

Peer Review File

Deep-living and diverse Antarctic seaweeds as potentially significant contributors to global carbon fixation



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Web links to the author's journal account have been redacted from the decision letters as indicated to maintain confidentiality

15th Nov 23

Dear Dr Tait,

Your manuscript titled "Deep-living and diverse Antarctic seaweeds as significant contributors to global carbon fixation" has now been seen by 2 reviewers, and we include their comments at the end of this message. They find your work of interest, but some important points are raised. We are interested in the possibility of publishing your study in *Communications Earth & Environment*, but would like to consider your responses to these concerns and assess a revised manuscript before we make a final decision on publication.

We therefore invite you to revise and resubmit your manuscript, along with a point-by-point response that takes into account the points raised. In particular, we ask that you address the concerns of Reviewer #2 and demonstrate that your analysis is sufficiently robust and accurate to support your claims. Please highlight all changes in the manuscript text file.

We are committed to providing a fair and constructive peer-review process. Please don't hesitate to contact us if you wish to discuss the revision in more detail.

Please use the following link to submit your revised manuscript, point-by-point response to the referees' comments (which should be in a separate document to any cover letter), a tracked-changes version of the manuscript (as a PDF file) and the completed checklist:

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Please do not hesitate to contact us if you have any questions or would like to discuss these revisions further. We look forward to seeing the revised manuscript and thank you for the opportunity to review your work.

Best regards,

Clare Davis, PhD
Senior Editor
Communications Earth & Environment

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REVIEWER COMMENTS:

Reviewer #1 (Remarks to the Author):

This is the most important paper on Antarctic ecology that I have read in quite a while. It dramatically extends the geographic and, particularly, the (believable) depth ranges for large Antarctic macroalgae but goes well beyond that using physiological and habitat modeling to convincingly demonstrate that they are probably making a much bigger contribution to benthic food webs and potentially to blue carbon sequestration than previously thought. I am confident that this paper will change how people think about the importance of the Antarctic macrobenthos.

My comments are all relatively minor and are listed more or less in order of appearance in the manuscript, not by importance. I am a firm believer that peer review should normally be anonymous, but feel that exceptions are appropriate where the review would pretty much identify the reviewer anyway and where having that explicit might be constructive. That is the case here. – Chuck Amsler

Introduction:

The last line of the first paragraph notes the lack of information on contributions of Antarctic macroalgae to blue carbon, but fails to cite perhaps the most relevant, recent paper on this topic. Morely et al. 2022 *Biology* 11:320 doi 10.3390/biology11020320

Third paragraph: This is a bit self-serving, but this paragraph notes that changes in sea ice coverage is one of the ramifications of climate change, and the authors come back to that in the Discussion. While the paragraph talks about what we know about the impacts of glacial retreat on macroalgae – both ‘positive’ and ‘negative’ – it says nothing about what we know about the impacts of decreasing sea ice. Amsler et al. 2023 *Elementa* 11:00020 doi 10.1525/elementa.2023.00020 is all about that, including very crude projections to future communities.

Last paragraph: The 2006 records of *Himantothallus* are not the southernmost – or only southernmost – that are in the literature. Zanaveld (1966) also reported it from the Possession Island (72° 00' S) plus from Cape Hallett (72° 25'). Zaneveld, J.S. 1966. The occurrence of benthic marine algae under shore fast-ice in the western Ross Sea, Antarctica. *Proceedings of the International Seaweed Symposium* 5: 217-231.

Zaneveld (1968) also has it from Cape Adair and the Possession Island. A plate from Neushul's contribution to the same publication has a dot for it much further south, but Zaneveld's plate does not and if there were a record of it there, it would have been his. So Wiencke and I concluded that was a mistake on Neushul's plate when we put together the 2014 map etc. contribution. Zaneveld, J.S. 1968. Benthic marine algae, Ross Island to the Balleny Islands. *Antarctic Map Folio Series* 10: 10-12, pl. 13.

Results and discussion:

Christian Wiencke has also observed *Himantothallus* at 70 m in ROV video from South Georgia. Unlike here though, he did not publish it other than to include it as an unpublished observation in our 2012 review. So I guess it is sort of “published unpublished.” 8^ Since it is not “published

published” I am not advocating one way or the other for its inclusion here, but in case the authors were not aware of it, felt I should mention it. It supports their observations.

There are a number of reports of Antarctic macroalgae in deep water and I tend to be skeptical of them. Figure 1 parts C and D, however, are absolutely convincing for *Himantothallus* and crustose corallines. That is exactly what attached *Himantothallus* should look like. Although I cannot be as certain of the fleshy reds, the way they are dispersed is certainly consistent with them being attached (drift is very often more clustered), and the fact that attached *Himantothallus* is there too makes me a believer.

With respect to Figure 1 C and D, and really B too, I could not tell that on a printout of the manuscript. I had to go to the electronic version and zoom the images 200-250%. It is even hard to read the labels on C and D. These images are very important for the believability of the story. They should be large enough that someone reading a printout of a PDF version of the paper could see them. Also with respect to these parts of the figure, I suggest noting the depth in the figure caption. I gather from where they are cited in the text that they are “c. 70 m” but it would be useful to have that explicit as part of the caption.

First line of bottom paragraph on pg. 3: Here and I think elsewhere (certainly once in the Methods) the term “species” is used too loosely. Neither “brown algae” nor “red algae” are “species” (and *Himantothallus* is a brown alga too). Reword.

Other than *Himantothallus* and *Palmaria*, there is no indication of what species were actually found. In the Specimen collections section of the Methods it says that they used grabs and benthic sleds to get actual specimens and that these will be deposited into a herbarium. It would be really valuable to have an idea just what species they found. Perhaps the authors intend a follow-on paper with more information about the depth distributions of individual taxa (I certainly hope they do!) but I would not think that mention of what species they found here (perhaps in supplementary material) would preclude that. I find their categories of turfs and greens particularly curious. I am not aware of Antarctic reports of algal turfs like those often reported at lower latitudes. I do know that *Ballia*, which I suppose could form something of a turf if growing much denser than I’ve ever seen it grow, is reported from the Ross Sea. As for greens, the only subtidal ones I am aware of are *Monostroma*, which is shallow-growing and ephemeral, *Lambia antarctica*, and *Chaetomorpha* (formerly *Lola*) *irregularis*. *Lambia* has never been reported south of the Peninsula but grows deep there. *C. irregularis* is only reported from the Ross Sea, which makes me think it may be this. Or is there something new?

The EBed methodology is new to me but the comments here and in the Methods about the impact of unrepresentative values of K_d would not surprise me. The times of year – mostly mid summer and its shoulders – when people are making measurements are in my experience at least when water clarity is the worst. It is much better for long periods thereafter, up until annual ice forms, and for shorter periods prior to that after the annual ice breaks out. The latter probably isn’t long enough to make much of a difference. But the later season period probably is long enough. It seems that somewhere in Antarctic waters there should be a quantitative report of such a pattern although I do not know of such a report and would be very surprised if it were from the study area.

End of last full paragraph on pg. 7: Krause-Jensen et al 2019 (doi 10.3389/fmars.2019.00375) reports kelp to at least 61 m (deepest they looked) in Greenland (67-70° N). I suggest replacing reference

54, which is a technical report, with this paper since people can actually get to and see it. There is also a Schimani et al. 2022 (doi 10.1007/s00300-022-03072-x) report of reds as deep as 68 m in Spitsbergen (78.9° N)

Reviewer #2 (Remarks to the Author):

The present article is relevant due to the pressing need to reduce emissions and increase carbon removal from the atmosphere that is now also leading to the development of natural climate solutions in the ocean. The ocean provides major opportunities to mitigate and adapt to climate change, and the largest habitat with primary productivity should not be ignored simply because it does not fit into existing frameworks.

The interest in the carbon sequestration potential of underwater macroalgal forests is growing rapidly among policy, conservation, and corporate sectors. Yet, our understanding of whether carbon sequestration from macroalgal forests can lead to tangible climate change mitigation remains severely limited, hampering their inclusion in international policy or carbon finance frameworks.

Pessarrodona et al. (2023)** used over 180 publications to synthesise evidence regarding macroalgal forest carbon sequestration potential. The authors showed that research efforts on macroalgae carbon sequestration are heavily skewed towards particulate organic carbon (POC) pathways (77% of data publications), and that carbon fixation is the most studied flux (55%). Fluxes leading directly to carbon sequestration (e.g. carbon export or burial in marine sediments, such as mentioned in the submitted article) remain poorly understood, mainly in polar ecosystems. Likely, hindering regional or country-level assessments of carbon sequestration potential, which are only available from 17 of the 150 countries where macroalgal forests occur. Current estimation of natural sequestration value of all macroalgal habitats is between 61–268 Tg C year⁻¹, depending on latitude, it suggests that macroalgal beds could add greatly to the coastal blue carbon. Mitigation in polar and temperate areas where blue carbon is currently low, and less studied, will depend on better operationalizing of that potential, development of models that reliably estimate the proportion of production sequestered, improvements in macroalgae carbon fingerprinting techniques, and a rethinking of carbon accounting methodologies. And the present article tries to add some information in these regards.

Also specific techniques related to bloom production and management, or the utilization of biomass for biomaterials, should be fostered. As example Gouvea et al. (2020) suggested that *Sargassum*, a tropical and subtropical brown seaweed, contribute with ca. of 13 Tg C/year at the global scale, which is a significant amount of carbon, comparable to other key marine/coastal ecosystems, including mangroves, salt marshes and seagrass meadows.

However the Questions that the authors could address in the present submission are:

- Are the combined methods used based on previous literature, ROV surveys and models really accurate to estimate the area and biomass for Antarctic seaweed beds between 70 and 100 m depth? ^[L1]_[SEP] Antarctic seaweed biomass, whose estimation in the article is non-destructive and of low accuracy, really shows a significant carbon stock, comparable to other marine ecosystems? compare

data in a Table from Temperate and tropical ecosystems? How much in fact Antarctic seaweeds may contribute to climate change mitigation by removing CO₂ atmospheric?
I suggest to Include in discussion data published in the South Shetland Islands (SSI) and WAP, higher seaweed richness zones (please see Pellizzari et al 2017, 2020 and 2023; Oliveira et al. 2020).
How do you recommend that restoration and management initiatives should be fostered to preserve the polar seaweed carbon in Southern Ocean ?

Other recommendations:

- This article used previous photosynthetic rates and global light modeling to estimate carbon fixation for antarctic seaweeds however ::
Assuming that ROV in general has grabbers or collecting arms, the absence of herbarium voucher numbers for the seaweed species new records (between 70 and 100 depth) also is a fragile point in the article

The article is quite speculative, and use many extrapolation data (please see an ex. At line 160) based on previous literature, ROV observations (with limited sampling ability), and modeling with low accuracy in some part of methodology.

MATERIALS AND METHODS ((should be placed before “Results and Discussion” aiming to provide a big picture of the study to the reader / reviewer)):

Should also refers to:

- (1) Literature searches and data compilation
- (2) Assessments of macroalgal beds sequestration potential using global light /irradiance modeling from the sea-bottom
- (3) ROV use
- (4) Functional seaweed groups analysis
- (5) Seaweed physiological capabilities

(please see manuscript in attach with detailed suggestions) and I recommend to update data along the text using the suggested references along the manuscript.

((Pessarrodona et al. (2023)** Carbon sequestration and climate change mitigation using macroalgae: a state of knowledge review.
Biol. Rev., doi: 10.1111/brv.12990))

I suggest to suppress "deep-living" seaweed from the title due to the simple ecological definition of euphotic zone limitation in Austral Ocean (less than 200 m), you could use another term such as "lower subtidal zone".

As well as to suppress "diverse"- due to low richness of seaweeds registered in Antarctica compared to other global areas (please see Pellizzari et al. 2023 - Antarctic Science; Pellizzari et al 2020 and Oliveira et al, 2020 both in Gomez & Huovinen 2020)) Besides the authors focused only in 3 Antarctic seaweed spp.

Deep-living and diverse Antarctic seaweeds as significant contributors to global carbon fixation

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Abstract

Global models predict that Antarctica has little suitable habitat for macroalgae and that Antarctic macroalgae therefore make a negligible contribution to global carbon fixation. However, shallow coastal surveys are rare at southern polar latitudes (beyond 71° S), and we here report diverse and abundant macroalgal assemblages in previously un-navigated coastal habitats of the Ross Sea near 72° S. We found significant macroalgal assemblages living at depths (>70 m) where they are rarely seen in temperate regions. Using global light modelling and published photosynthetic rates we estimate that Antarctic macroalgae may contribute between 0.05 – 6 % of the estimated global macroalgal carbon fixation. Combined, these factors suggest that Antarctic macroalgae may be a greater contributor to global carbon fixation and sequestration than previously thought, and that the vulnerability of coastal environments to climate change, especially sea ice extent and persistence, should be considered in Southern Ocean carbon budgets.

please check this info or rewrite the sentence aiming to clarify

Key words: macroalgae, carbon fixation, carbon sequestration, light, Antarctica, Blue-carbon, climate change

Introduction

Seaweeds are increasingly recognised for their value in contributing to global carbon sequestration or 'Blue Carbon' [1-5]. Transport of seaweed biomass to subtidal sediments can result in between 0-10% of that biomass becoming buried and locked away from the atmosphere [6], with cold polar environments likely to encourage greater rates of sequestration [7]. Efforts to quantify Arctic macroalgal blue carbon suggest that the carbon sequestered is globally significant [7-9] but there is almost no information on the blue carbon contribution of Antarctic seaweeds [10-12].

Please check: Pessarrodona et al (2023)
Biol. Rev. (2023), pp. 000–000. doi: 10.1111/brv.12990
Carbon sequestration and climate change mitigation using macroalgae:
a state of knowledge review

39 Global models predict that the Antarctic continent has very little suitable habitat for marine
40 macroalgae [13]. Large-brown macroalgae (e.g., kelps, fucoids and desmarestiales) provide key
41 ecological functions such as habitat provision and are the dominant contributor to global macroalgal
42 primary productivity [13]. However, observations of Antarctic macroalgae are sparse and limited to
43 particular regions, such as the Antarctic Peninsula (for review see Wiencke et al. 2014 [14]). Despite
44 this paucity of data, Antarctic macroalgae have been identified reaching standing biomass
45 comparable to temperate kelp forests [15-17]. These macroalgae provide key habitat for microalgae,
46 invertebrates and fish [18-20], are important drivers of benthic foodwebs through detrital subsidies
47 [21,22], and may contribute significantly to carbon sequestration [1,10]. High rates of macroalgal
48 material delivered to deep water in the Antarctic (>2000 m; [23]) indicate that Antarctic macroalgae
49 meet key criteria for long-term carbon sequestration [1].

50 Greenhouse gas emissions and the associated atmospheric and oceanic warming are causing
51 unprecedented glacial retreat [24,25] and changes in sea-ice cover [26-28]. Glacial retreat and the
52 associated increases in meltwater and delivery of sediments to coastal environments are rapidly
53 changing the land-sea dynamics of the Antarctic continent with both positive and negative
54 implications for macroalgal carbon sequestration [29,30]. While there has been particular focus on
55 the gains in blue-carbon associated with new benthic territory availability with glacial loss [30-33],
56 there are, however, several mechanisms that could result in losses of blue-carbon, such as increasing
57 benthic disturbance from ice bergs [34, 35]. Increasing water column suspended sediments
58 (associated with glacial meltwater) or phytoplankton abundance have direct effects on the
59 attenuation of light through the water column [36,37], the impacts of which are felt greatest at
60 depth [38]. Understanding the depth distribution of Antarctic macroalgae is critical in assessing
61 existing carbon sequestration pathways and changes to these pathways as glacial and sea-ice
62 dynamics shift biophysical parameters of the Southern Ocean. biotic, physical and chemical parameters

63 Light availability at the seafloor is a fundamental physiological limitation that determines both the
64 latitudinal and depth ranges occupied by benthic macroalgae [37]. Despite the challenges for light
65 harvesting at polar regions, thriving populations of benthic algae (particularly rhodophytes) are
66 found at latitudes approaching 78° north and south [16]. As exploration of Antarctic benthic
67 ecosystems increases, records of deep living algae are increasingly being reported (e.g., red alga
68 *Palmaria decipiens* found at c. 100 m; [39]). Adaptation to low light intensities is a key attribute of
69 Antarctic macroalgae [40,41], but there are few verifiable records of large canopy-forming brown
70 algae beyond the Antarctic Peninsula [14]. The southernmost observed population of the large
71 brown algae *Himantothallus grandifolius* were found at 72° S in the Ross Sea in 2006, during
72 explorations at 20 m depth [42-45]. Therefore, the current paradigm is that canopy-forming brown
73 macroalgae are greatly limited in both their southern distribution [14] and their habitable depth
74 range in Antarctica.

Methods ??

75 Results and discussion

76 Here, we report dense populations of attached canopy-forming brown algae (ochrophytes *H.*
77 *grandifolius*) at up to c. 75 m depth at multiple locations on the northern Victoria Land Coast in the
78 Ross Sea, Antarctica; Robertson Bay, Cape Adare, Possession Islands, Cape Hallet. At several stations,
79 including a transect completed at c. 70 m depth at the Possession Islands in 2021 (Figure 1 A), dense
80 populations of large, attached specimens with fronds up to c. 3 m length were identified (Figure 1 B,
81 C), as well as dense populations of fleshy red algae, and encrusting calcareous algae (Figure 1 D).

see also:
Pellizzari et al.
2017; 2020,
and 2023

please see Gouvea et al.
(2020)
Golden carbon of
Sargassum forests
revealed as an
opportunity for climate
change mitigation
April 2020 The Science of
The Total Environment
729(10):138745
DOI:10.1016/
j.scitotenv.2020.138745
and also mentions and or
compare with
tropical budgets

icebergs // no -

at higher bathymetric zones
vertical distribution

line 65 - at SSI
Himantothallus
grandifolius
(Phaeophyceae) and
crustose calcareous
red algae may be
found below 40-50 m
depth in Antarctic
waters

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Arctic
and Antarctic? please
provide more
references and check
info regarding
seaweed groups
distribution
(Rhodophyta,
Phaeophyceae and
Chlorophyta)

Ochophyta /
Phaeophyceae

Please provide
voucher herbarium
numbers
for the sampled
biological material

assuming that the ROV
possess grabs

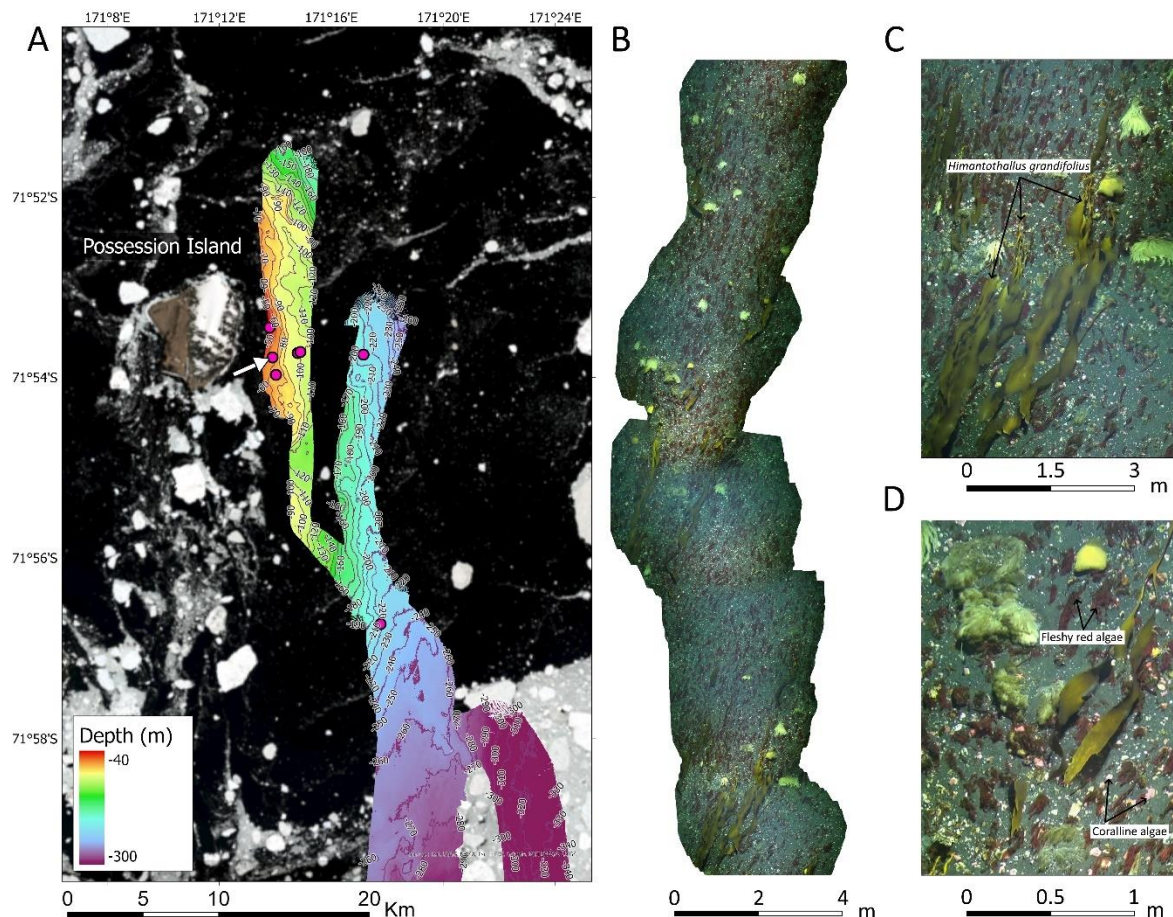


Figure 1. Multi-beam echosounder map of the seafloor bathymetry near the Possession Islands, Ross Sea, overlaid on Landsat (USGS) satellite imagery (A). Each station surveyed in 2021 and 2023 are shown by circles, including the first station where large macroalgae were detected in 2021 (as indicated by white arrow). Orthoimage of the benthos at this station shows dense macroalgal assemblages on the seafloor (B), including dense stands of *H. grandifolius* (C), coralline, and fleshy red algae (D).

Several species and distinct macroalgal taxonomic groups were identified across the northern Victoria Land Coast, including rhodophytes (red algae), chlorophytes (green algae), and ochrophytes (brown algae) (Figure 2 A). *H. grandifolius* was found as far south as Cape Hallet (72.2° S) but did not extend to the southern-most site (Wood Bay, 74.5° S), and has not to our knowledge been observed previously at the intermediate latitudes. Observations of macroalgae across depths revealed that coralline algae were present at depths greater than 100 m, while red bladed algae, brown algae, and *H. grandifolius* were observed between depths of 75 – 90 m (Figure 2 B).

H. grandifolius is a brown algae

Drift algae of several different species (e.g., brown algae, *H. grandifolius*, and red algae) were common at depths beyond 100 m, including several incidences of *H. grandifolius* at depths greater than 200 m. The high frequency of apparent drift algae at a range of depths increases the difficulty in reconciling the true habitable range of macroalgae in Antarctica but suggests that transport rates to deeper water may be high.

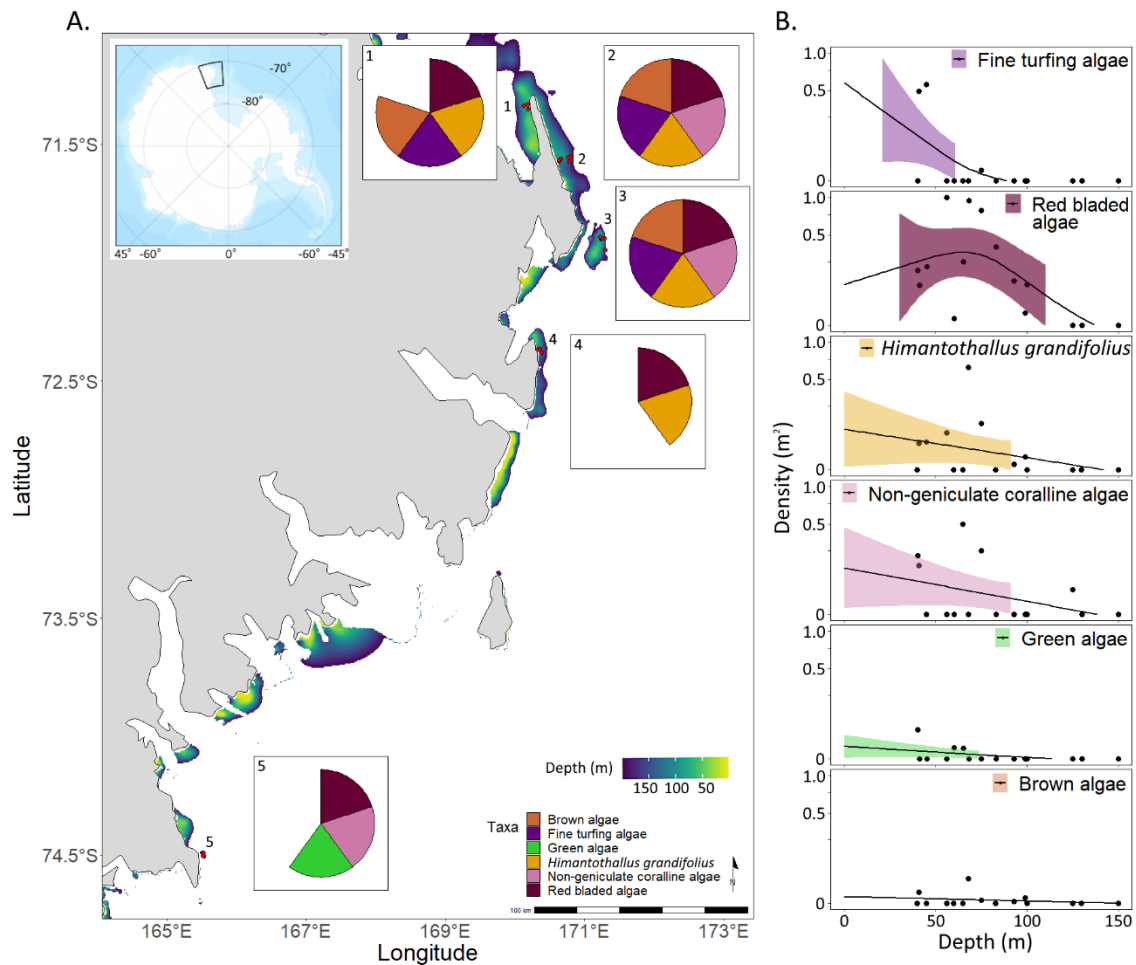


Figure 2. Presence and depth distribution of several functional groups of macroalgae across stations (red dots) in the Ross Sea Region (A). Available global bathymetric data are presented and bounded between 0-200 m depth. Pie charts show the presence of macroalgal functional groups at each location (numbered 1-5, for Robertson Bay, Cape Adare, Possession Islands, Cape Hallet and Wood Bay, respectively). The depth distribution of each macroalgal group across all stations (B) shows the density of individual thalli for each transect. Note the y-axes are square root transformed to visualise transects where very low densities were recorded. Depth and density data are fitted using general additive models (GAM).

The presence of deep-living macroalgal populations and the high incidence of drift algae required a closer look at light budgets at these depths for the Antarctic region. To explore this, we used estimates of light at the seabed (EBed; [37]), to: 1) understand the likelihood that these populations are a persistent feature (i.e., is the modelled available light consistent with known limits); and to 2) re-assess estimates of the possible regional distribution of Antarctic macroalgae.

Global seafloor light [37] showed that light intensities at our surveyed locations and depths were in some cases $< 0.1 \text{ mol m}^{-2} \text{ day}^{-1}$ (Figure 3). When mapped against modelled seafloor light intensities, there were some observations that were inconsistent with expected light intensities at the surveyed depths and latitudes (e.g., $< 0.02 \text{ mol m}^{-2} \text{ day}^{-1}$) (Figure 3). We expect that three key mechanisms may be responsible for these observations: 1) Antarctic macroalgae are remarkably adapted to low light intensities, 2) transport of macroalgae to deeper water, even while still attached to substrata, occurs frequently in the Antarctic, and 3) estimated EBed may be less than realised EBed during certain periods.

please provide detailed methodology

please provide detailed methodology

it is! there are several physiological special features and biochemical arsenal that provide low light adaptation

estimates of light at the seabed

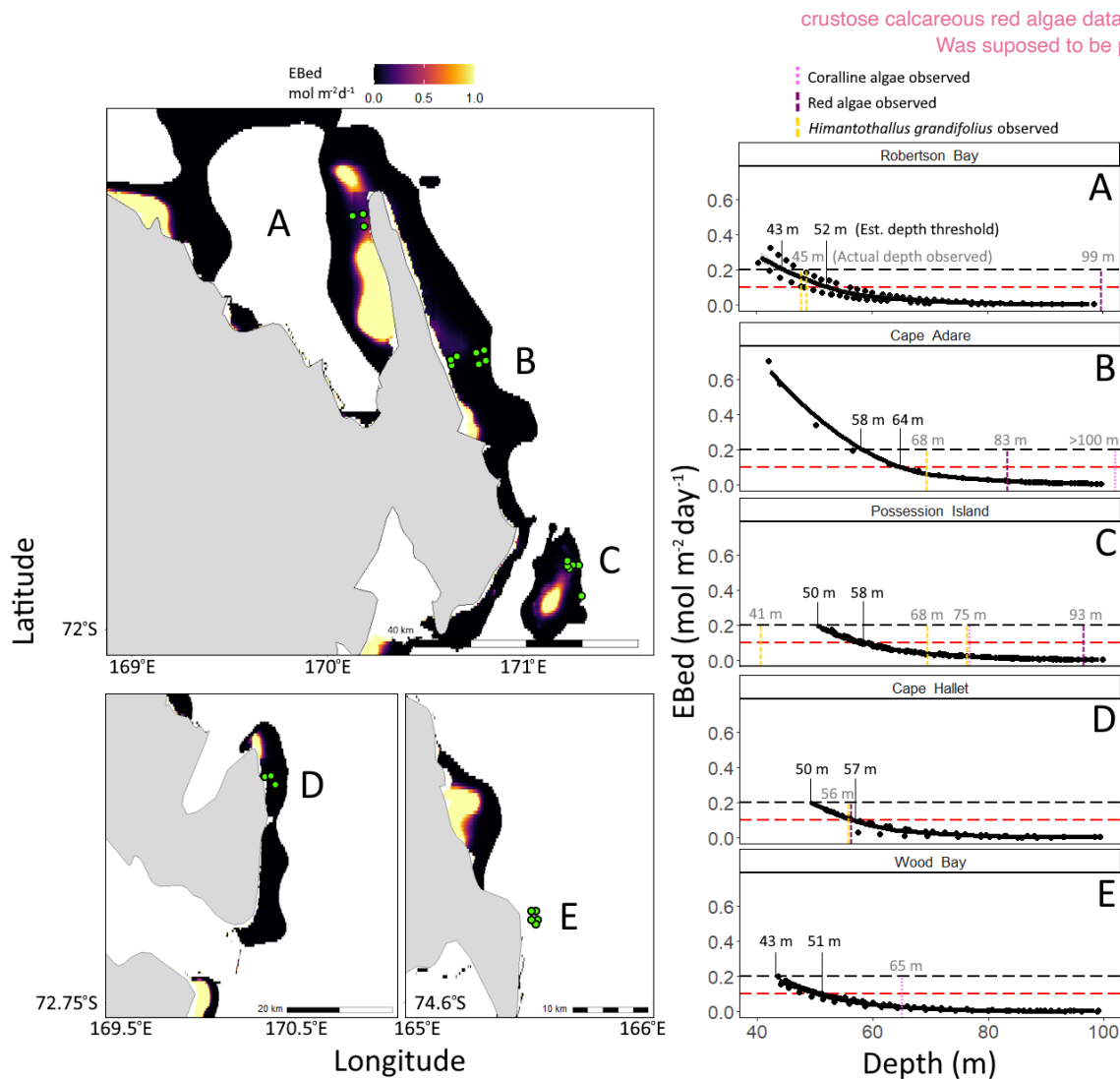
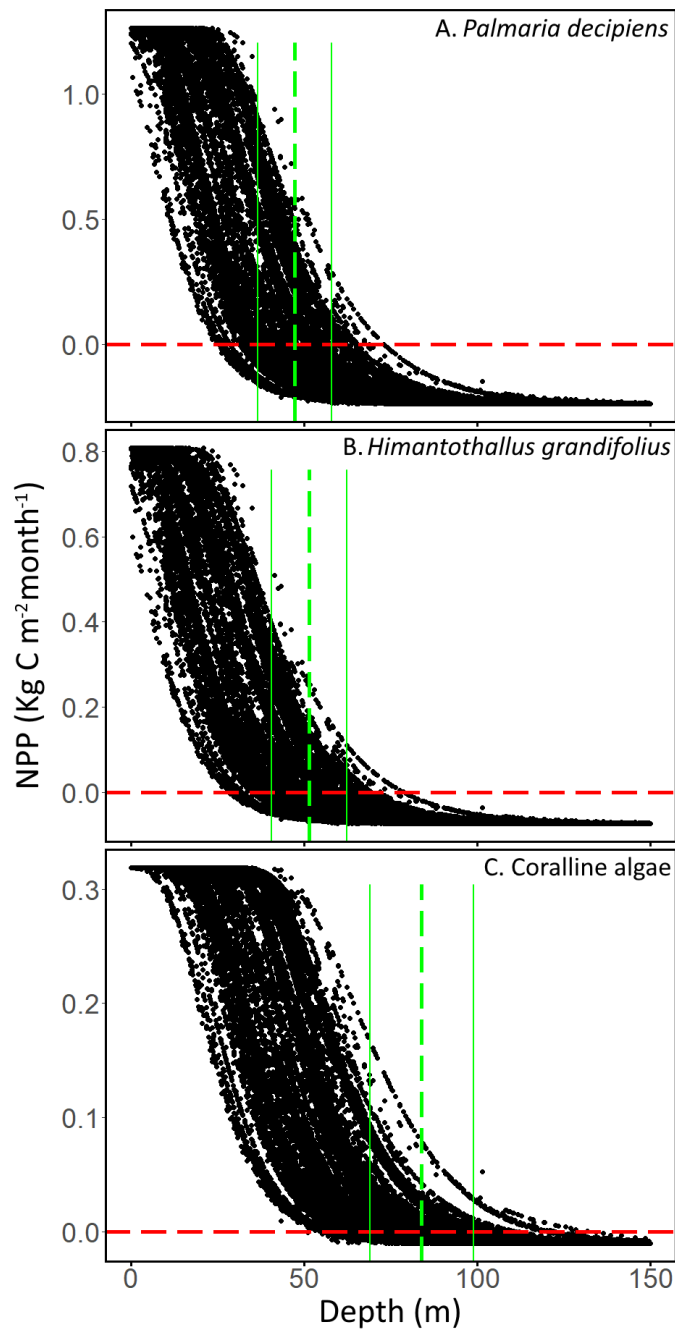


Figure 3. Seabed light availability for the coastal Ross Sea ($\text{EBed mol m}^{-2} \text{ day}^{-1}$) as identified with global bathymetric layers, annual surface light budgets, and water clarity estimates (Gattuso et al. 2020 [37]). Green points show locations of benthic surveys performed in 2021 and 2023. EBed across depths is reported for the five surveyed regions (A – E), averaged over three transects (across depth gradients, perpendicular to shore). The depths at which light falls below two thresholds (0.1 and $0.2 \text{ mol m}^{-2} \text{ day}^{-1}$; indicated by red and dashed horizontal lines, respectively) was reported for each region (vertical solid black lines), as well as the depths at which clearly attached populations of *H. grandifolius*, red algae, and coralline algae were observed (vertical dashed lines). Note that the bathymetry at some sites (i.e., Wood Bay, E) was not resolved by global products and therefore not included in global models (e.g., Duarte et al. 2022 [13]).

We examined the physiological capabilities, and possible depth thresholds of several Antarctic macroalgae by extrapolating seabed light (EBed) across modelled values throughout ice-free regions of the Ross Sea region. The results indicate that the red algal species *P. decipiens* has potential net carbon gains at depths between 0 – 70 m (mean = 45 m), *H. grandifolius* to approximately 75 m (mean = 50 m), and coralline algae as deep as 125 m (mean = 80) (Figure 4). While results showed some alignment with our observations of macroalgal maximum depths (i.e., 75 m and 120 m for *H. grandifolius* and coralline algae, respectively), we note that occurrences of red algae were seemingly beyond the edge of physiological capabilities for light harvesting according to modelled Ebed, and greater than expected from physiological modelling of *P. decipiens*.



Crustose coralline algae (CCA)

Figure 4. Net primary productivity of three species (*P. decipiens*, A), (*H. grandifolius*, B), (~~coralline algae~~, C), against depth for every tile (1/4 degree) of seafloor that has estimated light at the seabed (EBed) for depths between 0-200 m (Gattuso et al. 2020 [37]). Light at the seabed for every tile was converted to net primary production (NPP) using literature derived photosynthetic parameters (*P. decipiens*, *H. grandifolius*, [Quartino & Boraso de Zaixso 2008](#) [46]; coralline algae Schwarz et al. 2005 [41]). The red horizontal line shows the [this reference is regarding biomass data](#) “compensation point” of each seaweed, the point at which photosynthesis and respiration are balanced. Points below this line show net carbon loss, while points above show net carbon gain. The vertical green dashed line shows the mean depth at which the compensation point is crossed, and the solid green lines are one SD from the mean.

Combined, our observations and modelling suggest that Antarctic algae are physiologically well adapted to ~~low light~~ (Figure 4) and may also experience high rates of dislodgement and transport to [low irradiances](#) deeper waters. While it is difficult to assess the accuracy of modelled seafloor light estimates without long-term moorings, it is likely that modelled seabed light (EBed) **is lower than realised light**

on account of the variability of atmospheric and oceanographic processes affecting the intensity and attenuation of light. We note that consolidated sea-ice, and drifting sea-ice floes likely represent a consistent feature across many of the regions surveyed here, with significant implications for the delivery of light to the seafloor. Despite these challenges, ~~diverse and~~ dense Antarctic macroalgae were found at depths with expected light intensities near the limits for photosynthetic organisms.

the author observed only 3 species, so delete diverse

We extrapolate estimates of biomass accumulation across the Antarctic region and provide updated estimates of the potential contribution of macroalgal productivity to global models, based on the physiological limits determined by metabolic models (e.g., Figure 4) and the apparent daily light threshold at locations where dense beds were found (e.g., 0.02 - 0.1 mol m⁻² day⁻¹). The area of seafloor was estimated for four thresholds of seabed light, 0.01, 0.02, 0.1, and 1.0 mol m⁻² day⁻¹ (Table 1) using the 'coastalLight' package [37] in the statistical software 'R'. When extrapolated to Teragrams (Tg) of carbon fixed using a range of NPP values reported for polar latitudes [47] this equates to 0.1-8% of the estimated global contribution of seaweeds [13] (Table 1).

also please provide biomass data to assume this info with scientific basis This sentence belongs to methodology and please clarify if this mentioned "package" was retrieved from Gattuso et al (2020)?

Table 1. Area of seafloor within four thresholds of light availability (i.e., EBed) as estimated by Gattuso et al. 2020 [37], the estimated range of carbon fixation (Tg yr⁻¹), and how these values compare to the global estimate of carbon fixed by macroalgae (see Duarte et al. 2022 [13]). Carbon fixed calculated by multiplying area within each threshold by the upper and lower global estimates of macroalgal NPP (i.e., g C m⁻² yr⁻¹) (Pessarrodona et al. 2022 [47]).

Here you should use Antarctic data, maybe comparing with Arctic data

Ebed mol m ⁻² day ⁻¹	Area (km ²)	Carbon fixed (Tg yr ⁻¹)	Percent contribution to global total
0.01	14009	1.4 – 105	0.1 – 8 %
0.02	11079	1.1 – 83	0.08 – 6 %
0.1	6578	0.7 – 49	0.05 – 4 %
1	3316	0.3 - 25	0.03 – 1.6 %

"large and conspicuous"macroalgae, because P decipiens and CCA are not "large" specimens of seaweeds

Here, we report some of the deepest verified records of large macroalgae in the Antarctic polar region. This coincides with increasing numbers of deep observations of Arctic seaweeds [43,44], and unprecedented declines in Antarctic sea-ice cover in recent years [26-28]. Using global seabed light products [37] and photosynthetic parameters of several Antarctic seaweed species [41,46], we examine the full profile of light attenuation scenarios in the Ross Sea and show that observed distributions are in line with, but in some cases beyond, the expected limits of physiological light requirements. From our observations of ~~deep-living~~ specimens, we conclude that Antarctic macroalgae may be more abundant than global models suggest [13], are transported at high rates to the deep ocean where sequestration can occur and are therefore poorly represented in estimates of global benthic primary productivity [47].

use the depht range

To our knowledge, there are not yet any direct observations of large brown macroalgae at depths beyond 20 m near their southern limits (e.g., 72°S in the Ross Sea), although there are direct observations from the Antarctic Peninsula (e.g., 60-65°S) of populations beyond 50-70 m depth [16,19], which fits well with physiological studies of minimum light requirements [50,51]. There are, however, deeper records (e.g., 70-100 m) of un-verified dredged material from locations including the Antarctic Peninsula [52], and the Ross Sea region as far south as 73° S [42,53]. Recent studies using Remotely Operated Vehicle (ROV) methods have verified rhodophytes as deep as 100 m in the Antarctic Peninsula region [39]. Similarly, Arctic kelps have been found as deep as 60 m at 69° N [54].

These discoveries are of global significance to the extrapolation of estimations of carbon fixation and sequestration by benthic macroalgae. Contemporary paradigms suggest that Antarctica has minimal

coverage of benthic photoautotrophs, and that shallow benthic habitats receive little annual solar radiation on account of sea-ice cover for long periods/most months of the year and low solar angles [55]. The Southern Ocean is a key carbon sink [56], and while phytoplankton undoubtedly drive CO₂ uptake [57,58], the role of macroalgae may be greatly underestimated. Our results identify both significant coverage of attached large macroalgae in relatively deep waters (e.g., 60-100 m) but also numerous observations of drift algae in deep water (e.g., > 200 m). Extension of macroalgal populations into deeper areas, and the apparent high densities of attached and drift algae beyond 100-200 m support the assertion that macroalgal carbon export and sequestration is potentially significant in the Antarctic region [10].

Newly ice-free areas in the Antarctic Peninsula have been followed by rapid colonisation by benthic macroalgae with substantial gains in carbon standing stock and possibly carbon sequestration [33]. However, increased meltwater input (and associated sediment or nutrient run-off), rising temperatures, reductions in sea-ice cover, and alterations in the timing and abundance of phytoplankton blooms, has major implications for light attenuation and therefore the habitable depth range of benthic macroalgae [30-33]. While reductions in sea-ice cover may increase the amount of light penetrating through the often remarkably clear surface waters to the seafloor [49,55,59], the earlier onset of phytoplankton blooms may offset these gains, especially at greater depths.

These findings shed light on the Antarctic coastal region as a potentially important habitat for benthic macroalgae. Our voyages targeted un-charted, shallow coastal waters of the Ross Sea region and identified widespread, dense macroalgal beds and high abundance of drift algae. Negligible contribution of Antarctic seaweed carbon fixation in global models [13] is likely a result of poor survey coverage and limited verified bathymetry (a key requirement for habitat suitability modelling) for the Antarctic coastal marine area.

Continuation of the recent unprecedented and record-breaking Antarctic sea-ice minima [26-28] will affect the balance of pelagic and benthic primary productivity. This highlights the urgent need to understand limitations on macroalgal distributions in the Antarctic region, in order to predict implications to benthic ecosystems and to carbon sequestration. With gaps in knowledge of current macroalgal distributions and abundance, we remain blind to the potential losses or gains in carbon sequestration at the seafloor. Significant populations of benthic macroalgae in Antarctica now appear more widespread than previously considered in global estimates of carbon sequestration. This research provides impetus to better understand the dynamics of benthic communities in the photic and mesophotic zone of the Antarctic region, the potential consequences of altered glacial and sea-ice dynamics, and to uncover the possible trajectories for polar carbon sequestration.

Methods

In January and February 2021 and 2023, the research vessel *Tangaroa* travelled to the Ross Sea region, focussing on coastal regions of northern Victoria Land, Ross Sea, Antarctica spanning Robertson Bay (west of Cape Adare) to Terra Nova Bay (71° - 75° latitude). Benthic surveys with towed and remote operated camera systems were completed at five locations (25 individual sampling stations) at depths between 40 and 250 m.

Benthic surveys

236 Un-navigated regions of the Ross Sea were mapped using RV *Tangaroa*'s Kongsberg EM302
237 multibeam echosounder (MBES) to survey coastal benthic habitats as shallow as 40 m. Once suitable
238 areas were covered by MBES, remote seafloor imaging using a deep-towed imaging system (DTIS)
239 was carried out across 200-500 m long transects parallel to shore. Although specific depth strata
240 were targeted, presence and movement of sea-ice affected the exact deployment depths at many
241 sites. In total, five ice-free locations from Robertson Bay to Terra Nova Bay were sampled.

242 DTIS is a battery-powered towed camera frame, which records continuous high-definition digital
243 video (1080 p, Sony HDR PJ 760VE) and simultaneously takes high definition still images (24
244 megapixel Nikon D3200) at 10 second intervals [60]. The video camera faces forward at about 35°
245 from vertical and the still camera faces directly downwards (0°). Full resolution video and still images
246 are recorded at the seabed and downloaded on return to the surface. A lower-resolution video
247 image is transmitted to the surface in real time enabling control of camera altitude and initial
248 evaluation of seabed substratum types and biological assemblages. DTIS transects were at a target
249 altitude above seabed of 2.0-3.5 m. The seabed position and depth of DTIS were tracked in real time
250 using the SIMRAD HiPAP system. Parallel lasers mounted on the towed platform allowed for scaling
251 of seafloor images and video.

252 The seabed position of DTIS was plotted in real time using OFOP software (Ocean Floor Observation
253 Protocol, www.ofop-by-sams.eu). All navigation data, camera commands, and spatially-referenced
254 observations of seabed type and the occurrence of biological assemblages were recorded to OFOP
255 log files and captured by the ship's Data Acquisition System (DAS). A Seabird Micocat CTD was
256 attached to the DTIS frame during all deployments, to record salinity, temperature, and depth data.

257 ***Imagery processing and analysis***

258 Video imagery collected by the DTIS system was processed by taxonomists. All macroalgal specimens
259 clearly attached to the seafloor were identified during processing. Macroalgal species were
260 identified to the highest taxonomic level possible using key morphological features from the video,
261 the higher resolution still images, and where available, via the collection of physical specimens.
262 Density of each taxonomic group was calculated by dividing abundance by the total area of the
263 transect (calculated using transect length and width). Transect width was calculated using the scaling
264 lasers to estimate frame coverage at multiple points along the transect.

And about Cryptic
species?

please provide
Herbarium
voucher number

265 The presence of unattached drift algae was common across all stations, including at two stations
266 that were greater than 200 m deep (Possession Islands). Stations where clearly attached specimens
267 were observed were noted separately to sites with infrequent and un-attached specimens. Some
268 stations where very low densities of apparently attached macroalgae were further assessed using
269 light and metabolic modelling to help determine the likelihood that these specimens were dislodged
270 drift algae or capable of inhabiting the observed depths/latitudes.

271 Individual stations were processed into ortho-mosaic imagery to enable measurements of
272 macroalgal specimens and analyse densities. Video was converted into stills using frame grabbing
273 procedures and subsequently stitched together using the software Agisoft Metashape®. Ortho-
274 mosaics were scaled using parallel lasers at six points evenly distributed along the transects. Both
275 high-resolution still imagery, and lower resolution stitched imagery were used for further taxonomic
276 identification of macroalgal species alongside collections.

Images used until level of morpho functional
groups, is ok...

but not as an accurate method for species
ID ...

277 ***Specimen collections***

278 During the 2023 voyage, macroalgal specimens were recorded from several locations. Benthic
279 samples were taken using grab and benthic sled sampling techniques in areas where video imagery

observed benthic macroalgae. These specimens were used to confirm species identification from imagery. Reference specimens were created, including samples for genetic sequencing. These collections will be catalogued at the New Zealand National Museum, Te Papa.

Benthic light availability and primary productivity modelling

Please provide Herbarium code and species voucher numbers

Alongside *in situ* surveys of macroalgal communities, we used global modelling of sea-floor light [37] to estimate photosynthetically active radiation (PAR) reaching the seafloor. We used the R-package “coastalLight” [37] to examine light quantity across the Ross Sea region. This package combines global bathymetric models, radiation at the sea surface and metrics for light attenuation through the water column to calculate the irradiance at the seabed. However, challenges in determining key water clarity metrics (e.g., the light attenuation coefficient K_d) greatly impact the retrieval of EBed in the Antarctic region. To accommodate this, we further estimate EBed for regions where K_d measures were unavailable by replacing missing values with regional averages of K_d using the formula [1] which calculated light at the seabed using irradiance at the surface (I_s), and water depth (d).

$$[1] \quad EBed = I_s(e^{K_d \cdot d})$$

Using the “coastalLight” package we explored light at the seabed for each region where seabed imagery was collected. For each individual region, we examined light at the seabed (EBed) across three replicate transects. Each transect was perpendicular to shore, covering shallow water to depths > 100 m. Limitations in available bathymetric information affected the retrieval of EBed at depths shallower than 50 m for some locations.

We combined outputs from [37] with published photosynthetic parameters for three major macroalgal species found in Antarctica (*Himantothallus*, *Palmaria*, [46] and coralline algae [41]) to examine net primary productivity (NPP). The photosynthetic parameters α (light use efficiency), R (respiration rate), and P_m (maximum productivity), were calculated for every tile where EBed was available, and the productivity (P) was calculated using the [61] formula [2]

$$[2] \quad P = P_m \left(1 - e^{\left(\frac{-\alpha I}{P_m} \right)} \right) + R$$

For every pixel (1/4 degree) in the wider Ross Sea region we estimated the balance of NPP based on light at the seafloor (a function of PAR at the surface, water clarity and depth). Given the variability in PAR at the surface and water clarity (K_d) potential NPP values are identified across the Ross Sea region, and the modelled depth thresholds for each species are identified (as defined by the compensation point, the light intensity at which respiration and primary productivity are balanced). All models and plots were run using the ‘R’ statistical software [62].

Estimates of carbon fixation

Estimates

Estimates of Antarctic wide macroalgal carbon fixation were estimated by calculating the area of Antarctic seafloor in km² within four light thresholds (0.01, 0.02, 0.1, and 1.0 mol m⁻² day⁻¹) using the “cl_surface” function of the ‘coastalLight’ package [37], run using the ‘R’ statistical software [62]. Area in km² was then converted to m² and multiplied by identified rates of macroalgal carbon fixation [47] to identify the range of NPP likely across the region. These values were then compared to global estimates of macroalgal carbon fixation identified by Duarte et al. (2022) [13] as c. 1.32 Pg C/year.

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Author contributions

LT, PM, CC, ML, SM, RO and SG contributed to voyage surveys, CC, LT, and WN analysed and processed video data from the voyage, LT performed modelling of seabed light and primary productivity, LT, WN, and VC drafted the manuscript, LT, VC, and ML conceived the research, and all authors contributed to the final draft manuscript.

Data availability

The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

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505

Response to reviewers:

Reviewer 1

Authors: We thank this reviewer for their kind comments and pointing us to various elements of the literature which we have missed during the preparation of this manuscript. We believe these efforts have greatly improved this manuscript, we thank you for your contributions.

Below we provide a comment-by-comment response to the reviewers points. We have copied each comment from the reviews and have replied to each in ***bold italics***, referring to line numbers in the marked-up version (“TRACKED CHANGES” version) of the manuscript (not the “CLEAN” version). Please note that some edits were made to the “CLEAN” version following accepting tracked changes.

We welcome further comment and discussion with the editors and reviewers and thank you all for your time and effort.

Introduction:

The last line of the first paragraph notes the lack of information on contributions of Antarctic macroalgae to blue carbon, but fails to cite perhaps the most relevant, recent paper on this topic. Morely et al. 2022 Biology 11:320 doi 10.3390/biology11020320

Thanks, we have added this to the manuscript at multiple points (see line 41 and line 61).

Third paragraph: This is a bit self-serving, but this paragraph notes that changes in sea ice coverage is one of the ramifications of climate change, and the authors come back to that in the Discussion. While the paragraph talks about what we know about the impacts of glacial retreat on macroalgae – both ‘positive’ and ‘negative’ – it says nothing about what we know about the impacts of decreasing sea ice. Amsler et al. 2023 Elementa 11:00020 doi 10.1525/elementa.2023.00020 is all about that, including very crude projections to future communities.

Yes, we are well aware of the strong influence of sea ice conditions on benthic communities, and realise that we could/should have discussed this more deeply in the Introduction. We now do this there, and also in the Discussion. We agree that this is a relevant reference and have further described the potential consequences of changing sea-ice. See lines 60-66, 272-275, and 282-285

Last paragraph: The 2006 records of Himantothallus are not the southernmost – or only southernmost – that are in the literature. Zanaveld (1966) also reported it from the Possession Island (72° 00' S) plus from Cape Hallett (72° 25').

Zanaveld, J.S. 1966. The occurrence of benthic marine algae under shore fast-ice in the western Ross Sea, Antarctica. Proceedings of the International Seaweed Symposium 5: 217-231.

Zanaveld (1968) also has it from Cape Adair and the Possession Island. A plate from Neushul’s contribution to the same publication has a dot for it much further south, but Zanaveld’s plate does not and if there were a record of it there, it would have been his. So Wiencke and I concluded that was a mistake on Neushul’s plate when we put together the 2014 map etc. contribution. Zanaveld, J.S. 1968. Benthic marine algae, Ross Island to the Balleny Islands. Antarctic Map Folio

Series 10: 10-12, pl. 13.

We greatly appreciate the clarification from these records and have updated the text and citations accordingly. Please find these details in lines 93-95.

Results and discussion:

Christian Wiencke has also observed Himantothallus at 70 m in ROV video from South Georgia. Unlike here though, he did not publish it other than to include it as an unpublished observation in our 2012 review. So I guess it is sort of “published unpublished.” 8^ Since it is not “published published” I am not advocating one way or the other for its inclusion here, but in case the authors were not aware of it, felt I should mention it. It supports their observations.

Thanks, we note this observation in the text of Wiencke, Amsler, and Clayton 2014 and have further cited this in the results (see line 105-106).

There are a number of reports of Antarctic macroalgae in deep water and I tend to be skeptical of them. Figure 1 parts C and D, however, are absolutely convincing for Himantothallus and crustose corallines. That is exactly what attached Himantothallus should look like. Although I cannot be as certain of the fleshy reds, the way they are dispersed is certainly consistent with them being attached (drift is very often more clustered), and the fact that attached Himantothallus is there too makes me a believer.

With respect to Figure 1 C and D, and really B too, I could not tell that on a printout of the manuscript. I had to go to the electronic version and zoom the images 200-250%. It is even hard to read the labels on C and D. These images are very important for the believability of the story. They should be large enough that someone reading a printout of a PDF version of the paper could see them. Also with respect to these parts of the figure, I suggest noting the depth in the figure caption. I gather from where they are cited in the text that they are “c. 70 m” but it would be useful to have that explicit as part of the caption.

Thanks. We have added the depths to the figure caption (see lines 117-118) and have enlarged parts of the figure (Line 105) to ensure these images are well resolved in all formats of presentation. Note that we have similarly enlarged parts of Figure 3.

First line of bottom paragraph on pg. 3: Here and I think elsewhere (certainly once in the Methods) the term “species” is used too loosely. Neither “brown algae” nor “red algae” are “species” (and Himantothallus is a brown alga too). Reword.

Very good point, we have tightened up the text on this matter. Also note that where possible we have provided additional names for species that have been identified morphologically.

Other than Himantothallus and Palmaria, there is no indication of what species were actually found. In the Specimen collections section of the Methods it says that they used grabs and benthic sleds to get actual specimens and that these will be deposited into a herbarium. It would be really valuable to have an idea just what species they found. Perhaps the authors intend a follow-on paper with more information about the depth distributions of individual taxa (I certainly hope they do!) but I would not think that mention of what species they found here (perhaps in supplementary material)

would preclude that. I find their categories of turfs and greens particularly curious. I am not aware of Antarctic reports of algal turfs like those often reported at lower latitudes. I do know that *Ballia*, which I suppose could form something of a turf if growing much denser than I've ever seen it grow, is reported from the Ross Sea. As for greens, the only subtidal ones I am aware of are *Monostroma*, which is shallow-growing and ephemeral, *Lambia antarctica*, and *Chaetomorpha* (formerly *Lola*) *irregularis*. *Lambia* has never been reported south of the Peninsula but grows deep there. *C. irregularis* is only reported from the Ross Sea, which makes me think it may be this. Or is there something new?

Reviewer 2 had some similar comments. We have now registered herbarium specimens for a range of samples. We have also added further images (Figure S1) and tables (Table S1-S4) to the appendices and provided definitive names for several more species (see lines 124-129). Further material is undergoing genetic analysis. .

For example, for the 'green' algae specimens *Monostroma hariotii* was physically sampled and identified (see line 127). We also note that the "turfig" algae may not resemble turfs as known from lower latitudes but was represented by very fine-branching red algae covering relatively large areas across several transects (particularly in Robertson Bay). Samples of *Ballia* were indeed formally identified (to Genus level at least) see line 127.

Although full resolution on species from genetic analysis may not be available within the frame of this review, we do intend to follow this up with at least one other publication on this matter.

The EBed methodology is new to me but the comments here and in the Methods about the impact of unrepresentative values of K_d would not surprise me. The times of year – mostly mid summer and its shoulders – when people are making measurements are in my experience at least when water clarity is the worst. It is much better for long periods thereafter, up until annual ice forms, and for shorter periods prior to that after the annual ice breaks out. The latter probably isn't long enough to make much of a difference. But the later season period probably is long enough. It seems that somewhere in Antarctic waters there should be a quantitative report of such a pattern although I do not know of such a report and would be very surprised if it were from the study area.

Yes, the trajectory of water clarity is critical to our understanding of annual light budgets, and unfortunately without continuous moorings we rely heavily on satellite imagery and optical measurements of water clarity. The reliance on satellites means that conditions of ice-cover and cloud cover return zero results of K_d . We are particularly interested in understanding what the water clarity looks like immediately after sea-ice breakup when we expect clarity to be very high, but perhaps, as you mention, there is a latter period where water clarity is also high. This is something we would like to do in the future by deploying further instrumentation (see lines 196-199) on long-term moorings in the region. We hope this can be a part of future programmes and appreciate your insights.

We have in recent years collected long-term light intensity data from more southerly locations, but have deemed these sites too distant to be relevant here. We hope to be able to remedy this with future research programmes.

End of last full paragraph on pg. 7: Krause-Jensen et al 2019 (doi 10.3389/fmars.2019.00375) reports kelp to at least 61 m (deepest they looked) in Greenland (67-70° N). I suggest replacing reference

54, which is a technical report, with this paper since people can actually get to and see it. There is also a Schimani et al. 2022 (doi 10.1007/s00300-022-03072-x) report of reds as deep as 68 m in Spitsbergen (78.9° N)

Excellent, thanks for pointing out these references, they have both been added to the text (see lines 249-250) and the reference list.

Reviewer 2:

Authors: We thank the Reviewer 2 for their detailed and helpful comments. The review is thorough and highly relevant to our work and the field in general. We appreciate the effort that has gone into marking up the PDF. We hope our detailed comments and text additions sufficiently address all the concerns raised and that Reviewer 2 is able to provide further feedback on our edits.

As above for Reviewer 1, for Reviewer 2 we have copied each comment from their review and have replied to each in ***bold italics***, referring to line numbers within the marked-up version of the manuscript (not the “CLEAN” version). Following this, we also provide details as to how we responded to markups that were made on the PDF version of the manuscript. In these comments we refer to the line numbers of the PDF attached by Reviewer 2, but line numbers in ***bold italics*** refer to the marked-up revision.

Reviewer #2 (Remarks to the Author):

The present article is relevant due to the pressing need to reduce emissions and increase carbon removal from the atmosphere that is now also leading to the development of natural climate solutions in the ocean. The ocean provides major opportunities to mitigate and adapt to climate change, and the largest habitat with primary productivity should not be ignored simply because it does not fit into existing frameworks.

The Interest in the carbon sequestration potential of underwater macroalgal forests is growing rapidly among policy, conservation, and corporate sectors. Yet, our understanding of whether carbon sequestration from macroalgal forests can lead to tangible climate change mitigation remains severely limited, hampering their inclusion in international policy or carbon finance frameworks.

Pessarrodona et al. (2023)** used over 180 publications to synthesise evidence regarding macroalgal forest carbon sequestration potential. The authors showed that research efforts on macroalgae carbon sequestration are heavily skewed towards particulate organic carbon (POC) pathways (77% of data publications), and that carbon fixation is the most studied flux (55%). Fluxes leading directly to carbon sequestration (e.g. carbon export or burial in marine sediments, such as mentioned in the submitted article) remain poorly understood, mainly in polar ecosystems. Likely, hindering regional or country-level assessments of carbon sequestration potential, which are only available from 17 of the 150 countries where macroalgal forests occur. Current estimation of natural sequestration value of all macroalgal habitats is between 61–268 Tg C year⁻¹, depending on

latitude, it suggests that macroalgal beds could add greatly to the coastal blue carbon. Mitigation in polar and temperate areas where blue carbon is currently low, and less studied, will depend on better operationalizing of that potential, development of models that reliably estimate the proportion of production sequestered, improvements in macroalgae carbon fingerprinting techniques, and a rethinking of carbon accounting methodologies. And the present article tries to add some information in these regards.

Thanks. We believe our article is a very early step along the trajectory outlined by Reviewer 2. We do not attempt to provide accurate rates of blue-carbon sequestration, because there are too many unknown links in the carbon sequestration pathway. However, we focus on the potential carbon fixation of these ecosystems using evidence gathered on two significant voyages targeting shallow coastal ecosystems of the Ross Sea. While we cannot quantify blue-carbon pathways in the Antarctic, our results and modelling suggest that annual carbon fixation may be larger than current models suggest and highlights the need for further studies to help understand the current standing biomass, turnover, and rates of sequestration so that future changes can be measured. It is in this context that we refer to “blue-carbon” and we do not attempt to provide mitigation solutions for carbon storage.

Also specific techniques related to bloom production and management, or the utilization of biomass for biomaterials, should be fostered. As example Gouvea et al. (2020) suggested that Sargassum, a tropical and subtropical brown seaweed, contribute with ca. of 13 Tg C/year at the global scale, which is a significant amount of carbon, comparable to other key marine/coastal ecosystems, including mangroves, salt marshes and seagrass meadows.

Thanks. We take this point, however, we have been unable to segue these types of techniques into the manuscript without moving outside of the scope of our contribution. In discussing this comment we have found few relevant techniques or mechanisms relevant to the Antarctic outside of the classic oceanic iron enrichment experiments*. Because these techniques relate to phytoplankton stimulation and are outside the scope of this study, we have refrained from any major edits in this regard. However, as per further comments from Reviewer 2, we have added additional context around the Ross Sea Marine Protected Area and the possible role of benthic protection. See lines 285-291.

* Boyd, P.W., Watson, A.J., Law, C.S., Abraham, E.R., Trull, T., Murdoch, R., Bakker, D.C., Bowie, A.R., Buesseler, K.O., Chang, H. and Charette, M., 2000. A mesoscale phytoplankton bloom in the polar Southern Ocean stimulated by iron fertilization. *Nature*, 407(6805), pp.695-702.

However the Questions that the authors could address in the present submission are:

- Are the combined methods used based on previous literature, ROV surveys and models really accurate to estimate the area and biomass for Antarctic seaweed beds between 70 and 100 m depth?-

We agree with Reviewer 2 that greater work is required to improve the accuracy of our biomass accounting, especially sequestration. We maintain throughout this article that the purpose of our contribution is to provide new evidence that places the role of Antarctic macroalgae in global carbon fixation in a new light. Establishing that this is greater than expectations is an important outcome and has implications for our view of the pathway to sequestration in this region. Our

broad-scale observations at very high latitudes provide important insights into the possible contribution of these ecosystems.

In our revised manuscript, we provide further qualification of the uncertainty of our carbon fixation modelling results. We also present a greater range of results, better separating species and geographic regions, and provide greater detail on the methodology used- see lines 195-219 and 388-404. We provide suggestions of key research required to better understand the true contribution of Antarctic macroalgae to global carbon fixation.

Antarctic seaweed biomass, whose estimation in the article is non destructive and of low accuracy, really shows a significant carbon stock, comparable to other marine ecosystems? compare data in a Table from Temperate and tropical ecosystems?-

We note that biomass estimates from this work and others are “comparable” with temperate and tropical systems but are still less than some of these systems; we make this clear in the revised manuscript (see Lines 48-50). While Reviewer 2 is requesting a table comparing these ecosystems, we believe our in-text citations are sufficient to make this point. In considering the request for a table we found hundreds of publications using variable biomass standardisations (e.g., fresh weight, dry weight, ash free dry weight, carbon weight), with samples taken from various depths, and from whole assemblages or from canopy species alone. Compiling this seems an important task, but we hope that our improved text and added citations sufficiently address the assertion that Antarctic macroalgal standing biomass is indeed comparable to many (though not all) tropical and temperate ecosystems.

With regards to our “non-destructive” estimation. We in fact do have physical specimens that were recorded, weighed and pressed that allow areal biomass estimates. However, our approach for estimating carbon fixation relies on well described physiological modelling of photosynthetic curves and in situ light estimates (Markager & Sand-Jensen 1992, Miller et al 2012, Tait et al. 2015, Rodgers & Shears 2016). While this is quite different from standing biomass estimates, it relates well to measured biomass accumulation (Miller et al. 2012) and allows the calculation of annual turnover.

Markager, S. and Sand-Jensen, K., 1992. Light requirements and depth zonation of marine macroalgae. *Marine Ecology-Progress Series*, 88, pp.83-83.

Miller, R.J., Harrer, S. and Reed, D.C., 2012. Addition of species abundance and performance predicts community primary production of macroalgae. *Oecologia*, 168, pp.797-806.

Tait, L.W., South, P.M., Lilley, S.A., Thomsen, M.S. and Schiel, D.R., 2015. Assemblage and understory carbon production of native and invasive canopy-forming macroalgae. *Journal of experimental marine biology and ecology*, 469, pp.10-17.

Rodgers, K.L. and Shears, N.T., 2016. Modelling kelp forest primary production using in situ photosynthesis, biomass and light measurements. *Marine Ecology Progress Series*, 553, pp.67-79.

How much in fact Antarctic seaweeds may contribute to climate change mitigation by removing CO₂ atmospheric? I suggest to Include in discussion data published in the South Shetland Islands (SSI) and WAP, higher seaweed richness zones (please see Pellizzari et al 2017, 2020 and 2023; Oliveira et al. 2020). How do you recommend that restoration and management initiatives should be fostered to preserve the polar seaweed carbon in Southern Ocean ?

We discuss data from the above publications suggested (as well as publications suggested by Reviewer 1) to further bolster our assertion that Antarctic seaweeds are under-represented in global models. (see lines 257-260)

While we do not attempt to provide solutions for growing or sustaining Antarctic macroalgal populations, we argue that without knowledge of the current status of these systems, we will remain unaware of how future climatic changes may drive changes in biomass and carbon sequestration. Changes to benthic light delivery could be both positive (e.g., less sea-ice) or negative (e.g., more sediments, nutrients and phytoplankton) with important consequences to the habitable range of macroalgae.

We also note that this study is associated with research and monitoring of the Ross Sea Marine Protected Area (MPA), and evidence collected in this MPA will help inform any future changes to its protected status. We highlight the need to understand these macroalgal habitats under the context of protection (see lines 285-291) and cite further research on the possible benefits of protection in macroalgal habitats (Arafteh-Dalmau et al. 2021) As per your suggestion, we do now state that management initiatives that protect the seafloor from anthropogenic disturbance is an important pathway to ensuring these pathways are not interrupted. See lines 287-288.

Other recommendations:

- This article used previous photosynthetic rates and global light modeling to estimate carbon fixation for antarctic seaweeds however ::

Assuming that ROV in general has grabbers or collecting arms, the absence of herbarium voucher numbers for the seaweed species new records (between 70 and 100 depth) also is a fragile point in the article

A ROV was not used in this survey, video data were collected using a towed camera system, and the physical samples were taken with either benthic sled, or a grab sampler (see lines 359-361). Furthermore, all of our specimens have now been registered (see lines 124-129 and 364-366). We have added a supplementary figure of a selection of specimens collected, and the herbarium vouchers. Please see Supplementary Figure S1 and Supplementary Tables S1-4. As noted in our responses to Reviewer 1, many of the samples have now been formally identified (see lines 124-129) and several are currently undergoing genetic analyses to confirm their taxonomic identification. We hope to follow up with future publications reporting the results from this analysis.

The article is quite speculative, and use many extrapolation data (please see an ex. At line 160) based on previous literature, ROV observations (with limited sampling ability), and modeling with low accuracy in some part of methodology.

Yes, it is true we have extrapolated data, however, we have utilised published data from a range of sources and our estimations are conservative and well parameterised based on what is available. Our samples are capable of being standardised by unit area (unlike with an ROV based grab sample).

We have used modelling techniques to provide a broad range of scenarios and to test how our observations relate to available light at these depths. The alignment of observations and modelling (e.g., maximum expected depth of CCA was 125 m which, a depth at which specimens

*were observed, *H. grandifolius* max modelled = 75m, max observed = 74m) is an important outcome and allows us to make some extrapolations based on this agreement. Nevertheless, to address the concerns of Reviewer 2, we also now provide more clarity on how we have performed our calculations of carbon fixation. We now show potential carbon fixation for each of the three modelled species and provide estimates of carbon fixation for defined spatial regions as related to the coverage and latitudinal ranges from our observations (see lines 204-215; Table 1). We provide further methodology (see lines 388-404) for these calculations, including greater detail on how models were parameterised.*

Ideally, we would have better biomass information across latitudinal and depth gradients to improve the accuracy of these extrapolations. However, we maintain that the purpose of these first order extrapolations is to re-assess what the contribution of Antarctic macroalgae might be and whether it is a realistic contributor to global carbon fixation or sequestration. We have provided further detail in the methodology (see lines 397-410). We welcome further comment on our updated methodology and the expanded explanations on the limitations of our methods.

MATERIALS AND METHODS ((should be placed before “Results and Discussion” aiming to provide a big picture of the study to the reader / reviewer)):

According to the layout of this particular journal, the Methods section comes after the Results and Discussion section. However, we now provide more context in the Results and Discussion section to better help guide the reader (See lines 152-155, line 174).

Should also refers to:

(1) Literature searches and data compilation

Done, please see lines 386-388.

(2) Assessments of macroalgal beds sequestration potential using global light /irradiance modeling from the sea-bottom

Please see our updated methodology (lines 399-410) and results (lines 204-215) for the calculation of carbon fixation (not sequestration).

(3) ROV use

Done, please see lines 359-361

(4) Functional seaweed groups analysis

Done, please see lines 337-342

(5) Seaweed physiological capabilities

Done, please see 384-390

Response to PDF annotations: Here we respond to edits that Reviewer 2 has provided on a PDF file alongside the revision above. We refer to the line numbers in the PDF provided by Reviewer 2.

Title. Reviewer 2 suggests two edits to the title of this manuscript. The two key aspects of our title that Reviewer 2 asks us to suppress are:

- 1) “Deep-living”
- 2) “Diverse”

We maintain that, in the context of Antarctica, these macroalgae are indeed both deep-living and diverse. Our study reveals a relatively high number of macroalgal species (i.e., 14 possible species, 9 confirmed) at depths beyond 50 m, something which is relatively uncommon even in temperate regions (see Nelson et al 2015*). We provide further rationale for this below and cite this in the text (see lines 109-110).

*Nelson, W., Neill, K., D’Archino, R., Anderson, T., Beaumont, J. and Dalen, J., 2015. Beyond diving depths: deepwater macroalgae in the New Zealand region. *Marine Biodiversity*, 45, pp.797-818.

1) Deep living. Yes, there are records for macroalgae living beyond 200 m. However, these records relate to the tropics where the euphotic zone extends far deeper than at the poles. Reviewer 2 states that the euphotic zone is anything less than 200 m in the Austral Ocean, however, when contending with the latitudes of this study (higher than 70 degrees), the euphotic zone will be significantly lower than this. On top of this, partial or periodic cover of sea-ice and phytoplankton blooms will further reduce the depths that light can penetrate. Our maximum verified records approach 125 m depth and we observe large perennial algae deeper than 70 m. These records should not be characterised as “lower subtidal zone”, a term suggested by Reviewer 2, but which is typically used to describe shallow coastal habitats, mesophotic might be more appropriate (Nelson et al 2015).

We remain open to further discussion on this matter, but we kindly ask Reviewer 2 to consider the very southern context of this study (with highly seasonal light availability) and the associated consequences to surface PAR irradiance, solar angle of incidence, and annual irradiance budgets.

2) Diverse We believe the taxonomic and morphological variation identified here qualifies as diverse in the context of Antarctic macroalgae. We have identified a moderate number of taxa and functional groups in areas that have typically been perceived as having no or at least very few species. We supply further evidence, including herbarium voucher specimen images (Supplementary material and see lines 125-130) and show that these macroalgal assemblages are made up of a variety of species, with varying morphologies, from the three macroalgal groups (red, green, brown).

Line 23: Thanks, this requires further qualification. Temperate macroalgae have been observed to depths approaching ... We have removed this reference and stated more clearly the maximum verified depths identified in our study.

Line 34: Thanks, we have further considered the finding of Pessardona et al 2023. While we believe there is agreement between our statement and the Pessarrodona et al (2023) publication, we agree that much of the nuance of this study has been missed. Therefore, we have modified the text to better reflect some of the uncertainties raised by the authors and have added the citation at a further sentence. Please see **lines 41**

Line 43: Thanks, these valuable references have been consulted and cited. (see **lines 258-261 in the Results and Discussion**)

Lines 76-77: Thanks, we have edited the phylogeny details to include Phaeophyceae (**lines 93-94**). Furthermore, we have added references to supplementary material which contains the details of herbarium voucher specimens (**lines 99-100 & SupplementaryTable S1, S2, S3, and S4**), a supplementary figure of a range of the specimens collected (**Figure S1**) and have provided more detailed methodology of the collections (see **lines 361-368**).

Line 94: Thanks. Yes, *Himantothallus* is a brown alga. We have kept this species separate from other brown algae for two reasons 1) the characteristic holdfast and stipe made positive IDs of this species possible, and 2) the large size/biomass and dominance of this species at several locations was a key finding of these research voyages. Additional brown algae were found in much lower densities, and were typically specimens with much finer branching thalli (see **supplementary material Figure S1, Table S1 and lines 126-131**).

Line 102: In the methodology section we have provided further details on the taxonomic assessment, and allocation of specimens to functional groups. We use methods widely accepted globally and provide references for our methodology. (see **lines 339-3344 in the Methods section**).

Lines 111-113: The detailed methodology is in the Methods section. However, we have briefly provided some detail in the Results section to better enable the reader to understand what was done (see **lines 154-157 and lines 388-390**). We are happy to elaborate further if the reviewer does not agree with our approach.

Lines 118-119: Yes, you are correct. This adaptation is well known in Antarctic macroalgae, we have modified the statement and have included several references that back up the low light tolerance of Arctic/Antarctic seaweeds (**line 163**).

Line 125: Figure 2 has bathymetric data mapped across the region, although we note this is set to a 200 m threshold. The bathymetry associated with transects intersecting the study sites is contained within the figures themselves. However, we can provide more details if elaboration is required

Line 132: Thanks, yes, we have not ourselves assessed the physiological capabilities of these species, but have used the literature to link photosynthetic parameters with light intensities at the seafloor for Ross Sea locations. We have modified this sentence to better reflect our approach (**see line 176**). Furthermore, full methodological details are contained detailed in the Methods section (**see lines 401-414**)

Line 142: We have now changed references of coralline algae to “crustose coralline algae” (CCA) throughout the manuscript.

Line 145-146: Yes, thanks. We have now updated this with the appropriate reference (**line 191**).

Gomez, I., Weykam, G., Klöser, H. and Wiencke, C., 1997. Photosynthetic light requirements, metabolic carbon balance and zonation of sublittoral macroalgae from King George Island (Antarctica). Marine Ecology Progress Series, 148, pp.281-293.

Lines 154-156: Thanks, we provide a citation for Gattuso et al. 2020. Those authors developed the global seafloor light models and acknowledge these limitations in their article

Line 158: Yes, we have changed the text to refer to multiple functional groups, as opposed to “diverse” as suggested by Reviewer 2

Line 160: Comments have already been addressed in the main response to Reviewer 2.

Line 165: Thanks. We have removed this text from this section as it already appears in the Methods.

Line 166: We have been more specific and now refer to “Antarctic” NPP values. While we have added further text about comparisons in the manuscript, in depth comparisons of NPP are not within the scope of this work and, as Reviewer 2 points out, are well described in Pessarrodona et al 2023. Our primary goal is to provide further evidence that Antarctic macroalgae may be greater contributors to benthic carbon fixation than current estimates, we expect that as investigations into these regions continue, the habitat available for benthic macroalgae will increase and modelled rates of carbon fixation may increase.

Line 174: Thanks, we have now modified this statement to be more accurate

Line 180: Thanks, we now provide the depth range, rather than referring to “deep-living” macroalgae (**line 265**).

Lines 259-260: We now provide further information about the handling of taxonomic labelling (**lines 340-344**).

Line 261: Yes, we now have herbarium voucher numbers, please see Supplementary material and text (**lines 126-131**).

Lines 275-276: Please see further information regarding taxonomic labelling (**Lines 340-344**)

Line 282: Please find the herbarium voucher specimen numbers, tentative species names in the supplementary material (Supplementary Table 4)

Line 372: Thanks, this reference has been amended, the chapter cited was “Carbon balance under a changing light environment” (Deregibus et al 2020)

Deregibus, D., Zacher, K., Bartsch, I., Campana, G.G., Momo, F., Wiencke, C., Gómez, I. and Quartino, M., 2020. Carbon balance under a changing light environment. In: *Antarctic Seaweeds: Diversity, Adaptation and Ecosystem Services*, eds. Gómez, I. and Huovionen, P., pp.3-20. Springer, pp.397.

4th Mar 24

Dear Dr Tait,

Your manuscript titled "Deep-living and diverse Antarctic seaweeds as potentially significant contributors to global carbon fixation" has now been seen by our reviewers, whose comments appear below. In light of their advice we are delighted to say that we are happy, in principle, to publish a suitably revised version in Communications Earth & Environment under the open access CC BY license (Creative Commons Attribution v4.0 International License).

We therefore invite you to revise your paper one last time to address the remaining concerns of our reviewers. At the same time we ask that you edit your manuscript to comply with our format requirements and to maximise the accessibility and therefore the impact of your work.

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Best regards,

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REVIEWERS' COMMENTS:

Reviewer #1 (Remarks to the Author):

I enjoyed reading this revision of the Tait et al. manuscript. The authors have gone beyond what was necessary to address my suggestions on the original version and I fully support its acceptance for publication. -- Chuck Amsler

One procedural comment is that the track changes version available on the review website is somewhat different (probably an earlier version) than the clean copy. In particular, the reference list differs substantially. My comments refer only to the clean copy version and are very minor.

Line 110: Ballia and Iridaea are misspelled

Lines 68 and 82: (This is a picky phylogenetic comment.) If you are going to use the formal taxon names Ochrophyta and Phaeophyceae they need to be capitalized as was done on line 83. Otherwise use the informal "ochrophytes" and "phaeophytes" as was done on lines 69 and 91. That said, "Ochrophyta" as usually used includes a lot more than just Class Phaeophyceae but only phaeophytes are "brown algae". What you've done is OK, but my personal preference is just to use the Class designation.

Lines 88-89 vs. line 70: The observation was at South Georgia (as noted on line 70). I cannot recall ever seeing that included as part of the WAP (lines 88-89). I suggest using South Georgia both places.

I feel that the authors have satisfactorily addressed the reviewer 2's comments. In many cases they have added information to the manuscript that directly and appropriately responds to the reviewer's

comments. In others, I feel that they do a good job of explaining why addressing the reviewer's suggestions in full would go beyond (sometimes way beyond) the scope of this work and/or what can be said from the available data or literature. My personal feeling is that the reviewer was asking them to do that a lot. They have added what was reasonable to add.

Responses to reviewers:

Author responses are in ***bold italics***.

Reviewer #1 (Remarks to the Author):

I enjoyed reading this revision of the Tait et al. manuscript. The authors have gone beyond what was necessary to address my suggestions on the original version and I fully support its acceptance for publication. -- Chuck Amsler

One procedural comment is that the track changes version available on the review website is somewhat different (probably an earlier version) than the clean copy. In particular, the reference list differs substantially. My comments refer only to the clean copy version and are very minor.

Apologies, unfortunately we had an issue with some initial edits in tracked changes being “accepted” on a shared online document. It was very difficult to go back and mark all of the changes back up and this resulted in some inconsistencies in the “tracked” version. Again, we apologise for this.

Line 110: Ballia and Iridaea are misspelled

Noted and edited. Thanks

Lines 68 and 82: (This is a picky phycological comment.) If you are going to use the formal taxon names Ochrophyta and Phaeophyceae they need to be capitalized as was done on line 83. Otherwise use the informal “ochrophytes” and “phaeophytes” as was done on lines 69 and 91. That said, “Ochrophyta” as usually used includes a lot more than just Class Phaeophyceae but only phaeophytes are “brown algae”. What you’ve done is OK, but my personal preference is just to use the Class designation.

Thanks, we have moved to the class designation in all cases and used the informal taxon names for consistency.

Lines 88-89 vs. line 70: The observation was at South Georgia (as noted on line 70). I cannot recall ever seeing that included as part of the WAP (lines 88-89). I suggest using South Georgia both places.

Thanks, we have changed this to be in line with your observations and cited research.

I feel that the authors have satisfactorily addressed the reviewer 2’s comments. In many cases they have added information to the manuscript that directly and appropriately responds to the reviewer’s comments. In others, I feel that they do a good job of explaining why addressing the reviewer’s suggestions in full would go beyond (sometimes way beyond) the scope of this work and/or what can be said from the available data or literature. My personal feeling is that the reviewer was asking them to do that a lot. They have added what was reasonable to add.

Thanks. We put a lot of effort into the changes requested by reviewer 2, or in cases where we felt the changes were out of scope, we further justified this in our rebuttal, and in the manuscript body by improving our justifications and citations. Thanks for assessing our responses to this reviewer, the authorship team greatly appreciate your efforts here.

