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Effects of elevated temperature on erosion of *Saccharina latissima* (Laminariales, sugar kelp) blades

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ABSTRACT

The critical role of kelp as an ecosystem engineer (nutrient cycling, habitat formation) is well recognized but under threat. Recent declines in natural kelp populations worldwide have been linked to global warming-induced rising temperatures of the ocean. There is, however, a noticeable gap in knowledge about the effects of temperature on the erosion of (distal parts of) the kelp blades. This erosion process, where blades tissue is lost, is crucial to understanding kelp health and nutrient dynamics in marine ecosystems. This study aimed to quantify the erosion rate of *Saccharina latissima* (Laminariales, sugar kelp) blades and the subsequent release of total organic carbon and total nitrogen during erosion under naturally increased temperatures (from 16.1 °C to 22.5 °C) and further elevated temperatures (from 16.1 °C to 27.1 °C). A significant increase in the erosion rate of the distal parts of blades was observed in both temperature treatments. Substantial amounts (4.24 ± 0.31 mg cm^{-2} of C and 0.32 ± 0.13 mg cm^{-2} of N) of nutrients were released from *S. latissima*, especially under sub-lethal temperature conditions. Under further elevated temperatures, with a prolonged period of higher temperature and a maximum temperature of 27.1 °C, the effects were stronger, and erosion occurred along the edges of the whole blade. Our findings suggest that rising temperatures accelerate the erosion of *S. latissima* blades, highlighting a reason for the decline of kelp forests under climate change, as well as the potential impacts on nutrient cycling in the oceans.

1. Introduction

Global warming is threatening the structure and function of marine ecosystems worldwide (Hoegh-Guldberg and Bruno, 2010). In 2023, the highest sea surface temperature was recorded in the north Atlantic Ocean (Copernicus Climate Change Service). Marine heatwaves (MHWs) have already been observed, for example, in the Baltic Sea and around the U.K. and Ireland (Hobday et al., 2016). The impact of such MHWs on marine ecosystems has persisted for years, including reduced marine productivity, biodiversity decline, habitat loss, and shifts in marine species distribution (Sala and Knowlton, 2006; Moore et al., 2018; Bindoff et al., 2019). MHWs can also lead to algal blooms that disrupt aquaculture efforts, increasing competitive interactions between cultivated and bloom-forming algae (Jiang et al., 2022; Gao et al., 2024). Moreover, the disappearance of kelp forests (large brown seaweed species) in the western and eastern North Atlantic over the past six decades has been strongly linked to MHW events (Filbee-Dexter et al., 2020). The effects of climate change on habitat-forming marine species are particularly crucial, as alterations in their distribution affect the provision of marine ecosystem services (Wernberg et al., 2013; Krumhansl et al., 2016; Arafeh-Dalmau et al., 2019; Wernberg et al., 2019).

Kelp forests dominate shallow rocky shores in temperate and polar coastal seas (Wernberg et al., 2019; Jayathilake and Costello, 2020) and protect the coastline from erosion (Steneck et al., 2002; Pfister et al., 2019; Morris et al., 2020). They form one of the largest habitats in the world, providing high biodiversity, carbon fixation, and productivity (Smale, 2020; Layton et al., 2020). Worldwide, these kelp forests generate an annual average worth of ecosystem services of $500 billion, mostly from related fisheries and nutrient removal (Eger et al., 2023). Global climate change-induced alterations in kelp forests around the

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world result not only in local extinctions, but also facilitate their replacement by turf algae (Filbee-Dexter and Wernberg, 2018; Smale, 2020; McPherson et al., 2021; Diehl et al., 2024). The presence of turf algae limits the potential for kelp forest recovery (Smale, 2020; Voerman et al., 2013; Wernberg et al., 2016; Filbee-Dexter and Wernberg, 2018). It has been reported that kelp forests are expected to move continuously northwards in the future (Krumhansl et al., 2016; Diehl et al., 2024).

As cool-water species, kelps seem particularly susceptible to increasing temperature, whether gradually due to global ocean warming or more sudden regional ocean warming by MHWs. Although enhanced temperature is recognized as a major stressor for kelp (Steneck et al., 2002), how temperature affects the growth processes and decay of kelp species needs further investigation. We know that the stability of cellular membranes, enzymatic reactions, and protein activity are typically negatively affected when physiological temperature thresholds are exceeded, despite the variation in optimal growth and lethal temperature thresholds for the different kelp species and ecotypes (Staehr and Wernberg, 2009; Mabin et al., 2019; Nepper-Davidsen et al., 2019; Forbord et al., 2020). Under sub-lethal temperature conditions, growth is reduced (Eggert, 2012; Olischläger et al., 2014; Nepper-Davidsen et al., 2019). The net loss in kelp blade area is not only caused by reduced growth but also comes from blade erosion. A few studies have monitored one-dimensional growth (net length) of kelp blades under elevated temperatures and reported accelerated tissue loss, but their limitation is the insufficient assessment of the two-dimensional area (Nielsen et al., 2014; Simonson et al., 2015).

As for our current study, we aimed to investigate not only the impact of temperature rise on both growth and erosion (an understudied combination thus far), but also quantify kelp erosion based on surface area (two-dimensional) of the distal parts of *Saccharina latissima* (sugar kelp). In addition, we determined the carbon (C) and nitrogen (N) concentration of the blades to examine how temperature-induced blade erosion contributes to C and N release, providing data that highlights kelp's role in nutrient cycling within marine ecosystems. We conducted two experimental studies, one under naturally increased temperatures during spring (Experiment 1) and one with additional further warming (Experiment 2). This enabled correlating elevated temperatures with resulting growth and erosion of *S. latissima* blades (Experiment 1) as well as examining the effects of more extreme warming conditions on growth and erosion of the blades (Experiment 2).

2. Material and methods

2.1. Experimental set up

Saccharina latissima sporophytes were collected in spring (first half of May 2022) from the coastal waters south of Texel, The Netherlands. Two experiments were performed side by side for a 4-week observation period, i.e., the sporophytes in Experiment 1 experienced natural increase in water temperature and those in Experiment 2 were exposed to further elevated temperatures. For Experiment 1, fifteen healthy sporophytes with a frond length range of 48 to 167 cm were selected to capture the natural variability of *S. latissima* across different development stages. They were then transferred to a 1500 L incubation tank with aeration and a flow-through system supplying fresh filtered seawater (10 % = 150 L per day) to ensure a continuous nutrient supply. For Experiment 2, a second batch of fifteen sporophytes (frond length range of 69 to 159 cm) were placed in another 1500 L incubation tank. This tank was equipped with a solar heating system that warmed the seawater by an additional 0.0–4.6 °C compared to Experiment 1. This set-up was designed to evaluate the effects of unprecedented high temperatures, which are becoming more relevant with the increasing frequency and intensity of MHWs (Hobday et al., 2016; Bindoff et al., 2019). A 4-week duration was selected to provide sufficient time to observe physiological responses to elevated temperatures. Tape around the stipes of all sporophytes was used to label each of *S. latissima* individual. Temperature was measured hourly by a HOBO logger (Onset. Massachusetts, USA), one was placed in each tank.

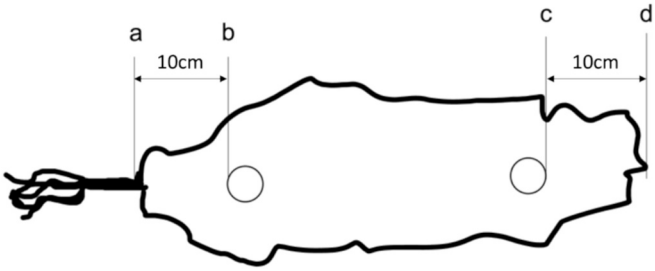

Fig. 1. Simplified diagram of markers (holes punched in the *S. latissima* blade) used for calculating biomass growth or erosion. Distance to measure meristem growth is a to b; distance to measure erosion is c to d. Photographs to measure condition of the distal end were taken from c to d.

2.2. Measurements of growth and erosion rates (both experiments)

Two holes (diameter = 1.2 cm) were punched into each blade: one 10 cm from the stipe (Fig. 1, from *a* to *b*) to measure meristem growth and the other 10 cm from the distal end of the blade (Fig. 1, from *c* to *d*) to measure the erosion rates (Parke, 1948). The total blade length, meristem length, and erosion were measured weekly by photographing the blade. Additionally, changes in the distal surface area were determined by photographing the entire distal part (Fig. 1, from *c* to *d*) of the blade. In all cases, a ruler was included in the photographs for exact determinations of the size.

Relative growth rate (%·d^{-1}) was calculated according to the following equation:

$$\text{Relative growth rate (RGR)} = (L2–L1)\cdot L1 - 1\cdot(t2 - t1) - 1$$

where L is the length of the meristem (Fig. 1, from *a* to *b*, respectively) or the length of the whole blade (Fig. 1, from *a* to *d*, respectively) of the individual and t is time in days. Surface area analysis of the distal part of the blade was carried out using the software ImageJ (National Institutes of Health. State of Maryland, USA). The absolute erosion rate (cm^2·d^{-1}) of the distal end of the blade was calculated according to the following equation:

$$\text{Absolute erosion rate} = (S1–S2)\cdot(t2 - t1) - 1$$

where S_T is the initial distal area and t is time in days.

2.3. TOC and TN analyses (Experiment 1)

The concentrations of TOC and TN in the distal part of *S. latissima* were analyzed on randomly selected 10 circle samples (diameter = 1.2 cm) taken at the beginning of the experiment and the end of the experiment. The samples were placed into grip seal bags and stored at −80 °C until further analysis. To obtain the dry weight, samples were lyophilized using a freeze-dryer (Christ alpha 1–4 LD plus). TOC and TN were measured with a Flash 1112 element analyzer (Thermo Electron). For this, dried samples (2.00 ± 0.05 mg) were packed in tin containers and combusted at 1020 °C into nitrous oxides and carbon dioxide (CO_2). The produced N_2O were reduced to N_2 with copper at 650 °C. N_2 and CO_2 were separated on a Haysep Q column and detected with a thermal conductivity detector (Nieuwenhuize et al., 1994). Based on the relation between surface area and average of dry weight of samples, the area of tissue that was lost was converted into its dry weight. The loss in surface area was subsequently converted to the amount of TOC and TN (mg d^{-1} ind^{-1}) released per day.

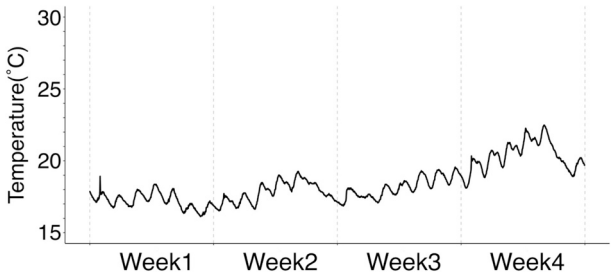

Fig. 2. Hourly recorded seawater temperature (°C) in Experiment 1. Vertical lines indicate the sampling points of the *S. latissima* blades.

2.4. Statistical analysis

All statistical analyses were performed using R version 4.1.3 (Team R core 2022). The general trends in the RGRs, absolute erosion rate and time of sampling were assessed with linear model (LM) based on the Spearman correlation coefficient. The LM was selected as it effectively captures general trends across the two temperature treatments. The correlation coefficient was displayed on the plot to assess the strength and direction of association between RGRs, absolute erosion rate and time of sampling. The *p*-value typically indicates the statistical significance of the relationship between two variables. The formula including the intercept and slope coefficients of the regression was displayed on the plot. Tukey analysis was applied to test the between the TOC and TN concentrations at the start and end of Experiment 1.

3. Results

3.1. Experiment 1: natural increase of water temperature

During the initial three weeks of the Experiment 1, temperatures stayed below 20 °C, followed by a significant rise in week 4 (Fig. 2). The weekly average temperature was 17.2 °C, 17.8 °C, 18.3 °C and 20.3 °C from week 1 to 4, with the lowest temperature of 16.1 °C recorded in week 1 and the highest maximum temperature of 22.5 °C in week 4.

The relative growth rate (RGR) of the meristem part of the blades (Fig. 3A) showed a significant negative correlation with temperature ($p = 0.0014$). The absolute erosion rates remained stable at 1.48 ± 0.24 cm^2 per day on average over the entire period of the experiment (no significant correlation, Fig. 3B). With decreasing RGRs of the meristem and equal erosion rates in time the RGR of the total blade showed a similar declining trend to that observed in meristem part at elevated temperatures (Fig. 3C). An example of the blade erosion patterns observed in a randomly selected *S. latissima* individual is shown (Fig. 4) to illustrate the erosion in the distal part of the blade. The distal part of this *S. latissima* individual exhibited a reduction in surface area with increasing temperature, resulting in a significantly diminished area by week 4 compared to its initial size in week 0.

The overall average TOC concentration in the distal part of *S. latissima* blades was 31.68 ± 0.02 % of the dry weight (DW) and 4.24 ± 0.31 mg C cm^{-2} (Table 1). The average TN concentration in the distal part was 2.20 ± 0.95 % DW and 0.32 ± 0.13 mg N cm^{-2}. For both TOC and TN there was a small but significant difference ($p < 0.01$, $n = 10$) between the concentrations at the start and the end of the experiment (4.06 ± 0.28 vs 4.41 ± 0.24 mg C cm^{-2}, and 0.45 ± 0.06 vs 0.18 ± 0.02

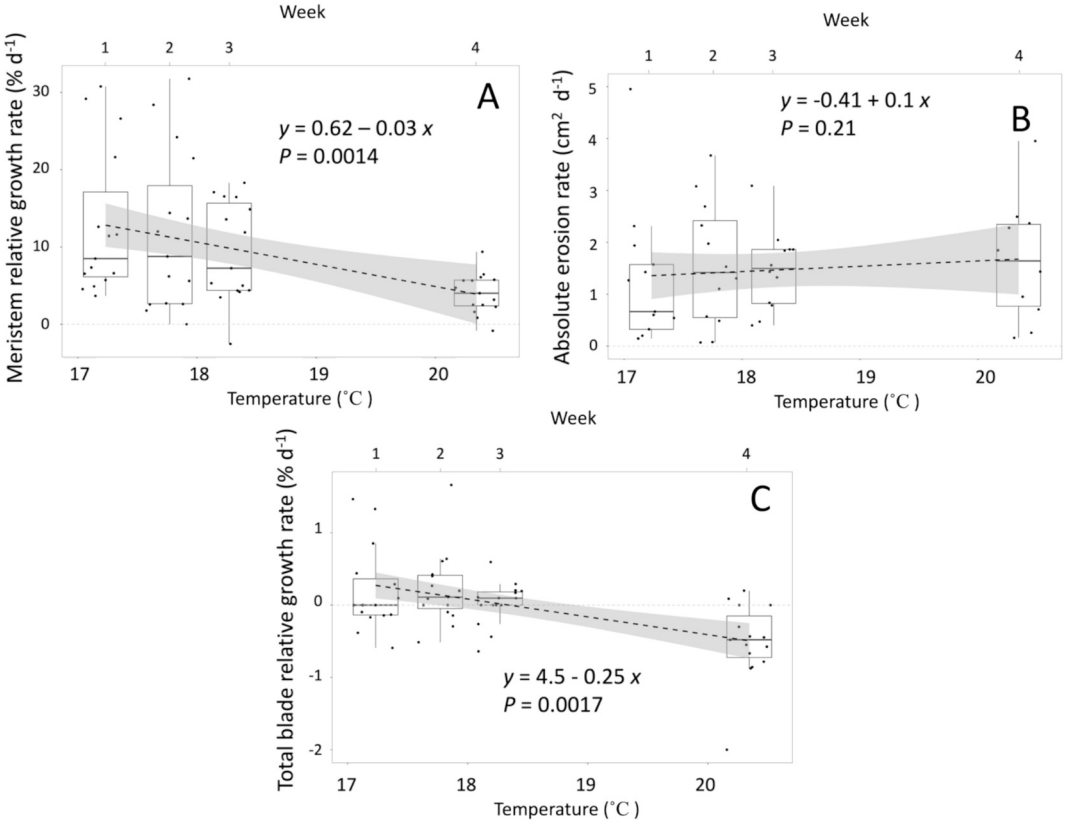

Fig. 3. Meristem growth (A), distal part erosion (B) and total blade growth (C) of S. latissima blades at 5 sampling points over time with increasing temperature in Experiment 1. (A) Relative growth rate of the meristem part (% d^{-1}). (B) Absolute erosion rate (cm^2 d^{-1}). (C) Relative growth rate of total blade (% d^{-1}). The x-axis represents temperature (°C), with a secondary x-axis displaying the corresponding week numbers. The boxes show the lower and the upper quartile, the horizontal line in the middle of each box indicates the median value. The dash lines show the relative regressions lines and shaded regions show the 95 % confidence interval. The regression equations and *p* values are listed in each plot.

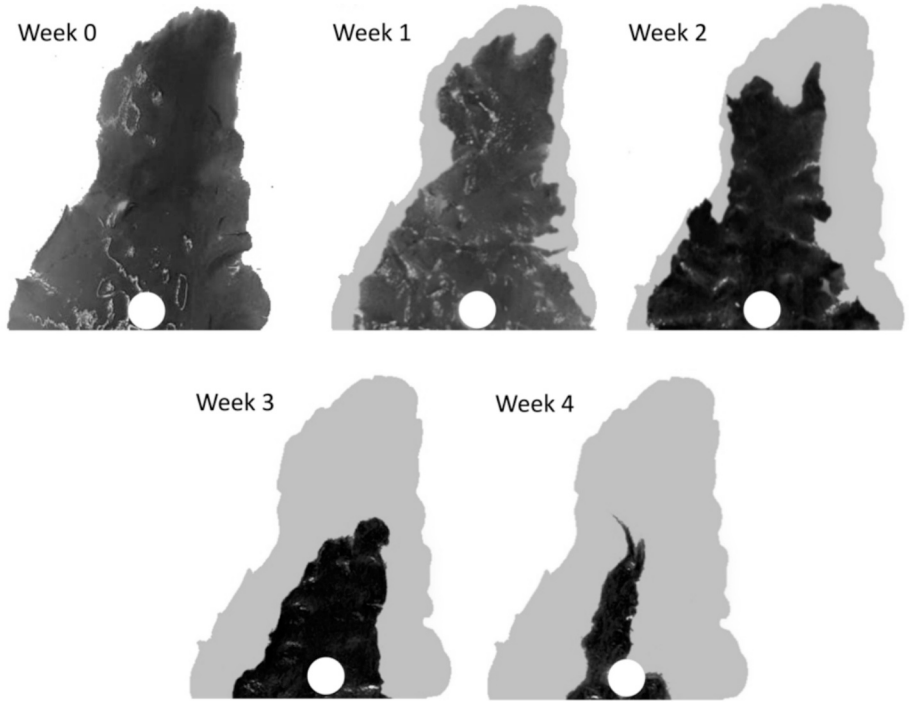

Fig. 4. Distal erosion in the randomly selected S. latissima individual, measured at 5 sampling points over time. White circles indicate where holes were punched on the distal part. Grey shadows indicate the initial surface area of the individual in week 0.

Table 1
The average concentration of total organic carbon (TOC) and total nitrogen (TN) in the distal part of *S. latissima* blades at the start and end of the experiment, expressed as % dry weight (DW) and in mg per cm^2. The significant level of $p < 0.01$ for each parameter was indicated by different letters.

Time	TOC (% of DW)	TN (% of DW)	TOC (mg cm^{-2})	TN (mg cm^{-2})
Start	30.37 ± 0.02 [a]	3.08 ± 0.45 [a]	4.06 ± 0.28 [a]	0.45 ± 0.06 [a]
End	32.98 ± 0.02 [b]	1.31 ± 0.15 [b]	4.41 ± 0.24 [b]	0.18 ± 0.02 [b]
Overall	31.68 ± 0.02	2.20 ± 0.95	4.24 ± 0.31	0.32 ± 0.13

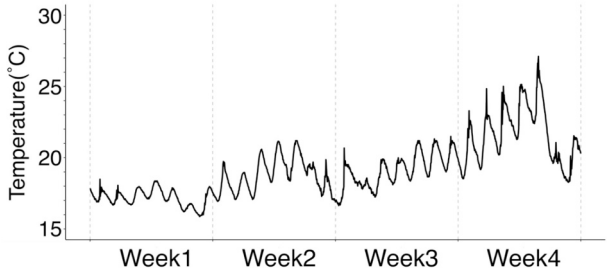

Fig. 5. Hourly recorded seawater temperature (°C) in Experiment 2. Vertical lines indicate the sampling point of the *S. latissima* blades.

mg N cm^{-2}, respectively). This indicated that for every unit area of blade eroded from *S. latissima*, 4.24 ± 0.31 mg of C and 0.32 ± 0.13 mg of N are released. Based on the absolute erosion rate in the blade surface area, we calculated 6.28 mg organic C and 0.47 mg N has been released per day per individual.

3.2. Experiment 2: further elevated temperature

As expected, water temperatures in the further elevated temperature treatment increased faster than under natural warming (Experiment 1),

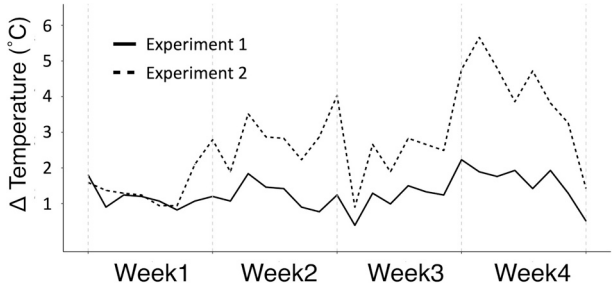

Fig. 6. Daily temperature amplitudes (°C) in both Experiment 1 & 2. Vertical lines indicate the sampling points of the *S. latissima* blades.

with temperatures above 21 °C for 13 days (Fig. 5). Weekly average temperatures were 17.2 °C, 18.8 °C, 19.1 °C and 21.6 °C in week 1 to 4, respectively. The highest daily temperature observed was 4.6 °C higher than in Experiment 1, i.e., 27.1 °C in week 4. The strong drop in temperature towards the end of week 4 caused the average weekly temperature to be relatively low. The mid-week 3 to mid-week 4 period displayed high average temperature of 24.2 °C.

The temperature profiles suggest a strong day / night rhythm and we checked for the difference in daily amplitude between the two experiments. For Experiment 2 this was with an average 2.70 ± 1.30 °C which is 2.0-fold higher than the 1.30 ± 0.44 °C for Experiment 1 (Fig. 6). The maximum daily amplitude was up to 5.7 °C for Experiment 2, which is 2.6-fold higher than the 2.2 °C for Experiment 1.

The RGR of the meristem part of *S. latissima* blades in Experiment 2 (Fig. 7A) showed a distinct and steady decline with increasing temperature ($p < 0.0001$), ultimately dropping to near 0 % (=no growth) per day by week 4 under 21.6 °C. In contrast to Experiment 1, the absolute erosion rate exhibited a significant increase ($p = 0.0018$) with increasing temperature, rising from 1.0 cm^2 per day in week 1 under 17.2 °C to 3.6 cm^2 per day in week 3 under 19.1 °C (Fig. 7B). The gradually increase in absolute erosion rate and the decrease RGR of meristem led to a faster decline in RGR of the total blade (slope = −0.47) compared to

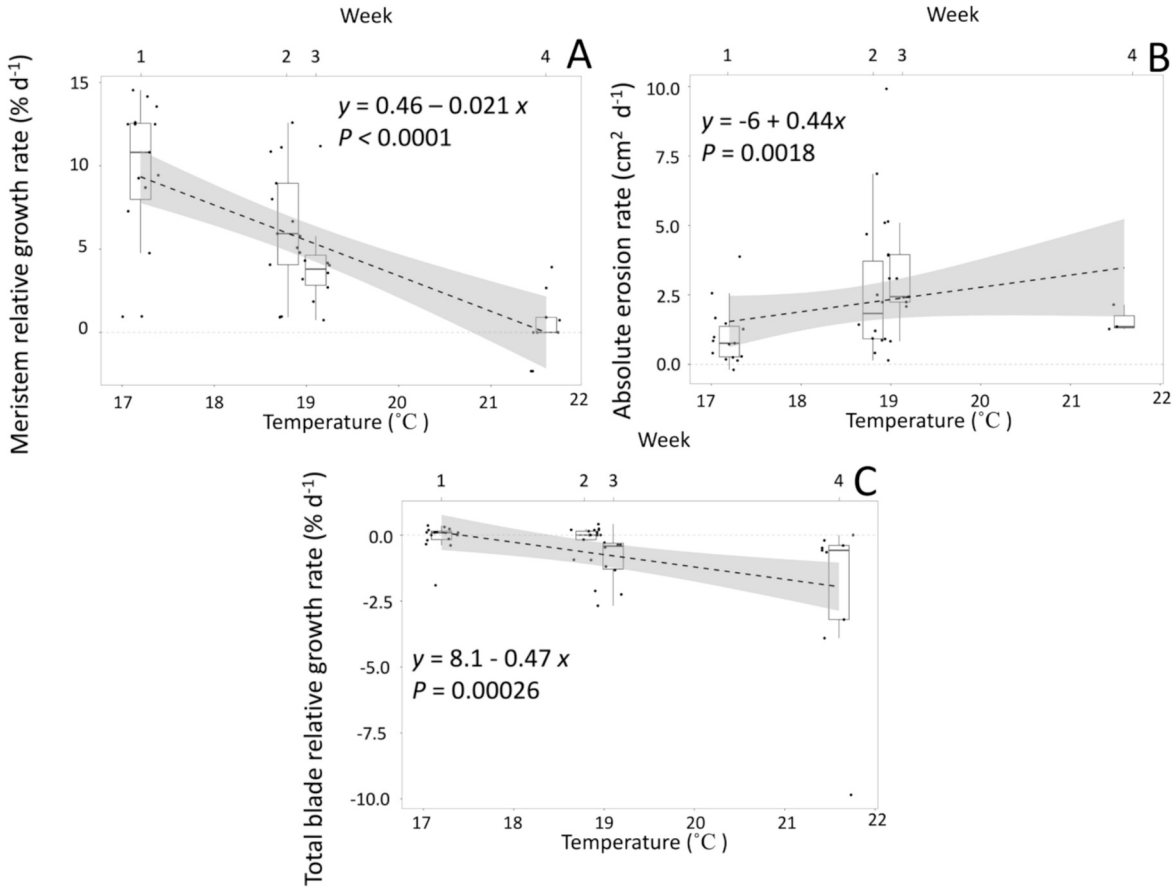

Fig. 7. Meristem growth (A) distal part erosion (B) and total blade growth (C) of *S. latissima* blades at 5 sampling points over time with increasing temperature in Experiment 2. (A) Relative growth rate (RGR) of meristem part (% d^{-1}). (B) Absolute erosion rate (cm^2 d^{-1}). (C) Relative growth rate of total blade (% d^{-1}). The x-axis represents temperature (°C), with a secondary x-axis displaying the corresponding week numbers. The boxes show the lower and the upper quartile, the horizontal line in the middle of each box indicates the median value. The dash lines show the relative regressions lines and shaded regions show the 95 % confidence interval. The regression equations and p value are listed in each plot.

Experiment 1 (slope = −0.25) and causing it to remain negative (Fig. 7C) throughout Experiment 2. Only 4 individuals (out of the 15) retained their distal parts of the blade by week 3. By week 4 only 2 individuals still had distal tissues beyond the hole punctured at 10 cm from the end of the blade. Obviously, higher water temperatures lead to higher erosion rates of *S. latissima* blades.

At the end of the experiments, the condition of the whole blades exposed to the artificially elevated temperature treatment showed that erosion had not only occurred in the distal part of the blade, but also along the edges of the whole blade (Fig. 8). This erosion of tissue along the blade indicates that blade erosion will be underrepresented when only consider the distal part, especially for the individuals exposed to the artificially elevated water temperatures.

4. Discussion

Effects of temperatures on growth rates of *S. latissima* have been investigated before, but to our knowledge, this is the first time a distinction was made between the effects of (elevated) seawater temperatures on growth and the quantification of blades erosion (two-dimensional approach), considering changes in total distal surface area and total organic carbon (TOC) and total nitrogen (TN) dynamics. The results of our study demonstrate that elevated temperatures accelerate the erosion of *S. latissima* blade and enhance the release of TOC and TN. Furthermore, our study provides insight into the decreased elongation rates and nutrient release of *S. latissima* at enhanced but still non-lethal temperatures.

In both experiments, temperatures exceeded 15 °C, which is reported as the maximum limit of optimal temperature for *S. latissima* growth (Bolton and Lüning, 1982). Still, temperature stayed below 20 °C the first three weeks in Experiment 1, which resulted in minor variation in RGR. Only after a further temperature increase in week 4 of Experiment 1 did the RGR decline substantially. The highest growth rate in this experiment was 13 % day^{-1} in week 1 (average temperature 17.2 °C), only slightly lower than the *S. latissima* meristem part growth rates of 15 to 18 % day^{-1} reported at 10–15 °C under natural conditions (Bolton and Lüning, 1982).

Water temperatures increased to a greater extent in Experiment 2, causing a steady decline in RGR. Although there was a significant drop in the growth rate of the meristem part in Experiment 2, it maintained positive until the end. The decrease in growth rate at elevated temperatures is probably due to reduced enzymes activity, which in turn limits the net photosynthetic capacity of *S. latissima*, thereby restricting its growth (Davison, 1991; Andersen et al., 2013; Nepper-Davidsen et al., 2019; Fales et al., 2023). It has been reported that in *S. latissima*, as a cold-water species, the Rubisco activase is sensitive to high temperatures (Salvucci and Crafts-Brandner, 2004). The meristem of *S. latissima* individuals only stopped growing above 23 °C, in line with the reported lethal temperature for this kelp species (Bolton and Lüning, 1982).

Net length and blade surface area changes under controlled temperatures were measured as indicators of *S. latissima* tissue loss, suggesting an increase in tissue loss with elevated temperature (Nielsen et al., 2014; Simonson et al., 2015). Our experiment not only supported these findings, but also quantified the erosion rate on the distal part of

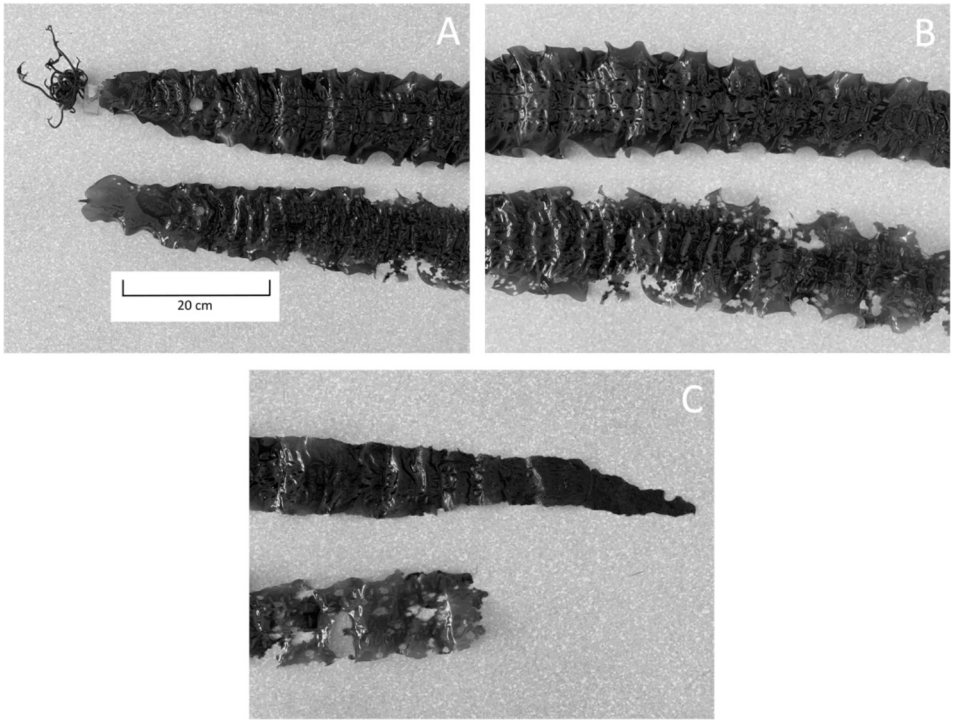

Fig. 8. Erosion in different areas of *S. latissima* blades measured at the end of the Experiment of 1 & 2. The top individual is from Experiment 1, the bottom individual is from Experiment 2. (A) The meristem part of blades. (B) The middle body of blades. (C) The distal part of blades.

S. latissima blades, both in surface area and in amounts of TOC and TN released. Substantial blade erosion occurred quickly with rising temperatures, even with relatively small temperature increases in Experiment 1. Blade erosion may thus serve as a rapid indicator of the effects of warming on kelps.

In addition, the effects of warming on kelps manifest through various internal and external stressors. High temperatures (18–21 °C) have been reported to cause damage and breaks in the cellular structure of *S. latissima* tissue (Simonson et al., 2015). It seems possible that *S. latissima* becomes more vulnerable once damage and breaks occur in the tissues, reducing its extensibility and increasing sensitivity to the effects of sub-lethal stressors such as unfavorable light conditions, waves, water quality, and even abrasion with other blades (Wernberg et al., 2013; Krumhansl et al., 2011; Krumhansl et al., 2016; Fales et al., 2023).

With the erosion of *S. latissima* blades, TOC and TN were released in the surrounding water, this carbon is either particulate organic carbon (POC), as detritus, or dissolved organic carbon (DOC) (Filbee-Dexter et al., 2024). Our measurements show that there is a significant difference in TOC and TN concentrations in the blades between the beginning and the end of the experiment. The decrease in TOC may be attributed to the destabilization of cell membranes caused by high temperatures, leading to the release of DOC (Gao et al., 2021), and breaks in the blade resulting in release of POC. Another potential factor is the reduced efficiency of photosynthesis under high temperatures, which limits C sequestration and contributes to the decrease in TOC. The low TN concentration at the higher temperature might be attributed to effects on enzyme activities: the optimal temperature for the key enzyme (nitrate reductase) in the N metabolism is 10 °C in *S. latissima* (Davison and Davison, 1987; Young et al., 2007). At elevated temperatures, the N uptake rate may have been limited, resulting in reduced TN concentration in the tissues.

With the quantification of TOC and TN release rates from *S. latissima* blades better estimations can be made of the coastal ocean nutrient cycle. Accurate measurement of these release rates is crucial because they should be included in the future models of the ocean carbon cycle.

Table 2
The concentration range of total organic carbon (TOC) and total nitrogen (TN) in the *S. latissima* blades, expressed as % dry weight (DW) and in mg per cm^2.

Sampling location of blade	TOC (% of DW)	TN (% of DW)	TOC (mg cm^{-2})	TN (mg cm^{-2})	Source
Distal part	30.4–33.0	1.3–3.1	4.06–4.41	0.18–0.45	This experiment
Blade	34.6–38.3	0.9–2.2	3.48–6.25	0.15–0.23	Nielsen et al., 2014
Blade	28.6–33.8	1.5–5.7	–	–	Sharma et al., 2018
Blade	21.3–28.5	1.6–3.8	–	–	Wang et al., 2014
Blade	23.4–29.8	1.0–2.0	–	–	Schiener et al., 2015

For instance, in the existing models, such as the one evaluating the potential of *S. latissima* in integrated multi-trophic aquaculture (IMTA) and the model of seasonal growth and TOC and TN concentrations of *S. latissima*, the erosion rate of blade was considered to be determined only by the size of the blade (Broch and Slagstad, 2012; Broch et al., 2013). However, our results demonstrate that the erosion rate of blades is significantly influenced by temperature. This finding suggests that temperature must be considered a key factor in determining the erosion rate of blades in these models. Considering temperature as a variable will refine the predictions of C and N release from kelp forests and enhance our understanding of the nutrient dynamics in coastal ecosystems.

To ensure that our results for C and N release rates is reliable and serve as a fundamental number for the future coastal ocean nutrient cycle, we compared our findings with data from the literature (Table 2). In our study, we used averages of TOC and TN concentrations to calculate nutrient release rate. Our results fall within a reasonable range compared to literature values, this alignment with existing data not only confirms the reliability of our results, but also underscores the

importance of our findings.

Based on findings from our experiments, we acknowledge that the C and N release rates in our study can be considered underestimates. Particularly under the more extreme elevated temperatures in Experiment 2, several individuals lost the entire distal parts (10 cm from the tip) of their blades before the end of this experiment. Once the erosion exceeded the mark we made, we could no longer quantify the area of tissue that had been eroded. We also observed (but could not quantify) that tissue erosion occurred all along the blade edges of individuals during Experiment 2. It is critical to recognize that these underestimates are not fully reflect the complex dynamics of kelp tissue erosion and nutrients release. Further investigations are needed to determine the mechanisms of nutrient release at different temperatures. A more detailed understanding of these processes is essential for assessing their ecological impacts and improve models of coastal nutrient cycle.

In our study, we used two 1500 L incubation tanks to contain the individuals of each treatment group, and a flow-through (10 % of volume added per day) filtered seawater system was employed to maintain consistent water quality. This design rendered equal conditions in both incubation tanks and minimized environmental competition effects between individuals, thereby reducing the potential for pseudoreplication. To further improve, we recommend future studies consider increasing the number of replicates with multiple tanks to reduce the possibility of potential design-related bias.

In conclusion, our findings underscore the adverse effects of elevated sea surface temperatures on the growth and erosion dynamics of *S. latissima*. Elevated temperatures not only suppress meristematic growth but also accelerate tissue loss and nutrient release, likely altering nutrient cycling within kelp ecosystems. These results consistent with previous studies (Nielsen et al., 2014; Simonson et al., 2015) highlighting increased kelp tissue loss under warming conditions. However, our study advances this understanding by quantifying blade erosion and nutrient release, offering critical insights into these processes. Furthermore, the observed changes in growth and erosion rates under elevated temperature scenarios underscore a significant threat to the resilience of kelp forests. Such dynamics suggest that rising temperatures, exacerbated by marine heatwaves, could impair the ability of *S. latissima* to sustain population structures and provide habitat. The accelerated release of TOC and TN could affect the surrounding marine ecosystem, potentially altering local biogeochemical cycles. Our research highlights the essential role of kelp ecosystems in global nutrient and carbon budget and underscores the consequences of underestimating their value. Protecting and restoring these ecosystems is vital to maintaining their ecological functions.

Author statement

This manuscript has not been published or presented elsewhere in part or in entirety and is not under consideration by another journal. We have read and understood your journal's policies, and we believe that neither the manuscript nor the study violates any of these. There are no conflicts of interest to declare.

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CRediT authorship contribution statement

Xiaowei Ding: Conceptualization, Data curation, Formal analysis, Investigation, Visualization, Writing – original draft, Writing – review & editing. **Corina P.D. Brussaard:** Conceptualization, Writing – review & editing. **Klaas R. Timmermans:** Conceptualization, Project administration, Visualization, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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