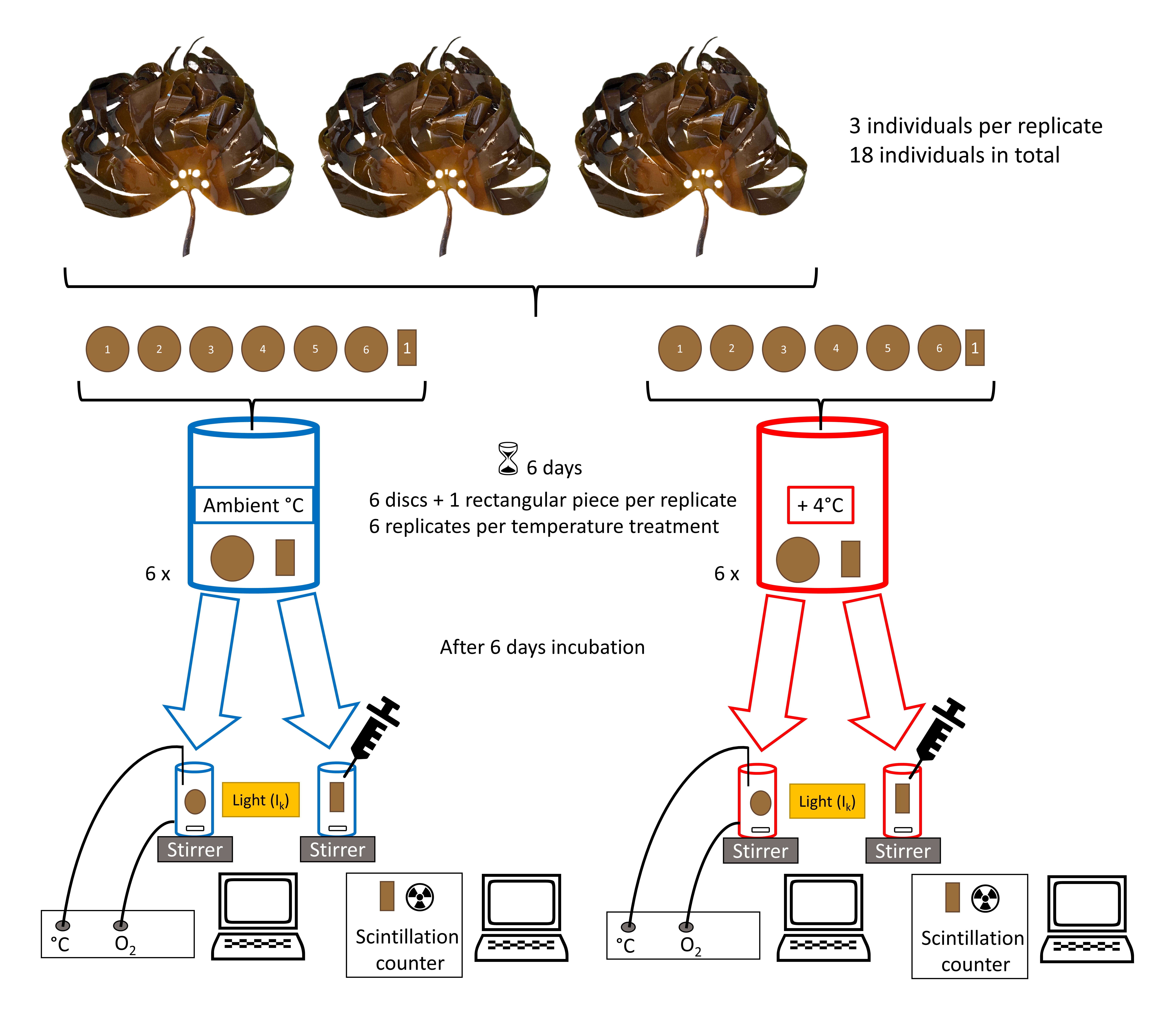
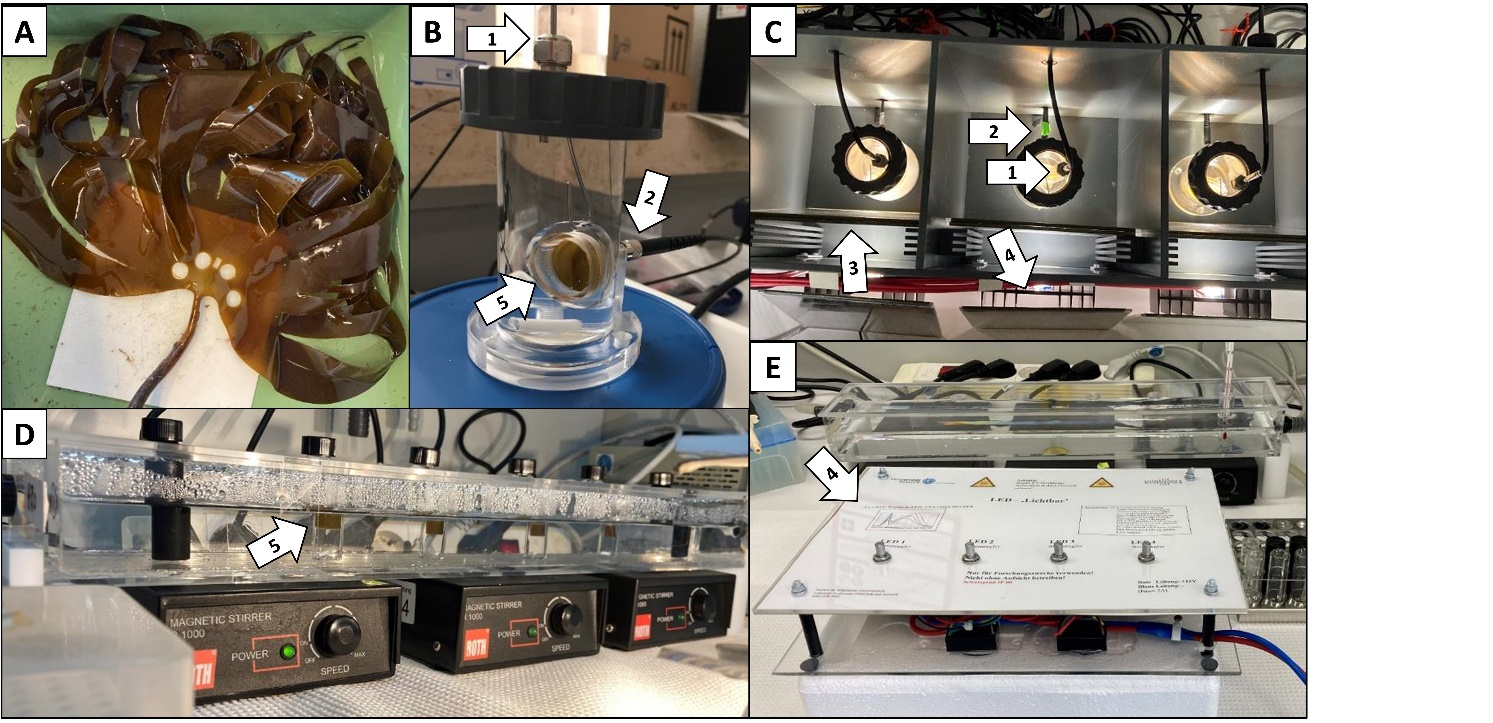
Supplementary Material



**Supplementary Figure S1.** Experimental design. In all four seasons and three depths a total of 18 *Laminaria hyperborea* individuals were collected and blade discs incubated at two temperature treatments (ambient & + 4°C) for 6 days. After the incubation, oxygen evolution and carbon fixation measurements were performed.

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**Figure S2** Sample processing and set-up for photosynthesis versus irradiance (P-I) curves and C-fixation measurements. (A) *Laminaria hyperborea* after cutting the pieces of thallus for the measurements. (B) Incubation chamber with kelp disc (5), temperature sensor (1) and optical fibre attachment (2). (C) Oxygen evolution measurement set-up in temperature-constant room with light source (4) and neutral grey filters (3). (D), (E) 14C-fixation measurement set-up with algae (5) incubated in medium within a tempered water bath.

Supplementary Table S1. Sampling information and storage information. Depth was measured at holdfast and is given below mean low water spring tide (n=6). For logistical reasons, algae were stored in the harbour at the same depth at which algae grew.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Season | Depth (m) | Coordinates | Harbour storage period (days) | Sampling time |
| Spring | 2 | N 54°11‘31  E 007°52‘42 | 3 | 03.05.21 11:25 |
|  | 4 | N 54°11.573’  E 007°52.709‘ | - | 15.04.21 18:10 |
|  | 6 | N 54°11‘49“  E 007°51‘27“ | - | 26.04.21 18:12 |
| Summer | 2 | N 54°11‘31  E 007°52‘40 | 4 | 01.07.21 15:45 |
|  | 4 | N 54°11.573  E 007°52.709 | - | 05.08.21 8:30 |
|  | 6 | N 54°11‘49‘‘  E 007°51‘25‘‘ | 2 | 20.07.21 13:09 |
| Autumn | 2 | N 54°11‘31  E 007°52‘43 | 3 | 18.10.21 9:30 |
|  | 4 | N 54°11.573  E 007°52.709 | 2 | 28.09.21 15:00 |
|  | 6 | N 54°11‘49‘‘  E 007°51‘27‘‘ | 3 | 08.10.21 12:24 |
| Winter | 2 | N 54°11‘528  E 007°52‘498 | 4 | 03.02.22 12:06 |
|  | 4 | N 54°11.573  E 007°52.709 | 2 | 25.01.22 14:35 |
|  | 6 | N 54°10’13.0‘‘  E 007°53’28.2‘‘ | 1 | 16.02.22 12:44 |

**Supplementary Table S2:** Saturating photosynthetically active radiation (PAR; unit: µmol photons m–2 s–1) for each depth (2, 4, 6 m below mean low water spring tide) and season combination obtained from photosynthesis versus irradiance curves applied to *Laminaria hyperborea* at day 0.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Depth (m) | Spring | Summer | Autumn | Winter |
| 2 | 138 | - | 120 | 91 |
| 4 | 104 | 137 | 137 | 100 |
| 6 | 117 | 116 | 115 | 53 |

**Supplementary Table S3:** Light-dependent and light-independent carbon fixation (Clight fixation and Cdark fixation, respectively), measured as 14C fixation (mean ±SD, Clight fixation: n=4; Cdark fixation as raw data: n=2) of *Laminaria hyperborea* after at least six days of incubation at two different temperature treatments (ambient and + 4°C as warming scenario). Mean ±SD

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Season | Depth | Temperature | Clight fixation | Cdark fixation |
|  | (m) | (°C) | (µmol C cm–2 h–1) | |
| Spring | 2 | 7 | 0.36 ±0.05 | 0.058; 0.058 |
|  |  | 11 | 0.48 ±0.06 | 0.066; 0.057 |
|  | 4 | 7 | 0.26 ±0.06 | 0.028; 0.030 |
|  |  | 11 | 0.42 ±0.09 | 0.057; 0.048 |
|  | 6 | 7 | 0.30 ±0.03 | 0.022; 0.030 |
|  |  | 11 | 0.39 ±0.09 | 0.042; 0.036 |
| Summer | 2 | 16 | - | - |
|  |  | 20 | - | - |
|  | 4 | 16 | 0.29 ±0.01 | 0.058; 0.084 |
|  |  | 20 | 0.37 ±0.09 | 0.083; 0.073 |
|  | 6 | 16 | 0.26 ±0.04 | 0.043; 0.027 |
|  |  | 20 | 0.42 ±0.03 | 0.058; 0.052 |
| Autumn | 2 | 14 | 0.41 ±0.06 | 0.062; 0.057 |
|  |  | 18 | 0.40 ±0.08 | 0.045; 0.056 |
|  | 4 | 14 | 0.25 ±0.05 | 0.046; 0.042 |
|  |  | 18 | 0.36 ±0.22 | 0.088; 0.068 |
|  | 6 | 14 | 0.25 ±0.05 | 0.062; 0.050 |
|  |  | 18 | 0.33 ±0.07 | 0.030; 0.087 |
| Winter | 2 | 6 | - | - |
|  |  | 10 | 0.26 ±0.05 | 0.039; 0.041 |
|  | 4 | 6 | 0.27 ±0.05 | 0.025; 0.019 |
|  |  | 10 | 0.28 ±0.07 | 0.016; 0.023 |
|  | 6 | 6 | 0.25 ±0.05 | 0.024; 0.028 |
|  |  | 10 | 0.34 ±0.04 | 0.039; 0.051 |

**Supplementary Table S4:** Net photosynthetic rate (ONet), respiration rate and gross photosynthetic rate (OGross), measured as oxygen evolution (mean ±SD). Light-dependent carbon fixation (Cgross fixation), measured as 14C fixation (mean ±SD), and photosynthetic quotient (PQ, mean ±SD) of *Laminaria hyperborea* after at least six days of cultivation at two different temperature treatments (ambient and + 4°C as warming scenario). Temp: temperature

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Season | Depth | Temp | ONet | Respiration | OGross | Cgross fixation | PQ | |
|  | (m) | (°C) | (µmol O2 cm–2 h–1) | | | (µmol C cm–2 h–1) | |  |
| Spring | 2 | 7 | 0.30 ±0.27 | 0.57 ±0.23 | 0.87 ±0.38 | 0.30 ±0.05 | 2.91 ±1.36 | |
|  |  | 11 | 0.47 ±0.20 | 0.37 ±0.11 | 0.84 ±0.23 | 0.41 ±0.06 | 2.03 ±0.64 | |
|  | 4 | 7 | 0.36 ±0.18 | 0.55 ±0.16 | 0.91 ±0.21 | 0.23 ±0.06 | 3.90 ±1.37 | |
|  |  | 11 | 0.48 ±0.05 | 0.29 ±0.04 | 0.77 ±0.06 | 0.37 ±0.09 | 2.08 ±0.51 | |
|  | 6 | 7 | 0.37 ±0.14 | 0.40 ±0.14 | 0.77 ±0.21 | 0.28 ±0.03 | 2.77 ±0.80 | |
|  |  | 11 | 0.44 ±0.14 | 0.26 ±0.06 | 0.70 ±0.14 | 0.35 ±0.09 | 1.98 ±0.64 | |
| Summer | 2 | 16 | - | - | - | - | - | |
|  |  | 20 | - | - | - | - | - | |
|  | 4 | 16 | 0.43 ±0.10 | 0.55 ±0.03 | 0.98 ±0.10 | 0.22 ±0.02 | 4.41 ±0.64 | |
|  |  | 20 | 0.62 ±0.24 | 0.45 ±0.07 | 1.07 ±0.18 | 0.29 ±0.09 | 3.74 ±1.33 | |
|  | 6 | 16 | 0.37 ±0.45 | 0.34 ±0.15 | 0.71 ±0.32 | 0.23 ±0.04 | 3.14 ±1.52 | |
|  |  | 20 | 0.61 ±0.10 | 0.33 ±0.12 | 0.93 ±0.08 | 0.37 ±0.03 | 2.54 ±0.32 | |
| Autumn | 2 | 14 | 0.29 ±0.18 | 0.44 ±0.12 | 0.74 ±0.16 | 0.35 ±0.06 | 2.08 ±0.56 | |
|  |  | 18 | 0.41 ±0.29 | 0.40 ±0.14 | 0.81 ±0.21 | 0.35 ±0.08 | 2.31 ±0.80 | |
|  | 4 | 14 | 0.22 ±0.17 | 0.38 ±0.09 | 0.60 ±0.14 | 0.20 ±0.05 | 2.99 ±0.97 | |
|  |  | 18 | 0.15 ±0.52 | 0.47 ±0.20 | 0.62 ±0.33 | 0.28 ±0.22 | 2.22 ±2.15 | |
|  | 6 | 14 | 0.21 ±0.11 | 0.42 ±0.15 | 0.64 ±0.14 | 0.20 ±0.05 | 3.25 ±1.15 | |
|  |  | 18 | 0.24 ±0.18 | 0.24 ±0.07 | 0.48 ±0.14 | 0.27 ±0.08 | 1.75 ±0.71 | |
| Winter | 2 | 6 | 0.28 ±0.18 | 0.20 ±0.15 | 0.48 ±0.07 | - | - | |
|  |  | 10 | 0.38 ±0.14 | 0.21 ±0.10 | 0.59 ±0.18 | 0.22 ±0.05 | 2.73 ±1.07 | |
|  | 4 | 6 | 0.28 ±0.15 | 0.12 ±0.05 | 0.41 ±0.18 | 0.24 ±0.05 | 1.66 ±0.79 | |
|  |  | 10 | 0.33 ±0.25 | 0.14 ±0.09 | 0.47 ±0.28 | 0.26 ±0.07 | 1.81 ±1.18 | |
|  | 6 | 6 | 0.26 ±0.22 | 0.14 ±0.10 | 0.40 ±0.21 | 0.22 ±0.05 | 1.83 ±1.03 | |
|  |  | 10 | 0.29 ±0.23 | 0.20 ±0.04 | 0.49 ±0.23 | 0.30 ±0.04 | 1.65 ±0.81 | |

**Supplementary Table S5:** Photosynthesis versus irradiance (P-I) curve parameters after three days of incubation presented in Franke et al. (2024). Maximum net oxygen production rate (Pmax), light utilization coefficient (*α*) and respiration rates (R) were gained P-I curves measured in *Laminaria hyperborea* from 4 m (below mean low water spring tide) during four seasons. P-I curves were conducted after three days of incubation at two different temperature treatments (ambient and + 4°C as warming scenario). Parameters (Pmax, α, R) were used for the net primary production (NPP) calculations in terms of C-fixed. NPPambient: using PQ under ambienttemperatures; NPPwarming: using PQ under warming scenario (ambient + 4°C); NPPMiller: using PQ of 1.18 according to Miller et al. (2009); NPPmean: using average PQ of 3.24 over all seasons under ambienttemperatures (for Statistics see Table 4). Mean ±SD, n=6 for each season

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
|  | Ambient  (NPPambient & NPPMiller & NPPmean) | | | Warming  (NPPwarming) | | |
| Season | Pmax | R | α | Pmax | R | α |
|  | (µmol O2 cm–2 h–1) | | (µmol O2 cm–2 h–1/  µmol photons m–2 s–1) | (µmol O2 cm–2 h–1) | | (µmol O2 cm–2 h–1/  µmol photons m–2 s–1) |
| Spring | 1.40 ±0.31 | 0.17 ±0.16 | 0.016 ±0.008 | 1.82 ±0.26 | 0.19 ±0.10 | 0.014 ±0.004 |
| Summer | 1.72 ±0.14 | 0.33 ±0.09 | 0.015 ±0.001 | 1.64 ±0.26 | 0.32 ±0.11 | 0.012 ±0.003 |
| Autumn | 1.21 ±0.26 | 0.11 ±0.11 | 0.011 ±0.005 | 1.38 ±0.27 | 0.27 ±0.10 | 0.011 ±0.004 |
| Winter | 0.64 ±0.09 | 0.07 ±0.05 | 0.011 ±0.006 | 1.02 ±0.12 | 0.08 ±0.09 | 0.012 ±0.003 |

**R-Script for data generation from mean, sd and samplesize:**

gen\_data<-function(means,sds,samplesizes){

n.grp<-length(means)

grps<-factor(rep(1:n.grp,samplesizes))

dat<-lapply(1:n.grp, function(i){scale(rnorm(samplesizes[i]))\*sds[i]+means[i]})

y<-do.call(rbind,dat)

out<-data.frame(group=grps,y=y)

out

}

(https://stackoverflow.com/questions/29260139/r-function-to-perform-anova-and-tukeyhsd-from-sample-mean-sd-and-n, accessed 04.08.2023 15:00)

***Total alkalinity and dissolved inorganic carbon***

Water samples were taken on the last day of cultivation to determine the total alkalinity (TA) in the medium. Two replicates were pooled into one 200 mL Schott flask (n=3), filled completely with the medium and closed. When the medium reached room temperature (approximately after 6 h), 50 mL were transferred to a beaker and stirred constantly. TA was determined by titration with 0.5 N HCl (Roth) to pH 4.0 (pH-meter: HANNA HI5521, pH-electrode: HANNA HI1131B, temperature sensor: HANNA HI7662-W, salinity sensor: HANNA HI76312, Hanna Instruments). Dissolved inorganic carbon (DIC) was calculated by adding TA, pH, salinity and experimental temperature to the program CO2SYS provided by Pierrot and Lewis (2006; Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy) and constants were chosen after Mehrbach et al. (1973).

**Supplementary references:**

Mehrbach, C., Culberson, C. H., Hawley, J. E., and Pytkowicx, R. M. (1973). Measurement of the apparent dissociation constants of carbonic acid in seawater at atmospheric pressure. *Limnol. Oceanogr.* 18:897–907. doi: 10.4319/lo.1973.18.6.0897

Pierrot, D., Lewis, E., and Wallace, D. W. R. (2006). "CO2SYS DOS Program developed for CO2 system calculations." ORNL/CDIAC-105. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, US Department of Energy, Oak Ridge, TN. doi: 10.15485/1464255