Appendix A

Model Description:

At each time step t of 1 day, biomass B_s increased through kelp production P_s and decreased through grazing by a sea urchin front U_s, erosion E_s, dislodgement D_s, and mortality M_s according to:

$$B_S(d, t+1) = B_S(d,t) + P_S(d,t) - U_S(d,t) - E_S(d,t) - D_S(d,t) - M_S(d,t) \quad \text{(A.1)}$$

Parameter abbreviations are given in Table B1.

Model Parameters

A Ricker population growth model (Turchin, 2003) was used to model kelp production P_s (kg y^{-1} in the model domain) of each kelp species s:

$$P_S(d,t) = r_M B_S(d,t)\left(1 - \frac{B_S(d,t)}{Kp_s(d)}\right) \quad \text{(A.2)}$$

where r_M is the *M. membranacea*-mediated rate of kelp production (kg kg^{-1} of kelp d^{-1}), K is total kelp carrying capacity for kelp (12.161 kg m^{-2}), and $p_s(d)$ is the proportion of species s at depth d. The effect of encrustation by *M. membranacea* on kelp production was modeled using a simple linear regression based on field data from Krumhansl & Scheibling (2011). Average biomass (fresh weight) of kelp at Splitnose Point is 9.1 kg m^{-2} (Krumhansl & Scheibling, 2011), which is assumed to represent 75% of carrying capacity. The biomass ratio of *S. latissima* and *L. digitata* changes with depth from 25:75 at 6 m to 55:45 at 11 m (Lauzon-Guay & Scheibling, 2007; Krumhansl & Scheibling, 2011). A linear fit to these data was used to model the proportion of species s at depth d.

Blade erosion of each kelp species E_s (kg y^{-1} in the model domain) was modeled as:

$$E_S(d,t) = \left(\varepsilon_{S0} + \varepsilon_{S1} w_d(d,t) + \varepsilon_{S2} L_S(d,t) + \varepsilon_{S3} m_S(d,t) + \varepsilon_{S4} T(t)\right) \times \frac{B_S(d,t)}{\varepsilon_{S5}} \quad \text{(A.3)}$$

where w_d is significant wave height (m) at depth d (m), L_s is the percentage of the distal third of the blade of kelp species s that is grazed by *L. vincta*, m_s is the percentage of total blade area covered by *M. membranacea, T* is temperature (°C), and ε_{S5} is the average mass of a kelp thallus (0.207 kg and 0.354 for *S. latissima* and *L. digitata* respectively, Krumhansl & Scheibling 2011a), which was used to convert per thallus measurements to per unit area (1 m^2). All parameter coefficient values ε were estimated using field data from Krumhansl & Scheibling (2011). Second-order bias corrected Akaike's Information Criteria (AICc), the values of the maximized log-likelihood function, model probabilities, and R^2 values were used to select the model that best predicted kelp erosion rate (kg d^{-1}) using percentage of blade area covered by *M. membranacea*, percentage of the distal third of the blade area grazed by *L. vincta*, temperature (°C), and significant wave height (m) for each kelp species (Krumhansl & Scheibling, 2011). Multiple linear regression was used to determine the coefficient ε and standard error for each parameter selected for the models, and the model intercept ε_0^S, for each kelp species (Table C1).

Dislodgment during storms of each kelp species D_s (kg y^{-1} in the model domain) was modelled as:

$$D_s(d,t) = \begin{cases} 0 & \text{if} \quad w_l(d,t) < \delta_s \\ \max\left(0, 0.05(w_l(d,t) - \delta_s + 1) B_s(d,t) - \sum_{\tau=t-7}^{t} D_s(d,\tau)\right) & \text{if} \quad w_l(d,t) \geq \delta_s \end{cases} \quad \text{(A.4)}$$

where w_l is wave height (m) measured as the mean of the highest 1/3 of significant wave heights, δ_s is the threshold w_l required for dislodgement to occur (4 and 5 m for *S. latissima* and

L. digitata respectively). Each 1 m increase in w_l over the threshold value resulted in an additional loss of 5% of kelp biomass. Any dislodgment that occurred over the previous 7-day period ($\sum_{\tau=t-7}^{t} D_S\,(d,t)$) was then subtracted from this quantity to yield an estimate of dislodgment that is the result of a wave event rather than the sum of dislodgment across multiple consecutive wave measurements over threshold values. Negative dislodgment values were not possible in the event that dislodgment at time *t* was less than that which occurred over the previous 7-day period.

Mortality of each kelp species M_s (kg y^{-1} in the model domain) was modeled as:

$$M_S(d,t) = \mu_S B_S(d,t) \tag{A.5}$$

where μ is daily mortality rate (0.14%) calculated from Chapman (1993).

The wave-adjusted individual grazing rate of sea urchins g_w (kg kelp urchin^{-1} d^{-1}) was modeled as:

$$g_w\, w_d = g\,\frac{1}{1+e^{-9.133+9.3141 w_d(d,t)}} \tag{A.6}$$

where *g* is individual grazing rate. The total amount of kelp consumed during one time step was obtained by multiplying the density of sea urchins *u* by g_w. Sea urchins consumed both kelp species according to their proportional abundances. Therefore, the biomass of each kelp species consumed by sea urchins U_s (kg y^{-1} in the model domain) is:

$$U_S(d,t) = u(d,t)\,g_w\left(\frac{B_S(d,t)}{B_T(d,t)}\right) \tag{A.7}$$

where B_T it the total kelp biomass (sum of both species).

In all simulations with sea urchins, the initial sea urchin population was located at the lower depth limit of the model. Urchins remained in that cell until kelp biomass within that cell reached 0, at which point sea urchins moved to the adjacent shallower cell. This is a simplistic representation of the behavior of an urchin front as it travels through a kelp bed, and does not include any demographic information on sea urchins comprising the front. For a more detailed model of sea urchin front dynamics and attendant transition from kelp bed to barrens, see Lauzon-Guay *et al.* (2008; 2009) and Lauzon-Guay & Scheibling (2010).

Wave Attenuation Function

The effect of waves diminishes with depth and we used a wave attenuation function to predict the impact of wave height at all depths (Holthuijsen, 2007). Wave-generated vertical v_d and horizontal h_d water velocity were calculated as:

$$v_d = \frac{\sin H\,(k(d+z))}{\sin H\,kd} \quad \text{(A.8)}$$

and

$$h_d = \frac{\cos H\,(k(d+z))}{\sin H\,kd} \quad \text{(A.9)}$$

where *k* is the wave number ($k = 2\pi/\lambda$) using an average wavelength λ of 13.9 m over the study period, *H* is wave height, and *z* is depth at which velocity is predicted (in this case it was assumed to be 1 m above bottom). We then calculated the combined velocity as $\sqrt{(h_d^2 + v_d^2}$ for each depth and calculated a coefficient of attenuation relative to 6 m by dividing the combined velocity at all depths by the expected velocity at 6 m = $\sqrt{(h_6^2 + v_6^2}$. This depth-specific coefficient of attenuation was applied to all significant wave heights in the model to obtain w_d.

$$w_d(d,t) = w(t)\frac{\sqrt{(h_d^2+v_d^2}}{\sqrt{(h_6^2+v_6^2}}$$

Initial Kelp Bed Conditions

Initial kelp bed conditions used in all simulations were obtained by running the model for 5 years at a time using environmental data (significant wave height and temperature) for each year over a 34-year period from 1976 to 2009. Each simulation started with a biomass of 0.910 kg m^{-2} from 3 to 14 m depth and a ratio of *S. latissima* to *L. digitata* varying with depth as described above. Biomass of *S. latissima* and *L. digitata* at each depth at the end of the 34 simulations were averaged and these averaged values were used for all remaining simulations.

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