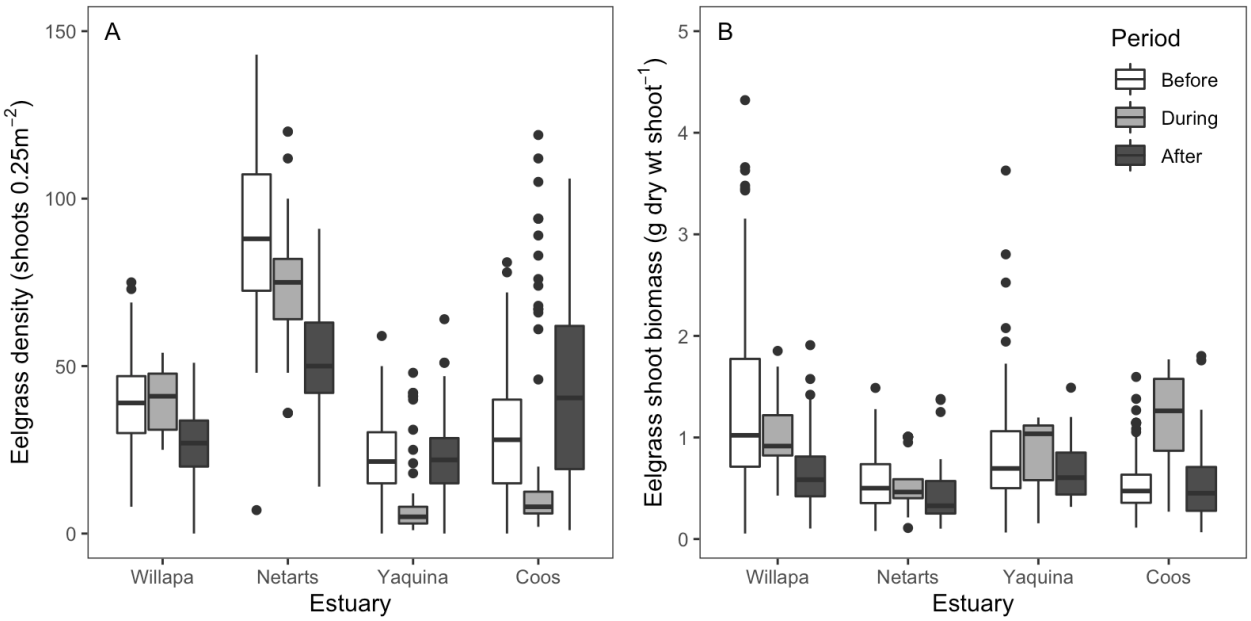

Fig. S2 Shoot density (shoots 0.25 m^{-2}) (A) and per shoot biomass (grams dry weight shoot^{-1}) (B) of eelgrass beds in four US Pacific Northwest estuaries (Figure 1) before (2006-2010, white fill), during (2015-2016, light gray fill), and after (2017-2019, dark gray fill) the NE Pacific Ocean marine heat wave (2013-2016). Boxes (with median centerline) encompass the interquartile range (25th-75th percentile) of the data for each estuary and period. Whiskers extend to the most extreme data point that is no more than 1.5 times the length of the box and values falling beyond that range are shown as points. For clarity, ANOVA comparisons are not shown but are discussed in text.

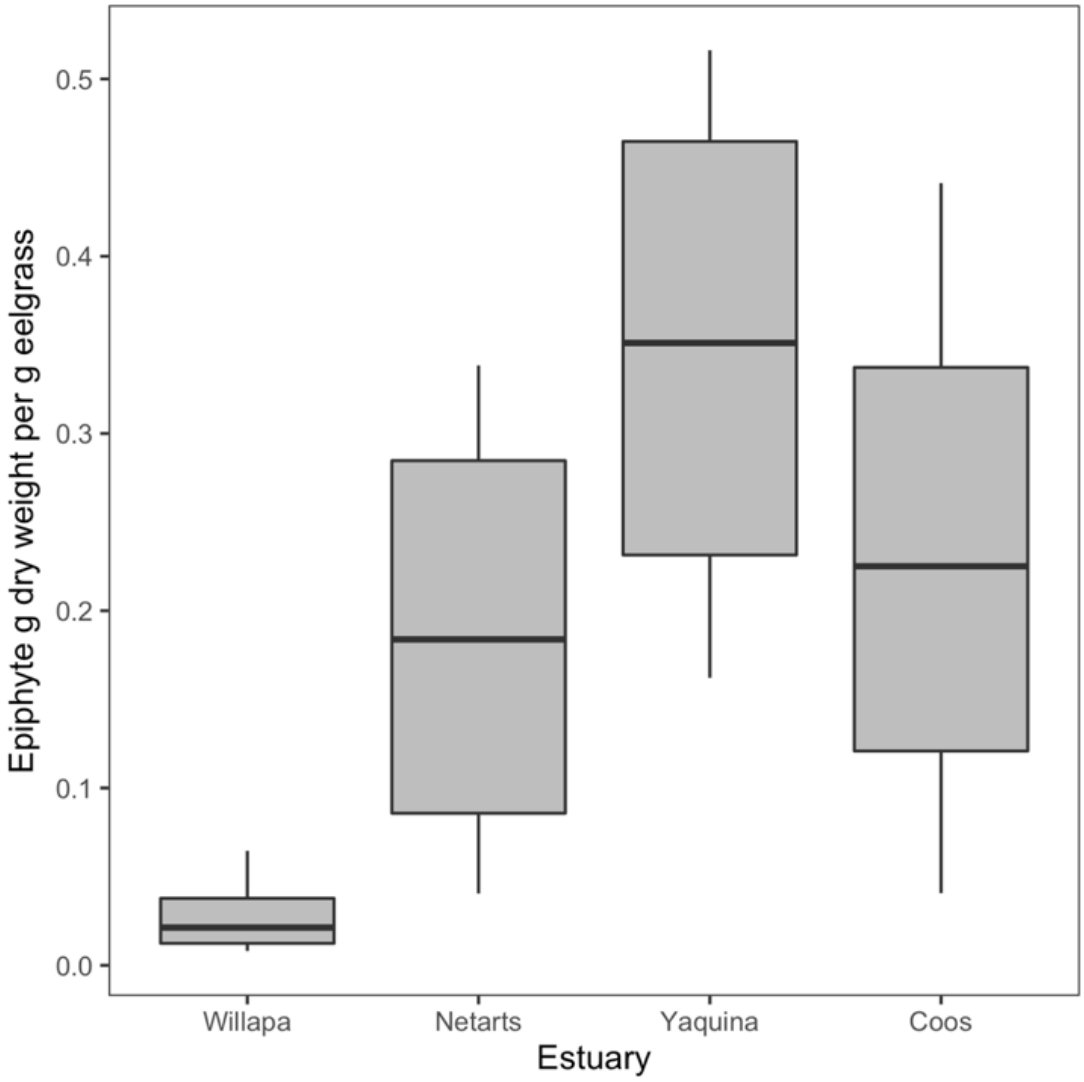

Fig. S3 Epiphyte load (g dry wt epiphyte per g dry wt eelgrass) across four US Pacific Northwest coast estuaries (Figure 1) between 2016-2019. Boxes (with median centerline) encompass the interquartile range (25th-75th percentile) of the data for each. Whiskers extend to the most extreme data point which is no more than 1.5 times the length of the box.

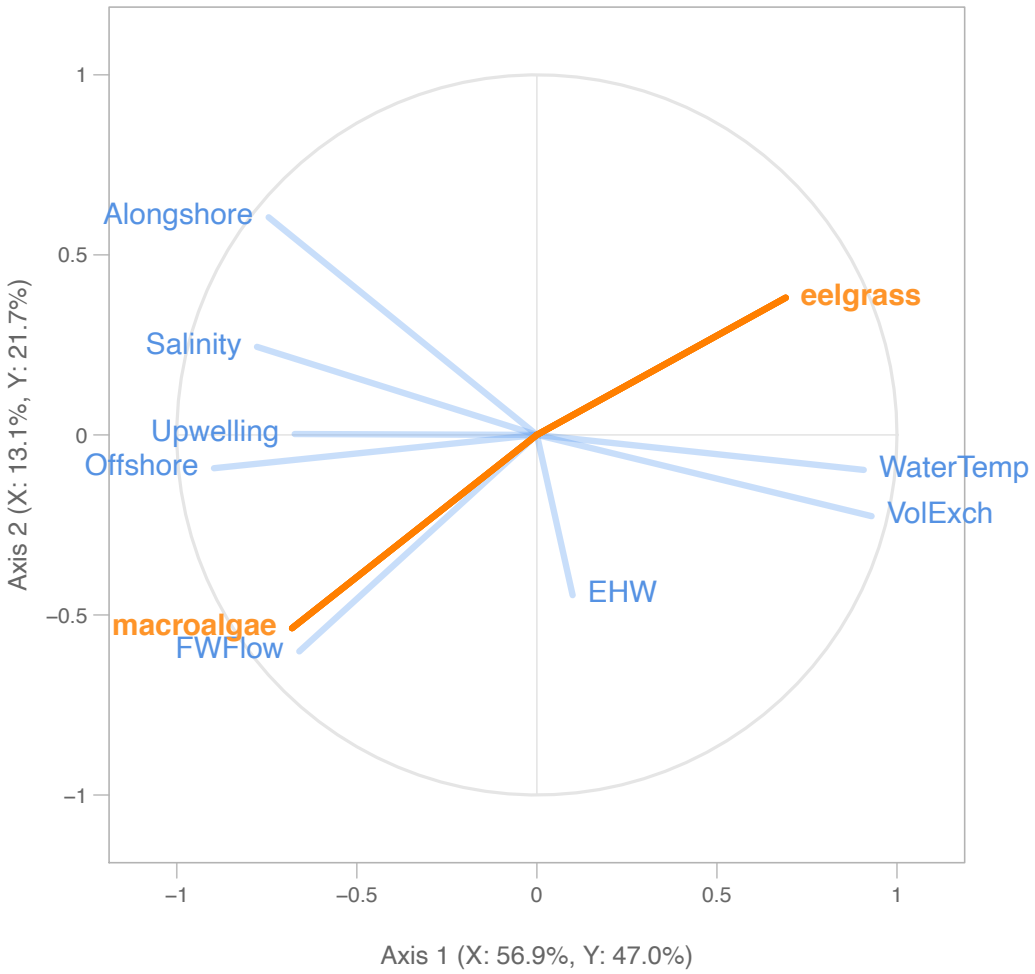

Fig. S4 Partial least squares correlation radar plot of 8 explanatory environmental variables (blue; see Appendix A: Table S1 and Table S2 for abbreviations) and response macrophyte variables (orange; Figures 2 and 3), including eelgrass biomass ("eelgrass") and ulvoid macroalgae biomass ("macroalgae"), in four US Pacific Northwest estuaries (Figure 1) before the marine heat wave (2006-2010). Eelgrass and macroalgae biomass were log-transformed for the analysis. Epiphyte load data was not available prior to 2016. Each segment represents a model variable. Longer segments (closer to the circle perimeter) indicate that the variable is better represented. Segments close together are highly and positively correlated variables. Segments in opposite directions are negatively correlated. Orthogonal segments indicate no correlation.

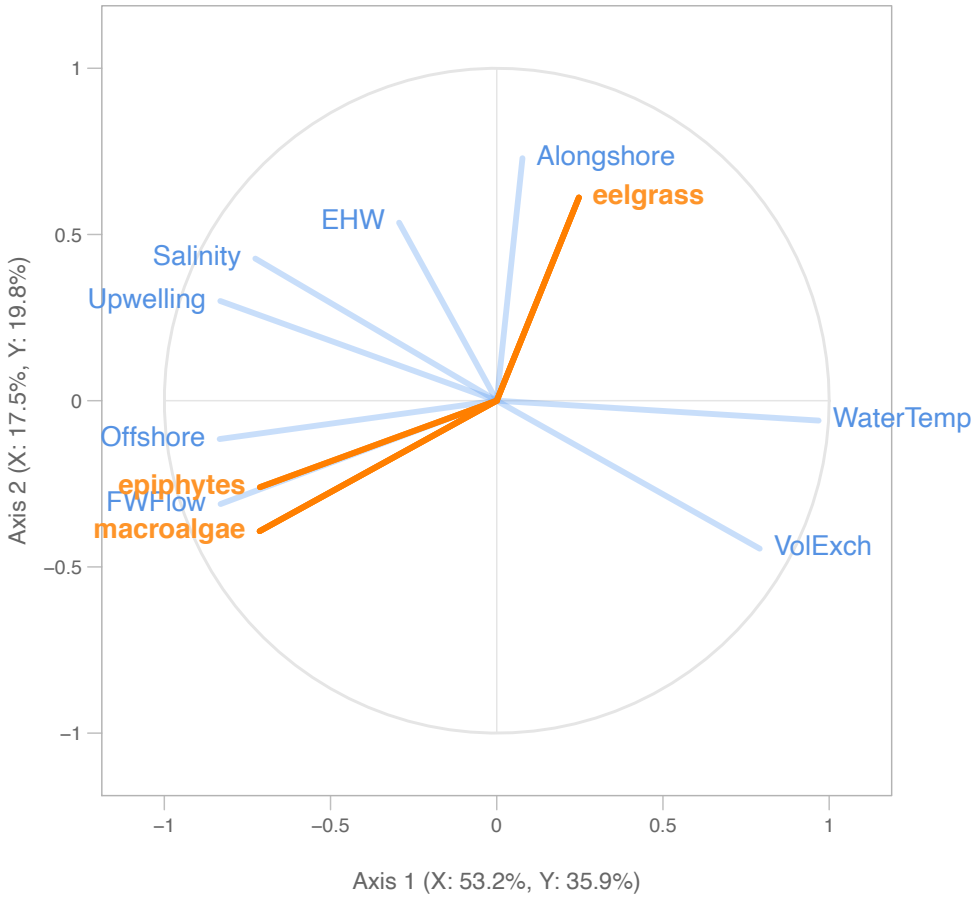

Fig. S5 Partial least squares correlation radar plot of 8 explanatory environmental variables (blue; see Appendix A: Table S1 and Table S2 for abbreviations) and response macrophyte variables (orange; Figures 2 and 3), including eelgrass biomass ("eelgrass"), ulvoid macroalgae biomass ("macroalgae"), and epiphyte load ("epiphytes"), in four US Pacific Northwest estuaries (Figure 1) during and after the marine heat wave (2015-2019). Eelgrass and macroalgae biomass were log-transformed for the analysis, epiphyte load was not transformed. Each segment represents a model variable. Longer segments (closer to the circle perimeter) indicate that the variable is better represented. Segments close together are highly and positively correlated variables. Segments in opposite directions are negatively correlated. Orthogonal segments indicate no correlation.

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