

Supplement to

Kelp decomposition hinges on physiology

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Figures

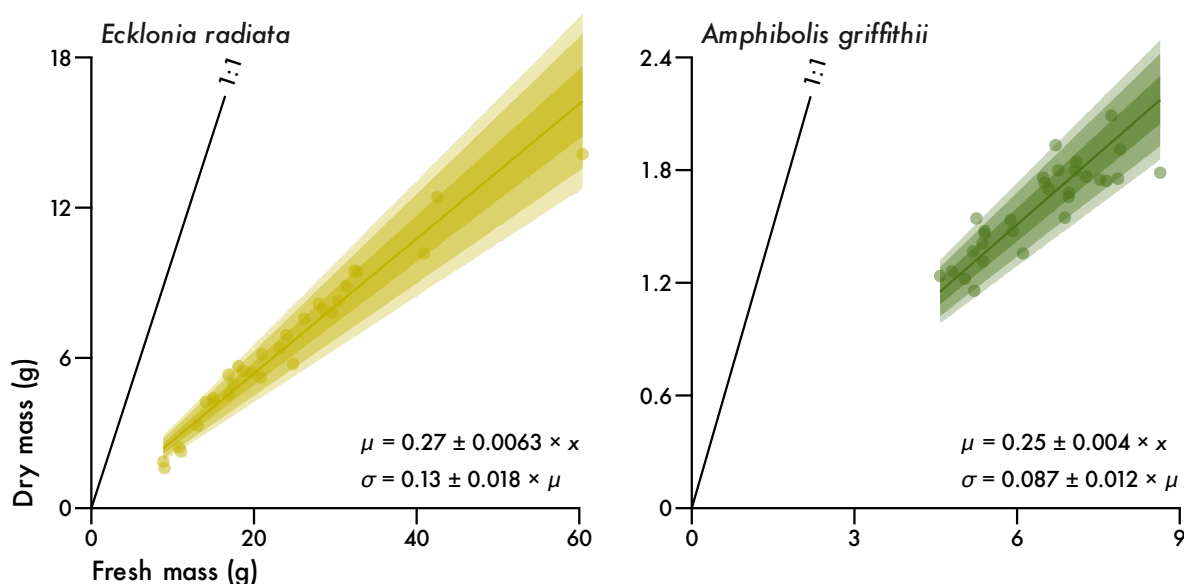


Figure S1. Mass relationship for kelp (*Ecklonia radiata*) and seagrass (*Amphibolis griffithii*). Each data point is a tissue sample measured before and after lyophilisation (n = 30 for each species). Lines and ribbons are the mean and 50%, 80% and 90% posterior probability intervals for predicted observations of dry mass (m_d in Equation 1). The functions describing the likelihood mean and standard deviation (μ and σ , Equation 1) are given in each panel. The slope is equivalent to the dry-fresh mass ratio.

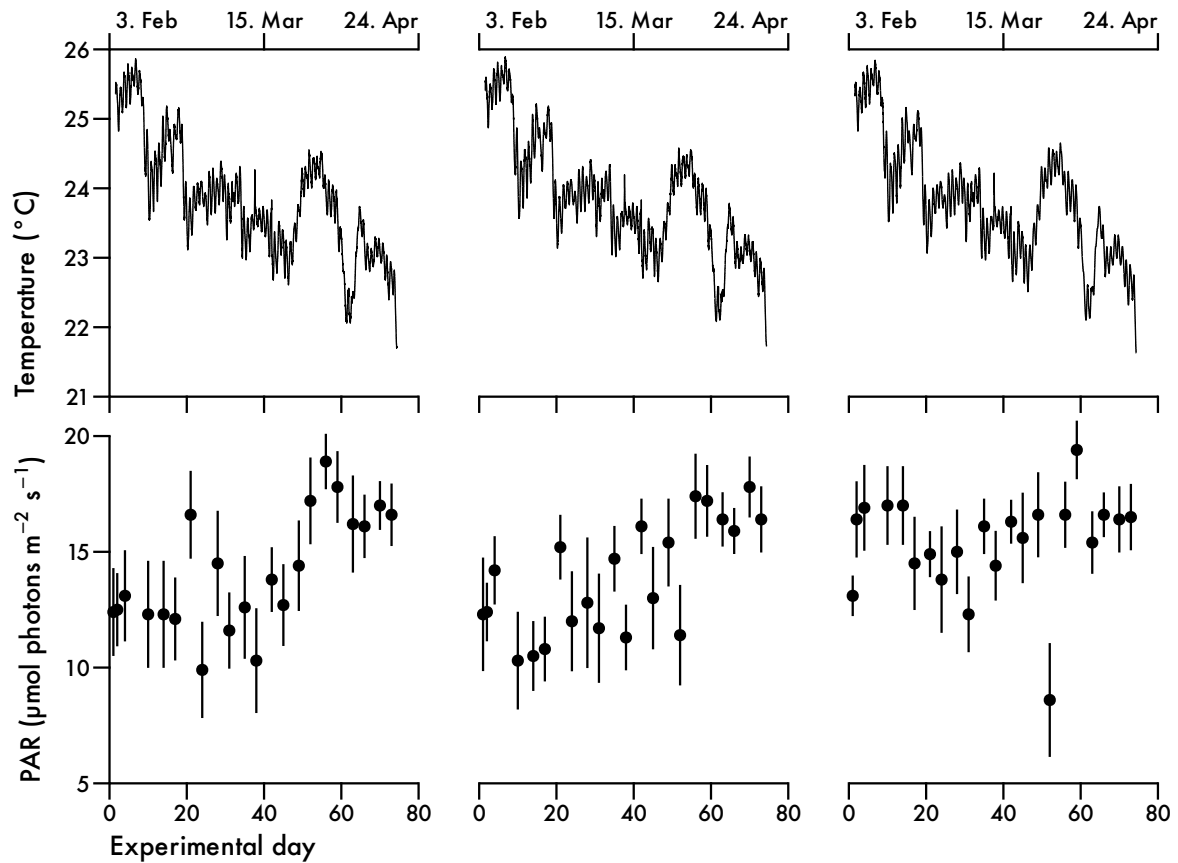


Figure S2. Temperature and photosynthetically active radiation (PAR) over the duration of the experiment on *Ecklonia radiata* and *Amphibolis griffithii*. The experiment was conducted in austral summer and autumn, starting on 3rd February and ending after 73 days on 17th April 2025. Each panel is an experimental tank. Temperature was measured every 5 minutes ($n = 20972$ per tank) and is therefore shown as a continuous trendline. Points and error bars for PAR are means \pm standard deviations ($n = 10$) for a single timepoint, i.e. error bars represent only spatial variation.

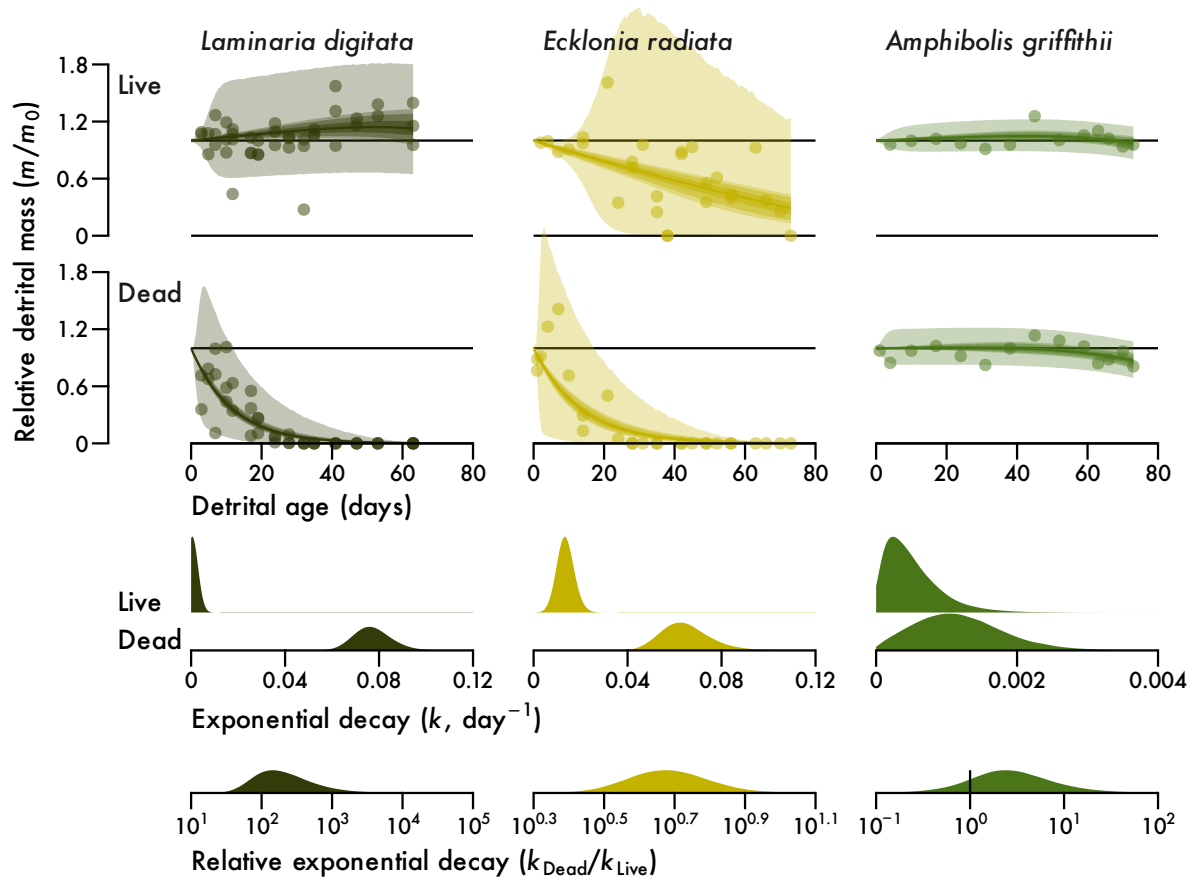


Figure S3. Decomposition of kelp (*Laminaria digitata* and *Ecklonia radiata*) is determined by physiology, unlike decomposition of seagrass (*Amphibolis griffithii*). Detrital mass is given as fresh mass (cf. Figure 2). Each data point is a destructively sampled litterbag ($n = 86$ for *L. digitata*, $n = 54$ for *E. radiata*, $n = 27$ for *A. griffithii*). Lines and ribbons are the median and 50%, 80% and 90% posterior probability intervals for the likelihood mean or expected value of the optimal model (μ_m in Equation 2). The widest ribbon in the 90% probability interval for predicted observations (m in Equation 2). Distributions are posterior probabilities for the naïve exponential decay constant (k in Equation 3) and their ratios (ratio = 1 means estimates are the same). Summary statistics for these distributions are given in Table S3.

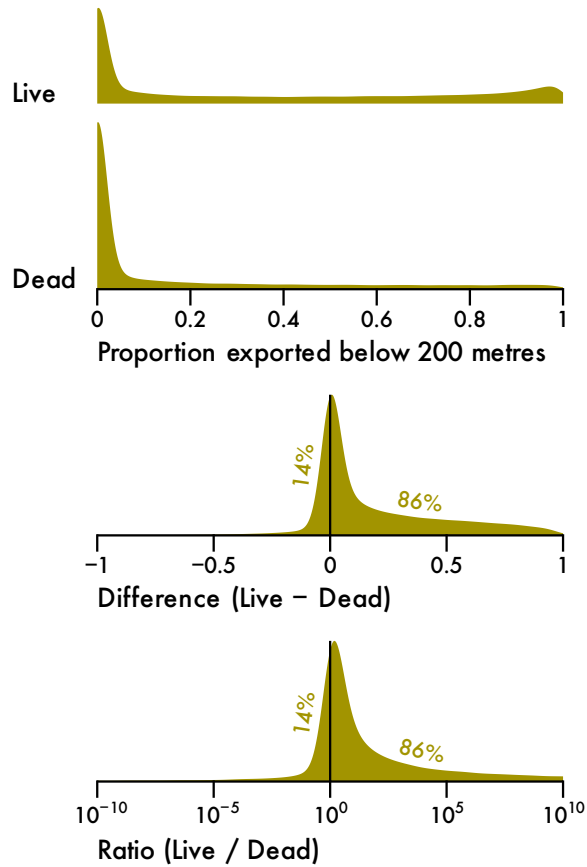


Figure S4. Detrital physiology affects estimates of kelp CO_2 removal. The proportion of carbon exported below 200 metres depth, which is frequently assumed to be sequestered by retention in deep ocean currents, is calculated as Ee^{-kt} where E is export relative to production, k is the kelp exponential decay constant (day^{-1}) derived from the meta-analysis (Figure 3, Table S2, S3) and t is the coastal residence time (days). Since E is beta-distributed and k and t are log-normally distributed, the resulting distribution is a proportion bounded by 0 and 1. Large uncertainty therefore leads to a concentration of probability density near the bounds, as can be seen in the top panel. Distributions for the difference and ratio display probabilities as percentages either side of difference = 0 or ratio = 1.

Tables

Table S1. Kelp and terrestrial forest turnover and predicted decomposition (cf. Figure 1) expressed as exponential decay (k) and half-life ($\ln 2 / k$). Data were analysed on the logarithmic scale but are more understandable on the linear scale. Hence all estimates are given as median (\log_{10} mean \pm standard deviation).

	Turnover (year^{-1})	k (day^{-1})	Half-life (days)
Terrestrial forests	0.16 (-0.8 ± 0.59)	0.0033 (-2.5 ± 1.3)	210 (2.4 ± 1.3)
Kelp forests	2.7 (0.43 ± 0.38)	0.015 (-1.8 ± 1.1)	46 (1.6 ± 1.1)
<i>Agarum clathratum</i>	1.5 (0.16 ± 0.34)	0.011 (-2 ± 1)	64 (1.8 ± 1)
<i>Durvillaea antarctica</i>	2.3 (0.37 ± 0.35)	0.014 (-1.8 ± 1)	49 (1.7 ± 1)
<i>Ecklonia cava</i>	2.4 (0.37 ± 0.35)	0.014 (-1.8 ± 1)	49 (1.7 ± 1)
<i>Ecklonia cava</i> subsp. <i>kurome</i>	2.7 (0.44 ± 0.36)	0.015 (-1.8 ± 1.1)	45 (1.6 ± 1.1)
<i>Ecklonia maxima</i>	3.5 (0.55 ± 0.35)	0.018 (-1.7 ± 1.1)	39 (1.6 ± 1.1)
<i>Ecklonia radiata</i>	2.2 (0.34 ± 0.33)	0.013 (-1.9 ± 1)	52 (1.7 ± 1)
<i>Eisenia arborea</i>	3.1 (0.49 ± 0.36)	0.016 (-1.8 ± 1.1)	43 (1.6 ± 1.1)
<i>Eisenia bicyclis</i>	2.4 (0.38 ± 0.36)	0.014 (-1.8 ± 1)	49 (1.7 ± 1)
<i>Hedophyllum nigripes</i>	3.5 (0.54 ± 0.35)	0.017 (-1.7 ± 1.1)	40 (1.6 ± 1.1)
<i>Hedophyllum sessile</i>	2.2 (0.35 ± 0.35)	0.013 (-1.9 ± 1)	52 (1.7 ± 1)
<i>Himantothallus grandifolius</i>	2.6 (0.42 ± 0.36)	0.015 (-1.8 ± 1.1)	47 (1.7 ± 1.1)
<i>Laminaria digitata</i>	2.1 (0.33 ± 0.33)	0.013 (-1.9 ± 1)	52 (1.7 ± 1)
<i>Laminaria hyperborea</i>	1.4 (0.15 ± 0.33)	0.011 (-2 ± 1)	65 (1.8 ± 1)
<i>Laminaria ochroleuca</i>	2.6 (0.41 ± 0.34)	0.015 (-1.8 ± 1)	47 (1.7 ± 1)
<i>Laminaria pallida</i>	3 (0.47 ± 0.35)	0.016 (-1.8 ± 1.1)	43 (1.6 ± 1.1)
<i>Laminaria setchellii</i>	1.4 (0.15 ± 0.36)	0.011 (-2 ± 1)	65 (1.8 ± 1)
<i>Laminaria solidungula</i>	1.3 (0.12 ± 0.35)	0.01 (-2 ± 1)	68 (1.8 ± 1)
<i>Lessonia corrugata</i>	2.6 (0.42 ± 0.36)	0.015 (-1.8 ± 1.1)	47 (1.7 ± 1.1)
<i>Lessonia nigrescens</i>	4.1 (0.61 ± 0.35)	0.019 (-1.7 ± 1.1)	37 (1.5 ± 1.1)
<i>Lessonia trabeculata</i>	1.8 (0.26 ± 0.34)	0.012 (-1.9 ± 1)	56 (1.7 ± 1)
<i>Lessoniopsis litoralis</i>	3.2 (0.51 ± 0.36)	0.017 (-1.8 ± 1.1)	42 (1.6 ± 1.1)
<i>Macrocystis laevis</i>	3.4 (0.54 ± 0.36)	0.017 (-1.7 ± 1.1)	40 (1.6 ± 1.1)
<i>Macrocystis pyrifera</i>	5.5 (0.74 ± 0.33)	0.023 (-1.6 ± 1.1)	31 (1.5 ± 1.1)
<i>Neoagarum fimbriatum</i>	3.8 (0.57 ± 0.35)	0.018 (-1.7 ± 1.1)	38 (1.6 ± 1.1)
<i>Nereocystis luetkeana</i>	2.9 (0.47 ± 0.34)	0.016 (-1.8 ± 1.1)	43 (1.6 ± 1.1)
<i>Phyllariopsis purpurascens</i>	3.6 (0.55 ± 0.36)	0.018 (-1.7 ± 1.1)	39 (1.6 ± 1.1)
<i>Pleurophycus gardneri</i>	2.4 (0.38 ± 0.35)	0.014 (-1.8 ± 1)	48 (1.7 ± 1)
<i>Postelsia palmiformis</i>	3.5 (0.54 ± 0.35)	0.017 (-1.7 ± 1.1)	40 (1.6 ± 1.1)
<i>Pterygophora californica</i>	3.1 (0.5 ± 0.36)	0.017 (-1.8 ± 1.1)	42 (1.6 ± 1.1)
<i>Saccharina angustata</i>	3.2 (0.5 ± 0.36)	0.017 (-1.8 ± 1.1)	42 (1.6 ± 1.1)
<i>Saccharina latissima</i>	2.5 (0.4 ± 0.33)	0.015 (-1.8 ± 1)	48 (1.7 ± 1)
<i>Saccorhiza polyschides</i>	3.3 (0.53 ± 0.34)	0.017 (-1.7 ± 1.1)	41 (1.6 ± 1.1)
<i>Undaria pinnatifida</i>	3.3 (0.52 ± 0.36)	0.017 (-1.7 ± 1.1)	40 (1.6 ± 1.1)

Table S2. Parameter estimates (mean \pm standard deviation, Equations 2 and 3) for all decomposition models. Note that the exponential rates k , α and τ are given as % day⁻¹ for readability and are not to be confused with linear rates. For highly right-skewed meta-analysis estimates, medians are additionally given in parentheses.

	Naïve model	Optimal model		
	k (% day ⁻¹)	α (% day ⁻¹)	μ (days)	τ (% day ⁻¹)
<i>Laminaria digitata</i>				
Fresh mass				
Live	0.052 \pm 0.042	0.38 \pm 0.17	96 \pm 45	2.5 \pm 0.92
Dead	7.7 \pm 0.78	-8.6 \pm 0.92	88 \pm 41	11 \pm 1.2
<i>Ecklonia radiata</i>				
Dry mass				
Live	1.8 \pm 0.29	-1.9 \pm 0.58	80 \pm 49	4.5 \pm 1
Dead	11 \pm 1.5	-8.8 \pm 1.4	103 \pm 62	11 \pm 1.6
Fresh mass				
Live	1.4 \pm 0.29	-1.2 \pm 0.31	71 \pm 32	4 \pm 0.99
Dead	6.5 \pm 1.1	-7.5 \pm 1.1	92 \pm 43	10 \pm 1.4
Kelp meta-analysis				
Live	13 \pm 108 (2)	-2.6 \pm 5.3	139 \pm 258 (74)	8 \pm 4.7
Dead	24 \pm 33 (17)	-9.8 \pm 6.4	93 \pm 58 (82)	14 \pm 6.1
<i>Amphibolis griffithii</i>				
Dry mass				
Live	0.98 \pm 0.082	-0.86 \pm 0.094	119 \pm 65	3.5 \pm 0.93
Dead	1.5 \pm 0.14	-1.3 \pm 0.11	130 \pm 78	3.8 \pm 0.9
Fresh mass				
Live	0.051 \pm 0.039	0.18 \pm 0.093	101 \pm 45	2.6 \pm 0.85
Dead	0.12 \pm 0.063	0.075 \pm 0.11	93 \pm 38	2.8 \pm 0.88

Table S3. The effect of physiology on exponential decay constants (k in Equation 3, % day⁻¹) for kelp and seagrass, estimated on the basis of fresh mass. Note that k is given as % day⁻¹ for readability and not to be confused with a linear rate. Corresponding probability distributions are given in Figure S3. Δ = Dead - Live, ratio = Dead / Live and $P = P(\Delta > 0) = P(\log_{10} \text{ratio} > 0) = P(\text{Dead} > \text{Live})$. All estimates are given as mean \pm standard deviation.

	Live	Dead	Δ	log₁₀ ratio	P
Kelp					
<i>Laminaria digitata</i>	0.052 \pm 0.042	7.7 \pm 0.78	7.7 \pm 0.78	2.3 \pm 0.42	1
<i>Ecklonia radiata</i>	1.4 \pm 0.29	6.5 \pm 1.1	5.1 \pm 1.1	0.68 \pm 0.12	1
Seagrass					
<i>Amphibolis griffithii</i>	0.051 \pm 0.039	0.12 \pm 0.063	0.068 \pm 0.072	0.43 \pm 0.48	0.84

Table S4. Species-specific parameter estimates (mean \pm standard deviation, Equations 2 and 3) for new experiments from the kelp meta-analysis. Note that the exponential rates k , α and τ are given as % day⁻¹ for readability and are not to be confused with linear rates. For highly right-skewed meta-analysis estimates, medians are additionally given in parentheses.

	Naïve model	Optimal model		
	k (% day ⁻¹)	α (% day ⁻¹)	μ (days)	τ (% day ⁻¹)
<i>Alaria esculenta</i>				
Live	10 \pm 41 (2.6)	-5.3 \pm 4.1	182 \pm 321 (98)	9.4 \pm 4.3
<i>Costaria costata</i>				
Live	35 \pm 280 (7.8)	-7.9 \pm 4.4	170 \pm 297 (93)	12 \pm 4.7
<i>Ecklonia radiata</i>				
Live	9.3 \pm 27 (3.2)	-5.9 \pm 3.5	197 \pm 363 (112)	10 \pm 3.8
Dead	22 \pm 23 (17)	-8.8 \pm 3.8	106 \pm 67 (92)	12 \pm 4
<i>Himantothallus grandifolius</i>				
Live	1.7 \pm 7.3 (0.49)	-0.006 \pm 2	174 \pm 328 (96)	5.2 \pm 2.6
<i>Laminaria digitata</i>				
Live	1.4 \pm 3.7 (0.5)	-0.061 \pm 1.9	123 \pm 194 (75)	5.6 \pm 2.3
Dead	18 \pm 21 (13)	-8.1 \pm 3.7	100 \pm 63 (88)	12 \pm 3.8
<i>Laminaria hyperborea</i>				
Live	1 \pm 2.6 (0.4)	-0.39 \pm 1.5	311 \pm 502 (181)	4.7 \pm 2
<i>Laminaria ochroleuca</i>				
Live	2 \pm 5.2 (0.72)	0.29 \pm 2.2	74 \pm 126 (42)	6.5 \pm 2.4
<i>Laminaria solidungula</i>				
Live	8.6 \pm 39 (2.2)	-1.9 \pm 3.2	141 \pm 267 (74)	6.9 \pm 3.3
<i>Macrocystis pyrifera</i>				
Live	1.8 \pm 4.4 (0.68)	0.68 \pm 3.3	99 \pm 161 (59)	9.9 \pm 3.8
<i>Neoagarum fimbriatum</i>				
Live	3.2 \pm 11 (0.85)	-0.28 \pm 2.5	149 \pm 301 (80)	5.8 \pm 2.8
<i>Nereocystis luetkeana</i>				
Live	8 \pm 23 (2.8)	-2.6 \pm 2.9	89 \pm 176 (39)	7.4 \pm 3
Dead	28 \pm 29 (22)	-13 \pm 6.2	93 \pm 58 (82)	16 \pm 6.3
<i>Saccharina latissima</i>				
Live	1.9 \pm 4.4 (0.71)	-0.57 \pm 1.7	142 \pm 226 (88)	5.4 \pm 2.1
Dead	27 \pm 30 (20)	-11 \pm 5.3	92 \pm 59 (81)	15 \pm 5.4
<i>Saccorhiza polyschides</i>				
Live	9.7 \pm 39 (2.9)	-4.8 \pm 3.4	195 \pm 352 (101)	8.8 \pm 3.7
<i>Undaria pinnatifida</i>				
Live	9.8 \pm 38 (3)	-4.3 \pm 3.9	98 \pm 177 (51)	9.4 \pm 3.9

Table S5. The effect of physiology on interspecific and experimental variation in kelp decomposition, expressed as the standard deviation (σ) of meta-analysis parameters (Equations 2 and 3). Corresponding probability distributions for $\sigma_{\ln k}$ are given in Figure 3. Δ = Live – Dead, ratio = Live / Dead and $P = P(\Delta > 0) = P(\log_{10} \text{ratio} > 0) = P(\text{Live} > \text{Dead})$. All estimates are given as mean \pm standard deviation.

	Live	Dead	Δ	$\log_{10} \text{ratio}$	P
Naïve model					
$\sigma_{\ln k}$					
Interspecific	1.1 \pm 0.27	0.4 \pm 0.28	0.7 \pm 0.39	0.58 \pm 0.46	0.96
Experimental	1.4 \pm 0.11	0.59 \pm 0.21	0.77 \pm 0.24	0.39 \pm 0.16	1
Optimal model					
σ_a					
Interspecific	0.039 \pm 0.012	0.036 \pm 0.026	0.0032 \pm 0.029	0.14 \pm 0.37	0.62
Experimental	0.023 \pm 0.0046	0.024 \pm 0.022	-0.0011 \pm 0.022	0.14 \pm 0.41	0.6
$\sigma_{\ln \mu}$					
Interspecific	0.58 \pm 0.24	0.25 \pm 0.19	0.32 \pm 0.31	0.47 \pm 0.56	0.85
Experimental	0.84 \pm 0.19	0.23 \pm 0.18	0.61 \pm 0.26	0.72 \pm 0.49	0.98
$\sigma_{\ln \tau}$					
Interspecific	0.38 \pm 0.11	0.22 \pm 0.15	0.15 \pm 0.19	0.36 \pm 0.47	0.8
Experimental	0.31 \pm 0.078	0.15 \pm 0.13	0.16 \pm 0.15	0.54 \pm 0.56	0.86