Supplementary Material

Table S1: Sampling information and storage information. Depth is below mean low water spring tide. n = 6.

Season	Blade depth (m)	Coordinates	Holdfast depth (m)	Storage period (days)	Sampling time
Spring	2	N 54°11'31", E 007°52'42"	2.5-2.7	3	03.05.21 11:25
	4	N 54°11.573', E 007°52.709'	4.7-5.3	-	15.04.21 18:10
	6	N 54°11'49", E 007°51'27"	7	-	26.04.21 18:12
Summer	2	N 54°11'31", E 007°52'40"	3.3-4.5	4	01.07.21 15:45
	4	N 54°11.573', E 007°52.709'	5.0-5.5	-	05.08.21 8:30
	6	N 54°11'49'', E 007°51'25''	7.5-6.0	2	20.07.21 13:09
Autumn	2	N 54°11'31", E 007°52'43"	4-4.9	3	18.10.21 9:30
	4	N 54°11.573', E 007°52.709'	5-6	2	28.09.21 15:00
	6	N 54°11'49'', E 007°51'27''	8	3	08.10.21 12:24
Winter	2	N 54°11'528, E 007°52'498	4	4	03.02.22 12:06
	4	N 54°11.573, E 007°52.709	6	2	25.01.22 14:35
	6	N 54°10'13.0'', E 007°53'28.2''	7.5-8	1	16.02.22 12:44

Table S2: Experimental set-up. Light:Dark (L:D) photoperiod, mean photosynthetically active radiation (PAR) and temperature treatments that were applied during the three days of incubation. Acclimation to the short-term warming treatment (+ 4°C) from *in situ* temperatures was achieved with 2°C increments starting from the *in situ* temperature over 2 days. The *in situ* temperature was averaged between 2016 and 2020. The seasonal data were provided by the CTD2 Underwater Node Helgoland, which is located next to the sampling area, but below 10 m (MLWS), and all data are archived in PANGAEA (Data Publisher for Earth & Environmental Science; Fischer et al. 2021a,b,c,d, 2022). Mean PAR was adjusted along the respective depth (2, 4, 6 m below mean low water spring tide) and season (spring, summer, autumn, winter). PAR was calculated based on incident irradiance measurements at Helgoland between 2014 and 2017 performed by the Helmholtz-Zentrum Hereon (https://codm.hzg.de/codm/). Irradiance available at the holdfast depths was estimated by applying the Beer-Lambert Law.

	Depth (m)	Spring	Summer	Autumn	Winter
L:D Photoperiod (h)		14:10	16:8	10.5:13.5	8.5:15.5
PAR (µmol photons m^{-2} s^{-1})	2	233	290	114	62
	4	86	114	37	18
	6	50	62	19	8
In situ (°C)		7	16	14	6
+ 4°C (°C)		11	20	18	10

Table S3: Maximum quantum yield measured after different dark acclimation times. Mean ± SD; n = 3.

Dark acclimation (min)	Maximum quantum yield
5	0.74 ± 0.03
10	0.74 ± 0.02
15	0.72 ± 0.01
20	0.76 ± 0.01

Table S4: Photosynthetically active radiation (PAR) levels used during the photosynthesis versus irradiance curves. Incident light was generated by a custom-made light bar with white LEDs (LUXEON Rebel, Model: LXML-PWN1-0100, Philips, Amsterdam, Netherlands) and four Schott neutral grey filters. PAR was measured in each season once: n = 4. Mean ± SD.

PAR level	LED 1 (µmol photons m^{-2} s^{-1})	LED 2 (µmol photons m^{-2} s^{-1})	LED 3 (µmol photons m^{-2} s^{-1})
1	19.3 ± 3.6	18.2 ± 3.3	19.6 ± 5.3
2	31.8 ± 4.3	31.7 ± 9.1	36.3 ± 6.8
3	59.0 ± 6.1	54.9 ± 12.1	62.1 ± 9.1
4	89.3 ± 4.3	91.1 ± 15.7	94.3 ± 10.8
5	161.0 ± 6.9	164.5 ± 29.6	159.8 ± 20.7
6	275.5 ± 10.1	282.0 ± 29.6	278.4 ± 10.7
7	353.5 ± 29.9	341.8 ± 71.0	388.7 ± 33.3
8	585.5 ± 45.6	569.9 ± 92.8	657.8 ± 45.1
9	1087.3 ± 28.3	1014.0 ± 128.3	1126.5 ± 57.9
10	1647.3 ± 104.0	1726.3 ± 282.7	1705.0 ± 111.3

Table S5: Mean ratios for conversion of oxygen production rates in *Laminaria hyperborea* measured after three days at two different temperature treatments: *in situ* and *in situ* temperature + 4°C as short-term warming; collected at different depths (2, 4, 6 m below mean low water spring tide) during four seasons. Dry mass (DM): Fresh mass (FM) ratio and DM: Area ratio were calculated after measuring each parameter for each disc. Mean ± SD; n = 6.

Season	Depth (m)	Treatment	Temperature (°C)	DM:FM ($g\ g^{-1}$)	DM:Area ($mg\ cm^{-2}$)
Spring	2	In situ	7	0.154 ± 0.009	24.92 ± 3.56
		+ 4°C	11	0.150 ± 0.006	24.98 ± 1.91
	4	In situ	7	0.135 ± 0.014	16.25 ± 3.32
		+ 4°C	11	0.133 ± 0.006	15.51 ± 2.16
	6	In situ	7	0.126 ± 0.006	24.68 ± 2.85
		+ 4°C	11	0.126 ± 0.006	19.98 ± 2.86
Summer	2	In situ	7	0.217 ± 0.018	35.78 ± 4.72
		+ 4°C	11	0.231 ± 0.015	43.82 ± 3.17
	4	In situ	7	0.243 ± 0.030	38.37 ± 7.10
		+ 4°C	11	0.226 ± 0.026	35.67 ± 6.00
	6	In situ	7	0.214 ± 0.016	32.97 ± 5.39
		+ 4°C	11	0.210 ± 0.017	35.90 ± 7.22
Autumn	2	In situ	7	0.239 ± 0.017	48.70 ± 11.11
		+ 4°C	11	0.234 ± 0.019	50.75 ± 4.47
	4	In situ	7	0.248 ± 0.014	40.20 ± 2.72
		+ 4°C	11	0.260 ± 0.035	44.41 ± 9.30
	6	In situ	7	0.244 ± 0.019	50.78 ± 9.14
		+ 4°C	11	0.236 ± 0.009	47.05 ± 3.92
Winter	2	In situ	7	0.215 ± 0.019	37.67 ± 8.00
		+ 4°C	11	0.223 ± 0.014	39.75 ± 7.57
	4	In situ	7	0.252 ± 0.025	36.16 ± 4.55
		+ 4°C	11	0.243 ± 0.039	31.60 ± 7.76
	6	In situ	7	0.256 ± 0.037	36.86 ± 10.54
		+ 4°C	11	0.261 ± 0.043	37.95 ± 8.37

Table S6: Initial values (Day 0) of the maximum quantum yield in *Laminaria hyperborea* measured over the seasons along the depth gradient (2, 4, 6 m below mean low water spring tide). Mean ± SD; n = 6.

Depth (m)	Spring	Summer	Autumn	Winter
2	0.75 ± 0.016	0.75 ± 0.024	0.76 ± 0.016	0.75 ± 0.014
4	0.77 ± 0.016	0.76 ± 0.052	0.75 ± 0.029	0.75 ± 0.020
6	0.78 ± 0.011	-	0.77 ± 0.022	0.75 ± 0.024

Table S7: Photosynthesis versus irradiance (*P-I*) curve parameter after three days incubation. Maximum oxygen production rate (P_{max}), light utilization coefficient (α), light compensation point (I_c), light saturation point (I_k) and respiration rates were gained *P-I* curves measured in *Laminaria hyperborea* from different depths (2, 4, 6 m below mean low water spring tide) during four seasons (Seas). *P-I* curves were conducted after three days in a temperature incubation at *in situ* and *in situ* temperature + 4°C as short-term warming. Photosynthesis versus respiration (*P:R*) ratios were calculated with P_{max} and respiration rates. Mean ± SD; n = 6.

Season	Depth (m)	Treatment	P_{max} (µmol O_2 cm^{-2} h^{-1})	α (µmol O_2 cm^{-2} h^{-1} / µmol photons m^{-2} s^{-1})	I_c (I_k) (µmol photons m^{-2} s^{-1})	Respiration (µmol O_2 cm^{-2} h^{-1})	*P:R* ratio
Spring	2	In situ	1.87 ± 0.40	0.011 ± 0.006	37.96 ± 17.74 (170.41 ± 72.55)	-0.36 ± 0.16	6.19 ± 2.87
		+ 4°C	1.74 ± 0.30	0.012 ± 0.004	30.59 ± 14.77 (146.13 ± 29.74)	-0.36 ± 0.14	5.54 ± 2.35
	4	In situ	1.69 ± 0.13	0.016 ± 0.002	15.03 ± 6.17 (107.81 ± 13.93)	-0.24 ± 0.12	8.70 ± 4.56
		+ 4°C	1.82 ± 0.26	0.014 ± 0.004	14.20 ± 5.86 (139.20 ± 28.29)	-0.19 ± 0.10	11.51 ± 5.62
	6	In situ	1.54 ± 0.22	0.014 ± 0.008	18.35 ± 7.50 (134.32 ± 56.37)	-0.28 ± 0.24	10.85 ± 12.14
		+ 4°C	1.81 ± 0.34	0.013 ± 0.003	16.07 ± 5.99 (137.24 ± 7.59)	-0.22 ± 0.09	10.21 ± 5.99

Summer	2	In situ	1.73 ± 0.26	0.013 ± 0.002	28.55 ± 7.38	141.12 ± 39.66	-0.36 ± 0.10	±	5.04 ± 1.31
		+ 4°C	2.05 ± 0.20	0.014 ± 0.002	23.98 ± 12.31	152.63 ± 31.51	-0.32 ± 0.13	±	7.68 ± 4.00
	4	In situ	1.47 ± 0.14	0.014 ± 0.002	29.54 ± 5.42	111.21 ± 21.41	-0.41 ± 0.12	±	3.97 ± 1.54
		+ 4°C	1.64 ± 0.26	0.012 ± 0.003	25.76 ± 6.80	134.50 ± 16.10	-0.32 ± 0.11	±	5.63 ± 1.90
	6	In situ	1.51 ± 0.30	0.014 ± 0.003	26.76 ± 11.04	114.65 ± 24.67	-0.36 ± 0.16	±	5.10 ± 2.76
		+ 4°C	1.51 ± 0.44	0.010 ± 0.003	37.15 ± 10.95	148.12 ± 32.04	-0.46 ± 0.17	±	3.77 ± 1.77
Autumn	2	In situ	1.44 ± 0.25	0.011 ± 0.003	27.89 ± 9.22	139.56 ± 31.27	-0.29 ± 0.07	±	5.17 ± 1.02
		+ 4°C	1.69 ± 0.25	0.013 ± 0.005	26.74 ± 9.65	147.48 ± 55.16	-0.33 ± 0.16	±	5.92 ± 2.44
	4	In situ	1.28 ± 0.22	0.010 ± 0.003	26.10 ± 7.42	132.33 ± 35.28	-0.28 ± 0.12	±	5.71 ± 3.05
		+ 4°C	1.24 ± 0.42	0.010 ± 0.004	24.34 ± 2.96	127.65 ± 23.00	-0.36 ± 0.25	±	4.61 ± 2.17

	6	In situ	1.08 ± 0.17	0.011 ± 0.004	32.69 ± 8.33	109.61 ± 34.92	-0.33 ± 0.06	±	3.31 ± 0.33
		+ 4°C	1.05 ± 0.16	0.008 ± 0.002	22.30 ± 9.77	134.38 ± 23.37	-0.18 ± 0.08	±	6.87 ± 2.71
Winter	2	In situ	0.97 ± 0.17	0.011 ± 0.004	8.95 ± 9.77	93.12 ± 26.59	-0.11 ± 0.10	±	14.96 ± 15.26
		+ 4°C	1.21 ± 0.18	0.012 ± 0.005	7.85 ± 5.59	111.33 ± 29.96	-0.10 ± 0.08	±	13.10 ± 24.29
	4	In situ	1.03 ± 0.08	0.010 ± 0.002	13.55 ± 6.11	103.65 ± 25.00	-0.14 ± 0.07	±	9.51 ± 6.36
		+ 4°C	1.02 ± 0.12	0.012 ± 0.003	8.10 ± 11.49	89.43 ± 27.92	-0.08 ± 0.09	±	26.80 ± 19.80
	6	In situ	0.75 ± 0.14	0.011 ± 0.006	5.82 ± 6.05	74.67 ± 23.16	-0.07 ± 0.09	±	21.23 ± 18.26
		+ 4°C	0.69 ± 0.08	0.008 ± 0.002	7.13 ± 6.16	88.84 ± 22.31	-0.05 ± 0.04	±	20.24 ± 15.15

Table S8: Intercepts and slopes with standard errors (SE) derived from linear mixed-effect models for photosynthesis versus irradiance (*P-I*) curve parameter and chlorophyll *a* (Chl *a*), chlorophyll *c* (Chl *c*) contents after three days incubation. Maximum oxygen production rate (P_{max}), light utilization coefficient (α), light compensation point (I_c), light saturation point (I_k) and respiration rates were gained *P-I* curves measured in *Laminaria hyperborea* from different depths (2, 4, 6 m below mean low water spring tide) during four seasons (Seas). *P-I* curves were conducted after three days in a temperature incubation at *in situ* and *in situ* temperature + 4°C as short-term warming. Mean ± SD; n = 6.

Season	Treatment	P_{max}		α		I_c		I_k	
		Intercept	Slope	Intercept	Slope	Intercept	Slope	Intercept	Slope
Spring	*In situ*	2.03 ± 0.16	-0.08 ± 0.04	0.0107 ± 0.0038	0.0007 ± 0.0009	43.40 ± 8.15	-4.90 ± 1.89	250.39 ± 62.15	-23.42 ± 14.39
	+ 4°C	1.72 ± 0.18	0.02 ± 0.04	0.0124 ± 0.0022	0.0002 ± 0.0005	34.81 ± 6.57	-3.63 ± 1.52	149.74 ± 14.57	-2.22 ± 3.37
Summer	*In situ*	1.79 ± 0.15	-0.05 ± 0.04	0.0125 ± 0.0016	0.0002 ± 0.0004	30.08 ± 5.04	-0.45 ± 1.17	148.80 ± 18.65	-6.62 ± 4.32
	+ 4°C	2.28 ± 0.20	-0.14 ± 0.05	0.0157 ± 0.0017	-0.0009 ± 0.0004	6.03 ± 14.36	6.95 ± 3.33	149.59 ± 17.36	-1.13 ± 4.02
Autumn	*In situ*	1.63 ± 0.13	-0.09 ± 0.03	0.0106 ± 0.0020	<0.0001 ± 0.0005	24.09 ± 5.21	1.20 ± 1.21	157.12 ± 20.59	-7.49 ± 4.77
	+ 4°C	1.96 ± 0.18	-0.16 ± 0.04	0.0153 ± 0.0024	-0.0012 ± 0.0006	37.26 ± 23.22	-1.11 ± 5.37	149.61 ± 22.75	-3.28 ± 5.27
Winter	*In situ*	1.14 ± 0.10	-0.06 ± 0.02	0.0108 ± 0.0025	<0.0001 ± 0.0006	12.57 ± 4.93	-0.78 ± 1.14	108.93 ± 16.28	-4.61 ± 3.77
	+ 4°C	1.49 ± 0.08	-0.13 ± 0.02	0.0152 ± 0.0022	-0.0011 ± 0.0005	8.41 ± 4.95	-0.18 ± 1.15	119.02 ± 16.59	-5.62 ± 3.84

Season	Treatment	Respiration		Chl *a*		Chl *c*	
		Intercept	Slope	Intercept	Slope	Intercept	Slope
Spring	*In situ*	-0.370 ± 0.112	0.019 ± 0.026	22.11 ± 5.74	-0.59 ± 1.33	10.64 ± 2.37	-0.44 ± 0.55
	+ 4°C	-0.395 ± 0.075	0.035 ± 0.017	25.41 ± 4.12	-1.79 ± 0.95	11.81 ± 1.79	-0.71 ± 0.41
Summer	*In situ*	-0.379 ± 0.079	0.001 ± 0.018	30.43 ± 3.85	-0.28 ± 0.89	13.64 ± 1.43	0.17 ± 0.33
	+ 4°C	-0.221 ± 0.085	-0.036 ± 0.020	34.58 ± 3.97	-1.26 ± 0.92	17.63 ± 2.27	-0.78 ± 0.53
Autumn	*In situ*	-0.257 ± 0.055	-0.010 ± 0.013	45.16 ± 2.38	-1.40 ± 0.55	22.80 ± 2.77	-0.80 ± 0.64
	+ 4°C	-0.444 ± 0.113	0.039 ± 0.026	47.43 ± 4.68	-2.31 ± 1.08	22.87 ± 2.06	-1.00 ± 0.48
Winter	*In situ*	-0.144 ± 0.043	0.009 ± 0.013	38.08 ± 4.95	-0.41 ± 1.14	17.18 ± 1.98	0.03 ± 0.46
	+ 4°C	-0.123 ± 0.043	0.012 ± 0.010	40.07 ± 3.25	-2.20 ± 0.75	19.60 ± 1.66	-1.35 ± 0.38

Table S9: Chlorophyll *a* (Chl *a*), chlorophyll *c* (Chl *c*) contents and Chl *c*: Chl *a* ratio in *Laminaria hyperborea* from different depths (2, 4, 6 m below mean low water spring tide) during four seasons. Contents were measured after three days in a temperature incubation at *in situ* and *in situ* temperature + 4°C as short-term warming. Mean ± SD; n = 6.

Season	Depth (m)	Treatment	Chl *a* (µg cm^{-2})	Chl *c*	Chl *c*: Chl *a* ratio
Spring	2	In situ	26.1 ± 2.7	11.8 ± 2.1	0.45 ± 0.04
		+ 4°C	24.9 ± 5.4	11.9 ± 1.6	0.49 ± 0.07
	4	In situ	9.4 ± 6.7	4.8 ± 2.2	0.64 ± 0.23
		+ 4°C	12.2 ± 5.6	5.9 ± 2.3	0.50 ± 0.08
	6	In situ	23.8 ± 5.2	10.0 ± 2.7	0.44 ± 0.13
		+ 4°C	17.7 ± 3.7	9.1 ± 1.4	0.52 ± 0.05
Summer	2	In situ	30.6 ± 3.1	14.8 ± 1.5	0.48 ± 0.04
		+ 4°C	33.3 ± 6.2	17.8 ± 1.9	0.54 ± 0.06
	4	In situ	27.9 ± 10.1	12.7 ± 2.8	0.48 ± 0.10
		+ 4°C	27.1 ± 8.2	11.1 ± 3.5	0.41 ± 0.03
	6	In situ	29.5 ± 2.7	15.4 ± 1.4	0.53 ± 0.04
		+ 4°C	28.2 ± 3.6	14.7 ± 2.5	0.52 ± 0.07
Autumn	2	In situ	42.9 ± 3.0	22.4 ± 3.4	0.53 ± 0.10
		+ 4°C	43.2 ± 5.7	21.8 ± 2.3	0.51 ± 0.04
	4	In situ	38.5 ± 3.2	17.3 ± 0.7	0.45 ± 0.04
		+ 4°C	37.4 ± 11.7	17.0 ± 4.5	0.47 ± 0.10
	6	In situ	37.3 ± 5.1	19.2 ± 6.4	0.51 ± 0.16
		+ 4°C	34.0 ± 3.1	17.8 ± 1.6	0.52 ± 0.03
Winter	2	In situ	38.5 ± 2.5	17.8 ± 1.3	0.46 ± 0.02
		+ 4°C	34.3 ± 4.6	16.7 ± 3.3	0.49 ± 0.06
	4	In situ	34.0 ± 11.4	16.2 ± 4.1	0.49 ± 0.08
		+ 4°C	34.0 ± 6.3	14.6 ± 2.5	0.43 ± 0.04
	6	In situ	36.8 ± 7.4	17.9 ± 3.3	0.49 ± 0.04
		+ 4°C	25.5 ± 3.6	11.3 ± 2.3	0.44 ± 0.04

Fig. S1: *Laminaria hyperborea* in different seasons. Red circles show cutting area in the meristem. In spring, some individuals had an old blade (1) attached to the tips of the new blade and in winter, the formation of the new blade (2) just started. Black squares are a reference area of 10 x 10 cm.

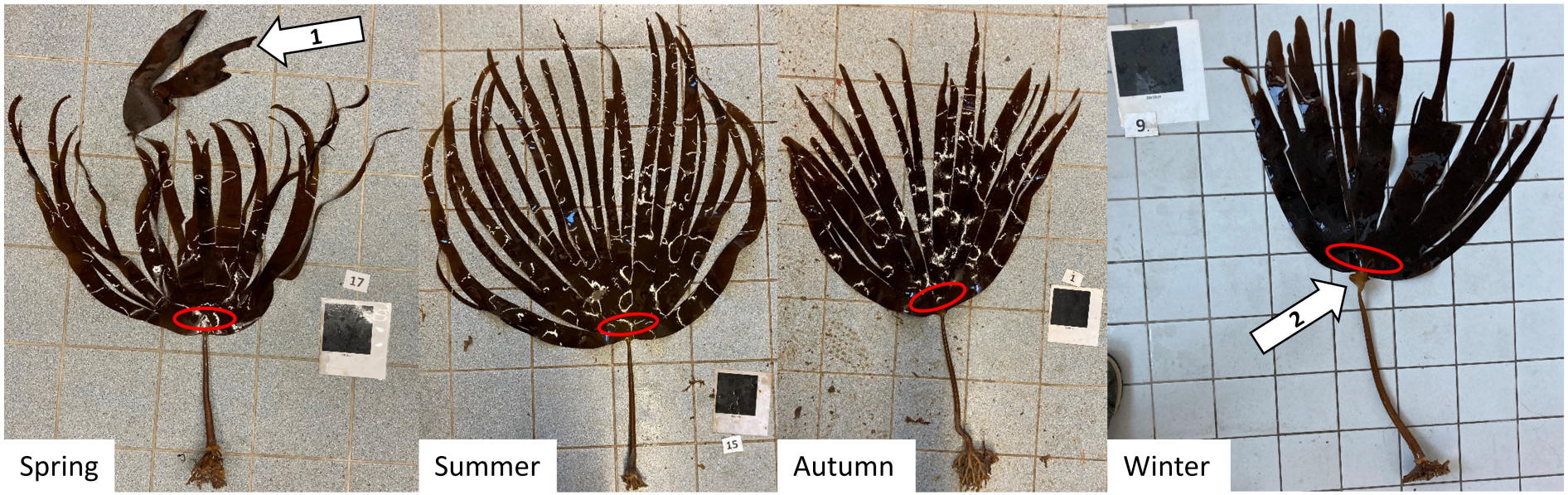
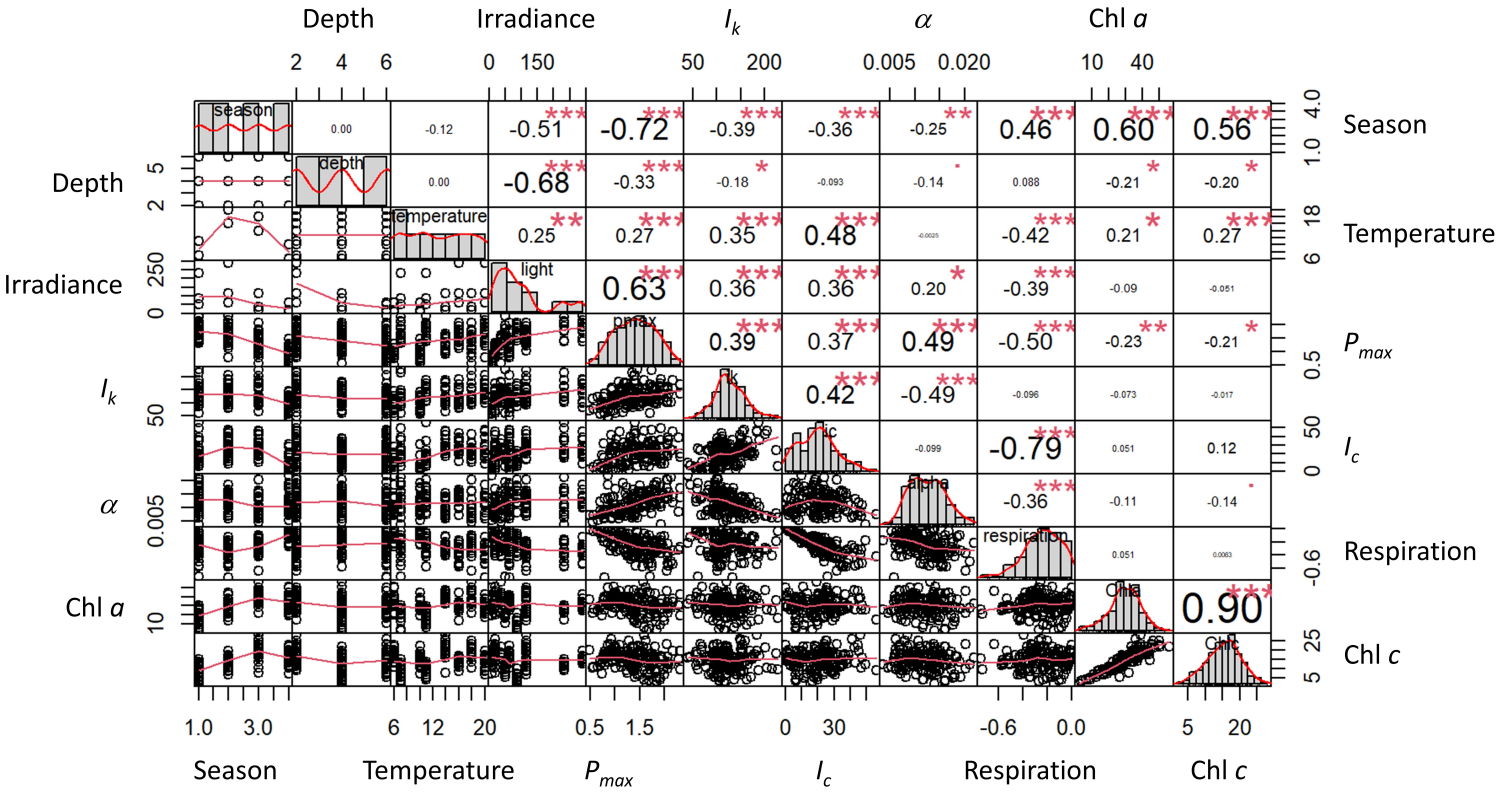


Fig. S2: Pearson correlations of photosynthesis versus irradiance curve parameters (maximum oxygen production rate: P_{max} (µmol O_2 cm^{-2} h^{-1}), light saturation point: I_k (µmol photons m^{-2} s^{-1}), light compensation point: I_c (µmol photons m^{-2} s^{-1}), light utilization coefficient: α (µmol O_2 cm^{-2} h^{-1} (µmol photons m^{-2} s^{-1})$^{-1}$) and dark respiration rate: respiration (µmol O_2 cm^{-2} h^{-1})) and chlorophyll (Chl) *a* (µg Chl *a* cm^{-2}) and *c* (µg Chl *c* cm^{-2}) contents of *Laminaria hyperborea* with seasonal varying factors (temperature (°C), irradiance (µmol photons m^{-2} s^{-1}) and season) and depth (m) extracted from the correlation chart function. Asterisks (*) denote significant correlations: *** p < 0.001, ** p < 0.01, * p < 0.05. n = 6.



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