Celina Burkholz

Aninda Mazumdar
Copernicus Publications
Handling Associate Editor

Dear Aninda Mazumdar,

We are pleased to submit the revised manuscript entitled "Warming enhances carbon dioxide and methane fluxes from Red Sea seagrass (*Halophila stipulacea*) sediments" by Celina Burkholz, Neus Garcias-Bonet, and Carlos M. Duarte.

We thank the referees for their suggestions, which have significantly improved the manuscript. In the following pages, you will find a detailed response to the referee's concerns specifying each action taken to address the referee's recommendations.

Best,
Celina Burkholz
On behalf of all co-authors

Authors' response

RC: Comments from referees/public,
AR: Authors' response,
AC: Authors' changes in manuscript

ANONYMOUS REFEREE #1

Interactive comment on "Warming enhances carbon dioxide and methane fluxes from Red Sea seagrass (*Halophila stipulacea*) sediments" by Celina Burkholz et al.

Received and published: 21 August 2019

1) **RC:** This manuscript presents the results of a study in which experiments on impacts of warming and prolonged darkness on CO2 and CH4 fluxes are conducted in seagrass ecosystems of the Red Sea. Results show upward shifts in carbon dioxide and methane fluxes with warming and in the dark with a few exceptions under varied experimental conditions. Though it is known that a rise in temperature would increase metabolic rates the present set of results confirm thus driven elevated CO2 and CH4 fluxes for seagrass meadows in the Red sea. These results are of significance to understanding and quantifying the forcings and feedbacks of climate system. The Results and Discussion Sections were presented well but I found it difficult to follow some statements in Introduction section. Besides there is need to improve clarity to Material Methods Section by furnishing more details.

AR: We thank the reviewer for the constructive comments. We have made some changes to the manuscript to improve clarity.

Specific comments are given below.

2) **RC:** Page 2 Lines 8-10: "where autotrophic communities [net community production (NCP) > respiration (R)] act as a sink for carbon dioxide (CO2), while heterotrophic communities [net community production (NCP) < respiration (R)] act as a source of CO2 (Duarte et al., 10 2011)." - Why not make it simple? Say 'where net community production (NCP) > respiration (R)] the system becomes a sink for carbon dioxide (CO2).'?

AR: In fact, the statement was in error, besides complex. The sentence now reads as follows, which is a simpler, and most importantly, correct statement.

AC: Page 2, line 7-9: *Ecosystem metabolism can also be a source of greenhouse gases, depending on the metabolic balance of the community, where autotrophic communities [net community production (NCP) > 0] act as a sink for carbon dioxide (CO2), while heterotrophic communities [net community production (NCP) < 0] act as a source of CO2 (Duarte et al., 2011).*

3) **RC:** Line 38-39: "warming at higher rates than those of the global ocean" - at what rates? Specific information will be helpful.

AR: We thank the reviewer for pointing out the missing information. We have added the rates as requested.

AC: Page 2, line 38-40: *The Red Sea ranks as the warmest sea in the world, with summer seawater temperatures reaching 35 ˚C, and is warming at higher rates (0.17 ± 0.07 °C decade⁻¹, Chaidez et al., 2017) than those of the global ocean (0.11 °C decade⁻¹, Rhein et al., 2013).*

4) **RC:** Page 3 Line 30: "Once the cores were opened, the first 10 cm of the sediment and the plant biomass were collected and dried" - Is this biomass picked from the same sediment core or was it collected separately? In fact Line 24 says that sediments were collected to a depth of 10 cm. If yes, then what is 'the first 10 cm' in Line 30? This is confusing.

AR: We agree with the reviewer's concern that this part can be confusing. We have edited the section accordingly. Regarding line 24, the cores were not taken at a depth of 10cm, the cores were pushed 10 cm into the sediment. We have added additional information for clarification.

AC: Page 3, line 18-20: *Two H.stipulacea meadows at a depth of 2-3 m, S1 (22˚56.775'N, 38˚52.677'E) and S2 (22˚54.742'N, 38˚53.848'E), were chosen to represent a range of organic matter content in the sediment, selected to evaluate greenhouse gas fluxes.*

Page 3, line 30-31: *Once the cores were opened, the first 10 cm of the sediment and the plant biomass from the same cores were collected and dried.*

5) **RC:** Page 4 Line 16 "triplicate cores from vegetated and adjacent bare (about 5 m from the edge of the seagrass patch)" - Can a sample just 5 m away from the edge of the seagrass patch be true representative of 'bare' sediment? Table 1 shows that sediment characteristics between vegetated and bare sediments of S2 are nearly the same but for marginal high organic matter content in the former. Only the other differences expected under these circumstances could be nature and density of microbes on which 'respiration rate' essentially depends on!

AR: We have chosen a distance of 5 m to show the difference between the absence and presence of seagrass. A further location would have implied a variation of many other factors (depth, sediment type, etc) that could have affected the results. By having similar sediment conditions, we can imply that differences can be caused by the presence/absence of seagrass biomass.

6) **RC:** Line 22: "We then sampled 10 mL of air from each core using a syringe". Which replacement air was used to put into headspace each time 10 ml of air sample was drawn and how?

AR: There was no replacement air used to add to the headspace. We followed the same methodology described in Garcias-Bonet et al. (2017) and Sea et al. (2018): First, the water inside the cores was replaced by fresh seawater leaving a headpsace, and the cores were closed again with stoppers containing gas tight valves. The cores were left for one hour to allow for equilibration between the seawater and the headspace air. We then sampled 10 mL of air from each core using a syringe and injected the air sample in a

cavity ring-down spectrometer through a small sample isotopic module extension (SSIM A0314, Picarro). One sample from each core was taken at the start (T0), after 12 hours of light (T1) and after 12 hours of dark (T2).

7) **RC:** Line 30-31: "In March 2018, we collected eight vegetated and eight bare sediment cores from site S2 to evaluate the response of greenhouse gas fluxes to warming." - This sentence says eight cores each from vegetated and bare sediments. But how the number became NINE each in

   AR: We thank the reviewer for pointing out the error. We have edited the sentence as follows:

   AC: Page 4, line 32-33: *In March 2018, we collected eighteen vegetated and eighteen bare sediment cores from site S2 to evaluate the response of greenhouse gas fluxes to warming.*

8) **RC:** Lines 32-33 ("Nine vegetated and nine bare sediment cores were placed in each two aquaria")? Also what is 'were placed in each two aquaria'? Did they mean 'were placed separately in two aquaria'? Since they collected 8 cores each from vegetative and bare sediment zones I would expect them to place 4 cores from each zone (total 8 cores) in each aquarium! Their write-up is confusing!!! Or more clarity is needed in presentation.

   AR: We share the reviewer's concern that this phrasing might have been confusing. We have changed the sentences as follows:

   AC: Page 4, line 34-36: *Nine vegetated and nine bare sediment cores each were placed in two aquaria with flow-through seawater set at in situ temperature (25 ˚C) and a 12 h L (up to 200 μmol photons m^{-2} s^{-1}): 12 h D cycle.*

9) **RC:** Page 6: Lines 24-25: "Carbon, nitrogen, and phosphorus concentrations in seagrass leaves were low, but C, N and P leaf concentrations were 4- to 25 40-fold" - Did the authors mean 'vegetative sediments or sediments for seagrass leaves'?

   AR: We agree with the reviewer that this is not clear, we have added the missing information that we were referring to both sediments, vegetated and bare.

   AC: Page 6, line 26-27: *Carbon, nitrogen (N), and phosphorus (P) concentrations in seagrass leaves were low, but they were 4- to 40-fold higher than vegetated and bare sediment concentrations (Table 1).*

10) **RC:** Page 8: Line 8: "ranging from a minimum average of -11.55 ± 5.32 ‰ to a maximum average of -17.89 ± 1.81 ‰ δ13C" – are minimum and maximum interchanged? Please note that these values are bear negative sign.

    AR: We thank the reviewer for pointing out this mistake. The sentence was corrected accordingly.

    AC: Page 8, line 9-12: *The isotopic signature of the $\delta^{13}C$-CO_2 became heavier with warming in the bare sediment, increasing from -22.36 ± -4.97 ‰ $\delta^{13}C$ at 25 ˚C to -9.01 ± 0.98 ‰ $\delta^{13}C$ at 37 ˚C (R^2 = 0.91, p < 0.001), while the other treatments showed similar*

values over time, ranging from a minimum average of -17.89 ± 1.81 ‰ to a maximum average of -11.55 ± 5.32 ‰ δ¹³C (Fig. 6A-D).

11) **RC:** Lines 20-21: "CO2 fluxes were also 10-fold higher in vegetated compared to adjacent, but bare sediments, indicating elevated microbial remineralization rates in vegetated sediments." Rewrite as words are repetitive and a bit confusing too. Given this statement minimal microbial description of these sediments will be very helpful.

   AR: We thank the reviewer for the comment, we changed the sentence for clarification. Since we are unable to relate specific metabolic processes to specific microbial taxa, we have removed the term "microbial", and just refer to remineralization, as we cannot exclude contributions from other components of the benthic community.

   AC: Page 9, line 15-17: *Both CO_2 and CH_4 fluxes were higher in vegetated compared to adjacent bare sediments, indicating elevated remineralization rates in vegetated sediments as well as a higher susceptibility of seagrass sediment to increasing temperatures.*

12) **RC:** Lines 34-35: "Mean CH4 fluxes at in situ temperature (25 ĚŽC) in vegetated sediments were lower than the mean value of 85.09 ± 27.80 35 μmol CH4 m-2 d-1" - Caution needs to be exercised when expressing flux values to the second decimal. This is unnecessary given the uncertainties associated with flux estimates in general and large mean deviation in this particular case. ***

   AR: We thank the reviewer for pointing this out, we have changed the sentence as follows:

   AC: Page 9, line 28-29: *Mean CH_4 fluxes at in situ temperature (25 ℃) in vegetated sediments were lower than the mean value of 85.1 ± 27.8 μmol CH_4 m^{-2} d^{-1} reported for other seagrass meadows in the Red Sea (Garcias-Bonet and Duarte, 2017).*

ANONYMOUS REFEREE #2

Review report of the paper entitled "Warming enhances carbon dioxide and methane fluxes from Red Sea seagrass (Halophila stipulacea) sediments" submitted by Celina Burkholz et al to Biogeosciences

Received and published: 17 September 2019

1) **RC:** Seagrass meadows, saltmarshes and mangroves are the "hot spot" blue carbon sinks and highly efficient in long-term carbon storage in the coastal marine ecosystems. Deterioration of these natural marine ecosystems through anthropogenic perturbation could change their carbon sinks efficiency and may contribute to climate change through re-emissions of locked carbon dioxide and other greenhouse gases. The warming-dependent emissions of metabolic GHG in the coastal ecosystems are likely to vary for coastal sediment of different geological origin. It is expected that in situ temperature increase is particularly important in seagrass meadows which have high carbon

sequestration with long-term storage capacity and trap organic matter from external sources. The extreme conditions in the Red Sea i.e. slower seagrass growth due to nutrient limitation and greater microbial degradation of soil organic carbon because of high temperature could be related to low Corg storage in the sediment compared to temperate meadows. This paper reports the results of the study on the response of sediment collected from two H.stipulacea meadows, S1 (22ËŽ56.775'N, 38ËŽ52.677'E) and S2 (22ËŽ54.742'N, 38ËŽ53.848'E) at Al Kharar, a lagoon on the Saudi coast of the central Red Sea in February-March 2018, in terms of air-seawater fluxes of CO2 and CH4 along with their isotopic signature from Red Sea meadows compared to for gradual increase of temperature from 25 ËŽC to 37 ËŽC and prolonged darkness. However, I had difficulties to understand certain sections of the manuscript including the methodology and discussion. Furthermore, the author did not address appropriately other important elements particularly the redox conditions, anthropogenic pressure in and around the the ecosystems (Seagrass and bare soil).

AR: We thank the reviewer for the thorough review and constructive comments. We have addressed the comments individually to revise and clarify any uncertainties.

2) **RC:** The sediment in the present study is of carbonate (82.61-91.75%) dominated. What constitutes the rest fraction (9-18%) of the   1It does not represent all types of sediment of different geological origin in Al Kharar lagoon. Previous reports (Serrano et al. 2018 Scientific Reports, 8:15037) indicate that soils in seagrass meadows in Saudi Arabia, Central Red Sea. are mainly constituted of clay and silt particles ($37 \pm 0.7\%$ on average), with a relatively high abundance of very fine sands ($21 \pm 0.4\%$) compared to fine sands ($16 \pm 0.4\%$), medium sands ($12 \pm 0.3\%$) and coarse sands ($14 \pm 0.7\%$). Youssef & El-Sorogy, 2016 (Arab J Geosci 9:474) showed that sediment textures consist of mud, gravelly sand, and sandy mud and organic matter in the sediment may also be derived from Mangroves which are common in Al-Kharrar lagoon between latitude 22◦ 45 and 23◦ 00 N and longitude 39◦ 00 and 38◦ 45 E.

AR: We agree with the reviewer that this study does not represent all types of different geological origin in Al Kharar. Our main focus was to see a difference between two different sites, and then focus on the difference between vegetated and bare cores. We have therefore made the decision not to include other sediment types. We have added some additional information to the discussion section regarding the origin of organic matter content.

AC: Page 10, line 4-25: *The isotopic composition of CO_2 in all treatments showed generally heavier isotopic signatures compared to previous reports of seagrass carbon (average $\delta^{13}C$ value of -7.73 $\pm$ 0.11 ‰ for Red Sea seagrass and -7.57 $\pm$ 0.15 ‰ for H. stipulacea in the Red Sea; Duarte et al., 2018), indicating various organic matter sources such as macroalgae blades (13.38 $\pm$ 0.3 ‰), mangrove leaves (26.58 $\pm$ 0.13 ‰) and seston (25.43 $\pm$ 0.42 ‰; Duarte et al., 2018). However, the mean $\delta^{13}C$ value of Red Sea seagrass sediments was reported to be -13.36 ± 0.4 ‰ (Garcias-Bonet et al., 2019a), similar to the results found in this study. Our chosen study sites were located in an enclosed lagoon with a high abundance of mangrove forests, leading to the conclusion that mangroves might be a major source of organic matter for our study sites. However, a recent study applying stable isotope mixing models found the major contributors to the organic matter in seagrass sediments in the Red Sea to be seagrass leaves and macroalgae blades, with contributions of 43 and 37 %, respectively (Garcias-Bonet et al., 2019a).*

The isotopic signature of CO_2 released from bare sediments shifted with warming, suggesting a shift from seston, mangroves and macroalgae as the organic matter supporting respiration to seagrass carbon as the source of CO_2. In the vegetated cores, the isotopic composition of CO_2 stayed rather constant, indicating several sources of organic carbon with no clear shift, regardless of warming.

The isotopic signature of CH_4 in vegetated sediments confirmed its biogenic source as previous reports have shown that the isotopic signature of CH_4 from biogenic sources can range from -40 to -80 ‰, while the isotopic signature of CH_4 from geological and thermogenic sources ranges from -30 to -50 ‰ (Reeburgh, 2014), The isotopic composition of CH_4 in bare sediments was generally at the lower end of this range, with no clear shift with increasing temperature.

The isotopic composition of CH_4 can be determined by the production of CH_4 (methanogenesis) leading to lower $\delta^{13}C$ values and the oxidation of CH_4 (methanotrophy) leading to higher $\delta^{13}C$ values (Whiticar, 1990). Garcias-Bonet and Duarte (2017) reported fluctuations in the isotopic signature of CH_4 in Red Sea seagrass meadows, suggesting an indication for both processes. When exposed to increasing temperatures, we observed a shift to a lighter isotopic signature of CH_4 in vegetated sediments, thereby indicating an increasing CH_4 production by methanogens with warming.

3) **RC:** Why you have collected sediment from two H.stipulacea meadows only?

   AR: We thank the reviewer for the comment. Only two meadows were chosen for this hypothesis as the main focus was to test the effect of warming. Al Kharar is an enclosed lagoon where H. stipulacea forms dense patches and can be found growing along an OM gradient. We have chosen these two meadows to test our hypothesis that there is a difference along an OM gradient. Both meadows are monospecific, while many other meadows in Al Kharar are comprised of different seagrass species.

4) **RC:** Why the sediment of two H.stipulacea meadows showed high bulk density (1.1-1.28 g cm-3) relative to silt-clay sediment (1.05 g cm-3) in seagrass meadows in Saudi Arabia, Central Red Sea Serrano et al. 2018 observed. The bulk density of carbonate sediment (carbonate 0.7 g/cm3) should be even lower than that of sediment containing mainly sand (1.586 g cm-3) and claysilt (1.0 to 1.6 g/cm3). Organic carbon content of both vegetated (0.43 -0.55%) and bare (0.41 - 0.52%) carbonate sediment of H. stipulacea meadows is greater than the value reported for clay-silty sediment of other seagrass meadows (0.33%, Serrano et al. 2018).

   AR: We thank the reviewer for pointing this out. Unfortunately, we don´t have more data on sediment composition and grain size to confirm the other parts of the sediment composition. We acknowledge that the sediment composition differed from that reported in Serrano et al. (which includes Professor Carlos M. Duarte, under whose supervision both that and this research was conducted). We do not expect the sediments we sampled to be representative of all sediment configurations found in seagrass meadows in the Red Sea, nor Serrano et al. (2018) designed their research to encompass all sediment types occurring across the Red Sea.

5) **RC:** Why the production of H. stipulacea is high at the study site S2 compared to S1 and other seagrass meadows along the Saudi coast even though there was almost no available nutrients (N & P), and no difference in nutrients between S1 and S2.

AR: We thank the reviewer for their concern. S2 had a higher organic matter content and a higher seagrass biomass compared to S1, which could have affected the fluxes. Additionally, previous studies have generally found a high variability in fluxes. We have rearranged this section to improve clarity.

AC: Page 8, line 20-page 9, line: 10:
4.1 Carbon dioxide and methane air-seawater fluxes
The values reported for CO_2 and CH_4 fluxes varied greatly between the two sites studied here, with higher fluxes in the more organic sediments with higher biomass (S2). CO_2 and CH_4 fluxes were also highly variable over time in the studied site, as the first evaluation of fluxes in the same location delivered rates up to 100-fold above the rates of the second measurement one week later. Hence, organic matter availability along with temperature may account for the large variation in CO_2 and CH_4 fluxes. Additionally, the variability of CO_2 and CH_4 fluxes could also be supported by infaunal species present in the cores that were not recorded in this study. These trends were similar to results reported in previous studies, as a high variability between species and locations was found (cf. Table 1 in Garcias-Bonet and Duarte (2017)).
Even though there were some differences, carbon, nitrogen and phosphorus concentrations were generally similar, and they didn't seem to have an effect on CO_2 and CH_4 fluxes. Carbon, nitrogen and phosphorus concentrations were low compared to mean values (Carbon: 33.6 ± 0.31 % DW, nitrogen: 1.92 ± 0.05 % DW, phosphorus: 0.23 ± 0.011 % DW) reported for seagrass leaves by Duarte (1990). Serrano et al. (2018) explained the discrepancy between Red Sea data and global data with the extreme conditions in the Red Sea, such as low nutrient input and high temperatures, as well as a limited data set favoring high carbon stocks in the Mediterranean.
The results presented here add to those by Garcias-Bonet and Duarte (2017) to identify Red Sea seagrass communities as a significant source of CH_4. The presence of seagrass resulted in a higher organic matter supply to the sediments, favoring the presence of methanogens, which led to higher CH_4 fluxes compared to those fluxes supported in bare sediments (Barber and Carlson, 1993; Bahlmann et al., 2015), consistent with the up to 100-fold higher CH_4 fluxes supported by vegetated compared to bare sediments in this study. Additionally, higher fluxes in vegetated cores could be an indicator of direct effects resulting from the presence of seagrass, as vascular plants on land have shown to have varying effects on methane emissions caused by differences in biomass and gross photosynthesis (Öquist and Svensson, 2002).
Similar trends were also seen by Garcias-Bonet and Duarte (2017) who reported an increase in CH_4 fluxes with increasing organic matter content in Red Sea seagrass sediments. They reported organic matter contents in Red Sea seagrass sediments ranging from 2.33 ± 0.07 % (Halodule uninervis) to 12.42 ± 0.23 % (Enhalus acoroides), including a mixed meadow with H. stipulacea and H. uninervis showing a slightly higher organic matter content of 3.51 ± 0.17 % compared to vegetated sediments at S2. Moreover, they found the highest CH_4 fluxes in meadows with the highest biomass, confirming our findings with higher fluxes in study site S2.
In terms of CO_2 equivalent greenhouse potential, only the bare sediment maintained at 25 °C seemed to act as a C sink over the experimental period, while the vegetated sediments, both maintained at 25 °C and exposed to warming, acted as sources of greenhouse gases. A sublethal disturbance, such as warming below the lethal threshold, can therefore lead to a shift of seagrass ecosystems from acting as net sinks to net sources of greenhouse gases, as demonstrated experimentally here.

6) **RC:** If seagrass detritus is the significant source of soil organic carbon, what is the source of organic carbon for bare sediment? Why vegetated and bare sediment of S1 showed no difference in soil organic carbon content?

AR: We thank the reviewer for their concern. Al Kharar is an enclosed lagoon receiving organic matter inputs from mangroves, macroalgae, phytoplankton, as well as from land occasionally. We have added some additional information to the discussion section

AC: Page 10, line 4-25: *The isotopic composition of CO_2 in all treatments showed generally heavier isotopic signatures compared to previous reports of seagrass carbon (average $\delta^{13}C$ value of -7.73 ± 0.11 ‰ for Red Sea seagrass and -7.57 ± 0.15 ‰ for H. stipulacea in the Red Sea; Duarte et al., 2018), indicating various organic matter sources such as macroalgae blades (13.38 ± 0.3 ‰), mangrove leaves (26.58 ± 0.13 ‰) and seston (25.43 ± 0.42 ‰; Duarte et al., 2018). However, the mean $\delta^{13}C$ value of Red Sea seagrass sediments was reported to be −13.36 ± 0.4 ‰ (Garcias-Bonet et al., 2019a), similar to the results found in this study. Our chosen study sites were located in an enclosed lagoon with a high abundance of mangrove forests, leading to the conclusion that mangroves might be a major source of organic matter for our study sites. However, a recent study applying stable isotope mixing models found the major contributors to the organic matter in seagrass sediments in the Red Sea to be seagrass leaves and macroalgae blades, with contributions of 43 and 37 %, respectively (Garcias-Bonet et al., 2019a).*

The isotopic signature of CO_2 released from bare sediments shifted with warming, suggesting a shift from seston, mangroves and macroalgae as the organic matter supporting respiration to seagrass carbon as the source of CO_2. In the vegetated cores, the isotopic composition of CO_2 stayed rather constant, indicating several sources of organic carbon with no clear shift, regardless of warming.

The isotopic signature of CH_4 in vegetated sediments confirmed its biogenic source as previous reports have shown that the isotopic signature of CH_4 from biogenic sources can range from -40 to -80 ‰, while the isotopic signature of CH_4 from geological and thermogenic sources ranges from -30 to -50 ‰ (Reeburgh, 2014), The isotopic composition of CH_4 in bare sediments was generally at the lower end of this range, with no clear shift with increasing temperature.

The isotopic composition of CH_4 can be determined by the production of CH_4 (methanogenesis) leading to lower $\delta^{13}C$ values and the oxidation of CH_4 (methanotrophy) leading to higher $\delta^{13}C$ values (Whiticar, 1990). Garcias-Bonet and Duarte (2017) reported fluctuations in the isotopic signature of CH_4 in Red Sea seagrass meadows, suggesting an indication for both processes. When exposed to increasing temperatures, we observed a shift to a lighter isotopic signature of CH_4 in vegetated sediments, thereby indicating an increasing CH_4 production by methanogens with warming.

7) **RC:** The δ 13 C-Corg showed depletion of 13C in comparison to leaf and both vegetated and bare sediment showed no significant difference of δ 13 C-Corg. Moreover, given δ 13C value of -7.96 ± 0.27 0/00 is lower than that of literature value for C4 plants -14 0/00. This needs clarifications. Use stable isotope mixing model to determine the actual contribution of seagrass on organic carbon content of the meadow sediment. CO2 fluxes were also 10-fold higher in vegetated compared to adjacent bare sediments, indicating elevated microbial remineralization rates in vegetated sediments.

AR: We share the reviewer's concern regarding the contributors to the organic matter in the sediment. Unfortunately, we cannot perform such analysis for the study site as we have not sampled all possible contributors for d13C analysis as it was out of the scope of this study. However, we are now discussing our results on the light of a comprehensive assessment of sources of organic carbon to sediments in Red Sea seagrass meadows we published since (Garcias-Bonet et al. (2019).

AC: Page 10, line 4-25: *The isotopic composition of CO_2 in all treatments showed generally heavier isotopic signatures compared to previous reports of seagrass carbon (average $\delta^{13}C$ value of -7.73 ± 0.11 ‰ for Red Sea seagrass and -7.57 ± 0.15 ‰ for H. stipulacea in the Red Sea; Duarte et al., 2018), indicating various organic matter sources such as macroalgae blades (13.38 ± 0.3 ‰), mangrove leaves (26.58 ± 0.13 ‰) and seston (25.43 ± 0.42 ‰; Duarte et al., 2018). However, the mean $\delta^{13}C$ value of Red Sea seagrass sediments was reported to be −13.36 ± 0.4 ‰ (Garcias-Bonet et al., 2019a), similar to the results found in this study. Our chosen study sites were located in an enclosed lagoon with a high abundance of mangrove forests, leading to the conclusion that mangroves might be a major source of organic matter for our study sites. However, a recent study applying stable isotope mixing models found the major contributors to the organic matter in seagrass sediments in the Red Sea to be seagrass leaves and macroalgae blades, with contributions of 43 and 37 %, respectively (Garcias-Bonet et al., 2019a).*

The isotopic signature of CO_2 released from bare sediments shifted with warming, suggesting a shift from seston, mangroves and macroalgae as the organic matter supporting respiration to seagrass carbon as the source of CO_2. In the vegetated cores, the isotopic composition of CO_2 stayed rather constant, indicating several sources of organic carbon with no clear shift, regardless of warming.

The isotopic signature of CH_4 in vegetated sediments confirmed its biogenic source as previous reports have shown that the isotopic signature of CH_4 from biogenic sources can range from -40 to -80 ‰, while the isotopic signature of CH_4 from geological and thermogenic sources ranges from -30 to -50 ‰ (Reeburgh, 2014), The isotopic composition of CH_4 in bare sediments was generally at the lower end of this range, with no clear shift with increasing temperature.

The isotopic composition of CH_4 can be determined by the production of CH_4 (methanogenesis) leading to lower $\delta^{13}C$ values and the oxidation of CH_4 (methanotrophy) leading to higher $\delta^{13}C$ values (Whiticar, 1990). Garcias-Bonet and Duarte (2017) reported fluctuations in the isotopic signature of CH_4 in Red Sea seagrass meadows, suggesting an indication for both processes. When exposed to increasing temperatures, we observed a shift to a lighter isotopic signature of CH_4 in vegetated sediments, thereby indicating an increasing CH_4 production by methanogens with warming.

8) **RC:** P 4: Before measuring fluxes, why the water inside the cores was replaced by fresh seawater ? Is it accumulated pore water ? Replacement of pore water saturated with CO2 and CH4 by fresh sea water may result serious error!

AR: We thank the reviewer for this comment as we realized the text was not clear enough. We did not replace the pore water, we replaced the water overlying the sediment inside the cylindrical core, in order to be sure that measurements started with the same initial concentrations. We have changed the text to avoid confusion.

AC: Page 4, line 19-22*: Before measuring fluxes, the water overlying the sediment inside the cores was carefully siphoned until only 5 mm of water remained over the sediment surface and fresh seawater was carefully siphoned in the core, to avoid disturbing the redoxcline, leaving a headspace of approx. 5 - 6 cm, and the cores were closed again with stoppers containing gas tight valves.*

9) **RC:** Sediment core was incubated at one particular temperature and CO2 and CH4 concentrations were measured in 10 ml of head space air samples from each core at 0, 12hrs (light) and 12 hrs (dark). Considering, efluxes of 10,422 μmol CO2 m-2 d-1 and 88.11 μmol CH4 m-2 d-1, simple calculation shows after 12 hrs increased amount of CO2 and CH4 should be 37 μmol and 0.31 μmol, respectively. But standards (A: 750 ppm CO2, 9.7 ppm CH4, B: 250.5 ppm CO2, 3.25 ppm CH4) used before each (?) measurement of samples are all above those values. A plot of observed mixing ratio of CO2 and CH4 versus temperature should be given for better understanding.

AR: We thank the reviewer for their concern. We reported rates in this study, meaning that we calculated the difference between the first measurement (T0) and the 3rd measurement after 24 hours (T2). The actual measurements of the headspace air sample in ppm are not reported in this study. To avoid confusion, we have deleted the sentences referring to the light and dark fluxes, as we only report the daily fluxes. We changed the method section accordingly:

AC: Page 4, line 27-28: *The daily CO_2 and CH_4 fluxes were calculated from the difference between T0 and T2 taking into account the core surface area ($μmol\ m^{-2}\ d^{-1}$).*

Page 5, line 34-page 6, line 2: *The daily CO_2 fluxes were calculated from the difference between T0 and T2 taking into account the core surface area ($μmol\ m^{-2}\ d^{-1}$). Daily CH_4 fluxes were estimated using the same calculations as for the CO_2 fluxes with the exception of the Bunsen solubility coefficient.*

10) **RC:** The mean ratio of CH4/CO2 was found to be ∼0.008 which seems to be higher than the previous value reported for seagrass meadows (Halodule uninervis, Halodule pinifolia, Halophila ovalis, Halophila ovata, and Halophila beccarii), Chilika Lagoon (PLoS ONE 13(10): e0203922. https://doi.org/10.1371/journal.pone.0203922).

AR: We thank the reviewer for pointing this out. We've added additional information to the result and discussion section.

AC: Page 7, line 31: *The CH_4/CO_2 ratio declined in the vegetated sediments exposed to warming from 7 to 0.8 %.*

Page 10, line 1-3: *Increasing water temperature led to a decrease in the CH_4/CO_2 ratio. While there was ~7 % of sequestered carbon released as CH_4 to the atmosphere in vegetated sediments at 25 ˚C (on day 2), it decreased to ~0.8 % in vegetated sediments at 37 ˚C. In contrast, Banerjee et al. (2018) reported ~1% of carbon being released as CH_4.*

11) **RC:** The organic matter content was higher in S2 (vegetated 0.55%) than in S2 (bare 0.52%) by 5% . Is it below the error limit of its determination?

AR: We thank the reviewer for the comment. We found slightly higher organic matter content in S2 compared to S, in both vegetated and bare sediments, and a t-test was used to determine significance. We have changed this section accordingly.

AC: Page 6, line 32-33: The organic matter content was slightly higher in S2 than in S1, in both vegetated (t-test, $p < 0.0001$) and bare (t-test, $p < 0.001$) sediments (Table 1).

12) **RC:** How do you explain 6-fold CO2 and 100-fold CH4 greater emission in S2 (vegetated) than in S2 (bare) ? Provide a plot of observed CH4 concentration versus temperature.

AR: We thank the reviewer for pointing this out. A 6-fold higher CO2 flux was reported for vegetated compared to bare sediments in both S1 and S2 indicating the difference between vegetated and bare cores. The same trend was seen for CH4 fluxes with up to 100-fold higher fluxes in vegetated compared to bare sediments. A plot of observed CO_2 and CH_4 concentrations vs temperature is shown in Fig. 2. The second x-axis indicates the experimental temperature for the community exposed to warming from 25 - 37 ˚C. We added some additional information to the discussion section.

AC: Page 8, line 21-40: *The values reported for CO2 and CH4 fluxes varied greatly between the two sites studied here, with higher fluxes in the more organic sediments with higher biomass (S2). CO2 and CH4 fluxes were also highly variable over time in the studied site, as the first evaluation of fluxes in the same location delivered rates up to 100-fold above the rates of the second measurement one week later. Hence, organic matter availability along with temperature may account for the large variation in CO2 and CH4 fluxes. Additionally, the variability of CO2 and CH4 fluxes could also be supported by infaunal species present in the cores that were not recorded in this study. These trends were similar to results reported in previous studies, as a high variability between species and locations was found (cf. Table 1 in Garcias-Bonet and Duarte (2017)).*
Even though there were some differences, carbon, nitrogen and phosphorus concentrations were generally similar, and they didn't seem to have an effect on CO2 and CH4 fluxes. Carbon, nitrogen and phosphorus concentrations were low compared to mean values (Carbon: 33.6 ± 0.31 % DW, nitrogen: 1.92 ± 0.05 % DW, phosphorus: 0.23 ± 0.011 % DW) reported for seagrass leaves by Duarte (1990). Serrano et al. (2018) explains the discrepancy between Red Sea data and global data with the extreme conditions in the Red Sea, such as low nutrient input and high temperatures, as well as a limited data set favoring high carbon stocks in the Mediterranean.
The results presented here add to those by Garcias-Bonet and Duarte (2017) to identify Red Sea seagrass communities as a significant source of CH4. The presence of seagrass resulted in a higher organic matter supply to the sediments, favoring the presence of methanogens, which led to higher CH4 fluxes compared to those fluxes supported in bare sediments (Barber and Carlson, 1993; Bahlmann et al., 2015), consistent with the up to 100-fold higher CH4 fluxes supported by vegetated compared to bare sediments in this study. Additionally, higher fluxes in vegetated cores could be an indicator of direct effects resulting from the presence of seagrass, as vascular plants on land have shown to have varying effects on methane emissions caused by differences in biomass and gross photosynthesis (Öquist and Svensson, 2002).

13) **RC:** The Fig 2 D and E shows large scatter of data and drawing those straight lines have no use.

AR: We thank the reviewer for their comment. Fig 2 D and E show a decline in CH_4 fluxes over time when the sediments were maintained at 25 ˚C, both in vegetated ($R^2 =$

0.43, $p < 0.001$, Fig. 2D) and, less strongly, bare sediments ($R^2 = 0.24$, $p < 0.01$; Fig. 2E, Table S2). Lines represent a fitted linear model. We have added the following sentence to the figure heading for clarification:

AC: Page 17, line 7: *Lines represent a fitted linear regression equation.*

14) **RC:** The CH4 fluxes declined over time when the sediments were maintained at 25 ËŽC, both in vegetated (Fig. 2D) and, less strongly, bare sediments. In contrast, CH4 fluxes tended to increase with temperature in vegetated (Fig. 2D) and bare (Fig. 2E) sediments gradually warmed from 25 ËŽC to 37 ËŽC, although it was not significant. Since the in situ redox condition of both water and sediment was not maintained during experiment that may affect the equilibrium between counteracting microbial processes of production and oxidation in the sediment. The study on the response of benthic net methane concentrations to higher temperatures needs also to take into account methane production rates, Q10 values, and community sizes of methanogens and methanotrophs in seagrass sediments. I believe that the manuscript needs significant revision before being considered for resubmission.

AR: We thank the reviewer for the thorough review and constructive comments. We have addressed the comments individually, and we have revised the discussion section accordingly.

Specific comments

Abstract:
15) **RC:** In the first sentence please mention if Seagrasses are net source of CO2 and CH4.

AR: We thank the reviewer for their comment, the first sentence mentions that seagrasses can be both, sources and sinks of CO_2 and CH_4. We have changed the sentence for better understanding.

AC: Page 1, line 9-10: *Seagrass meadows are autotrophic ecosystems acting as carbon sinks, but they have also been shown to be sources of carbon dioxide (CO_2) and methane (CH_4).*

16) **RC:** Line 17: "We detected distinct differences between vegetated and unvegetated sediments, with the vegetated sediments supporting 6-fold higher CO2 fluxes, and 10- to 100-fold higher CH4 fluxes" This is a confusing statement. What are the conditions for the high flux was not mentioned?

AR: We thank the reviewer for pointing this out. The sentence only relates to the difference between vegetated and bare sediment, not different conditions. We changed the sentence for clarification.

AC: Page 1, line 17-18: *We detected 6-fold higher CO_2 fluxes in vegetated compared to bare sediments, as well as 10- to 100-fold higher CH_4 fluxes.*

Methodology

17) **RC:** "Assessment of carbon dioxide and methane air-seawater fluxes" This section is not clear. Please clarify the total number of samples collected from each core.

AR: We thank the reviewer for their comment. Three samples were taken from each core. The following sentence was changed for clarification:

AC: Page 4, line 26-27: *One sample from each core was taken at the start (T0), after 12 hours of light (T1) and after 12 hours of dark (T2).*

18) **RC:** Was there a periodic collection?

AR: When referring to the collection of cores, cores were collected in February (comparison S1 and S2), March (temperature) and May (darkness) 2018. Samples from each core were collected taken at the start (T0), after 12 hours of light (T1) and after 12 hours of dark (T2). After the 24 hours measuring period, cores had time to acclimate to the new temperature before another measurement period happened.

19) **RC:** Did the cores have seagrass in the top surface? What was the depth of the core sample?

AR: We thank the reviewer for pointing out the missing information. Yes, there was seagrass in the vegetated sediments. We added the depth to the text for clarification.

AC: Page 3, line 18-20: *Two H.stipulacea meadows at a depth of 2-3 m, S1 (22˚56.775'N, 38˚52.677'E) and S2 (22˚54.742'N, 38˚53.848'E), were chosen to represent a range 20 of organic matter content in the sediment, selected to evaluate greenhouse gas fluxes.*

20) **RC:** What were the criteria for fixing the light condition at 70 µmol photons m-2 s-1 and 200 µmol photons m-2 s-1 at different incubation conditions?

AR: 70 µmol photons m^{-2} s^{-1} was the setting in the incubator chambers where the samples stayed only during the measurements, while the cores were exposed to 200 µmol photons m^{-2} s^{-1} in the aquaria between sampling days.

21) **RC:** "The temperature in the second aquarium was increased at a rate of 1 ËŽC day-1." Why this was done? Is this a natural increase (with 1day time) for the physiological adaptation by of seagrass?

AR: We thank the reviewer for pointing out the missing information. A temperature increase of 1 ˚C d^{-1} was chosen to allow the seagrass to adjust to the higher temperature instead of creating stress by raising the temperature abruptly. We have added the missing information.

AC: Page 4, line 37-38: *The temperature in the second aquarium was increased at a rate of 1 ˚C day^{-1} to allow for acclimatization of the vegetated and bare cores.*

22) **RC:** I wander how they have measured water-air flux from a system enclosed with sediment- water-air.

AR: We thank the reviewer for his/her comment. We followed the headspace technique as described in Garcias-Bonet et al. (2017) and Sea et al. (2018) that allows to measure air-sea fluxes: The water inside the cores overlying the sediment was replaced by fresh seawater leaving a headspace, and the cores were closed again with stoppers containing gas tight valves. The cores were then left for one hour to allow for equilibration between the seawater and the headspace air. 10 mL of air were sampled from each core using a syringe, and injected the air sample in a cavity ring-down spectrometer through a small sample isotopic module extension, which provided both the partial pressure and the isotopic carbon composition of the CO_2 and CH_4 in the air sample.

23) **RC:** Lots of Q10 values are available in the literature. Do those values agree with the present report?

AR: We thank the reviewer for his/her comment. Q10 values in the literature indicate that respiration rates in seagrass have a higher temperature dependence compared to photosynthesis, while methanogenesis has a higher thermal dependence compared to photosynthesis and respiration. Our results agree with these findings as we saw an increase in CO_2 and CH_4 fluxes with warming. We added some additional information to the result and the discussion section:

AC: Page 7, line 31-33: *For CO_2 and CH_4 fluxes in vegetated sediments, the Q10 value for the temperature range 25-37 ˚C was 9 and 1.5, respectively, while the Q10 value for bare sediments was 13.8 and 4.2, respectively.*

Page 9, line 32-33: *Additionally, previous research has shown that methanogenesis has a higher thermal dependence than respiration and photosynthesis (Yvon-Durocher et al., 2014) confirming the trends seen here with increasing fluxes at higher temperatures.*

Results:
24) **RC:** The first sentence needs to be revised.

AR: We thank the reviewer for pointing this out. We have changed the sentence for clarification.

AC: Page 6, line 26-27: *Carbon, nitrogen (N), and phosphorus (P) concentrations in seagrass leaves were low, but they were 4- to 40-fold higher than vegetated and bare sediment concentrations (Table 1).*

25) **RC:** Page 6 line 28: "There were no consistent differences in C, N and concentration in bare and vegetated sediments (Table 1)." Does it indicate limited influence of additional carbon storage in the seagrass sediment? "The mean C, N content is significantly lower in the seagrass leaf (Table 1) compared to global average carbon content of 35% (Duarte 1990; Fourqurean et al. 2012).

AR: We thank the reviewer for his/her concern. Serrano et al. (2018) also reported low organic carbon content for Red Sea seagrass sediments due to the extreme conditions in the Red Sea (high temperatures and low nutrient input).

AC: Page 8, line 29-34: *Even though there were some differences, carbon, nitrogen and phosphorus concentrations were generally similar, and they didn't seem to have an effect on CO2 and CH4 fluxes. Carbon, nitrogen and phosphorus concentrations were low*

compared to mean values (Carbon: 33.6 ± 0.31 % DW, nitrogen: 1.92 ± 0.05 % DW, phosphorus: 0.23 ± 0.011 % DW) reported for seagrass leaves by Duarte (1990). Serrano et al. (2018) explains the discrepancy between Red Sea data and global data with the extreme conditions in the Red Sea, such as low nutrient input and high temperatures, as well as a limited data set favoring high carbon stocks in the Mediterranean.

26) **RC:** There are several other seagrass sps apart from Halophila sp. in Kharar lagoon with considerable spatial variation sediment composition. Those Sps should also directly or indirectly affect the sediment composition. The sediment in the present study is manly composed of coral sand. Is it possible for the occurrence of such high concentration of OM in the sediment with no clay and silt?

AR: *Halophila sp.* is by far the dominant species in Al Kharar lagoon, forming a large monospecific meadow. Mixed meadows do occur, but the contribution of species other than *Halophila* is anecdotal at the ecosystem level. We did not measure the grain size distribution of the sediments sampled, so we have no basis to suggest that there was no clay or silt, as the reviewer infers (but we did not suggest such thing).

27) **RC:** Page 6 Line 38: "The daily CO2 flux was up to 6-fold higher in vegetated compared to bare sediments, and tended to be generally higher in S2 compared to S1, where bare sediments showed net CO2 uptake, although differences were not significant" This result need to be discussed in details in the discussion section.

AR: We thank the reviewer for pointing this out. We rearranged the discussion section accordingly.

AC: Page 8, line 20-page 9, line 10:
4.1 Carbon dioxide and methane air-seawater fluxes
The values reported for CO2 and CH4 fluxes varied greatly between the two sites studied here, with higher fluxes in the more organic sediments with higher biomass (S2). CO2 and CH4 fluxes were also highly variable over time in the studied site, as the first evaluation of fluxes in the same location delivered rates up to 100-fold above the rates of the second measurement one week later. Hence, organic matter availability along with temperature may account for the large variation in CO2 and CH4 fluxes. Additionally, the variability of CO2 and CH4 fluxes could also be supported by infaunal species present in the cores that were not recorded in this study. These trends were similar to results reported in previous studies, as a high variability between species and locations was found (cf. Table 1 in Garcias-Bonet and Duarte (2017)).
Even though there were some differences, carbon, nitrogen and phosphorus concentrations were generally similar, and they didn't seem to have an effect on CO2 and CH4 fluxes. Carbon, nitrogen and phosphorus concentrations were low compared to mean values (Carbon: 33.6 ± 0.31 % DW, nitrogen: 1.92 ± 0.05 % DW, phosphorus: 0.23 ± 0.011 % DW) reported for seagrass leaves by Duarte (1990). Serrano et al. (2018) explains the discrepancy between Red Sea data and global data with the extreme conditions in the Red Sea, such as low nutrient input and high temperatures, as well as a limited data set favoring high carbon stocks in the Mediterranean.
The results presented here add to those by Garcias-Bonet and Duarte (2017) to identify Red Sea seagrass communities as a significant source of CH4. The presence of seagrass resulted in a higher organic matter supply to the sediments, favoring the presence of methanogens, which led to higher CH4 fluxes compared to those fluxes supported in bare

sediments (Barber and Carlson, 1993; Bahlmann et al., 2015), consistent with the up to 100-fold higher CH4 fluxes supported by vegetated compared to bare sediments in this study. Additionally, higher fluxes in vegetated cores could be an indicator of direct effects resulting from the presence of seagrass, as vascular plants on land have shown to have varying effects on methane emissions caused by differences in biomass and gross photosynthesis (Öquist and Svensson, 2002).

Similar trends were also seen by Garcias-Bonet and Duarte (2017) who reported an increase in CH4 fluxes with increasing organic matter content in Red Sea seagrass sediments. They reported organic matter contents in Red Sea seagrass sediments ranging from 2.33 ± 0.07 % (Halodule uninervis) to 12.42 ± 0.23 % (Enhalus acoroides), including a mixed meadow with H. stipulacea and H. uninervis showing a slightly higher organic matter content of 3.51 ± 0.17 % compared to vegetated sediments at S2. Moreover, they found the highest CH4 fluxes in meadows with the highest biomass, confirming our findings with higher fluxes in study site S2.

In terms of CO2 equivalent greenhouse potential, only the bare sediment maintained at 25 ℃ seemed to act as a C sink over the experimental period, while the vegetated sediments, both maintained at 25 ℃ and exposed to warming, acted as sources of greenhouse gases. A sublethal disturbance, such as warming below the lethal threshold, can therefore lead to a shift of seagrass ecosystems from acting as net sinks to net sources of greenhouse gases, as demonstrated experimentally here.

28) **RC:** Page 7 Line 21: "Despite CO2 and CH4 fluxes showing the same response to warming in both types of sediment, vegetated sediments held higher fluxes than bare sediments. The relationship between net CO2 and CH4 fluxes in bare vs. vegetated sediments showed that both bare and vegetated communities tended to act as net CO2 sinks at 25 ËŽC, but tended to act as CO2 sources at warmer temperatures (Fig. 3A), whereas net CH4 fluxes were 3- to 8-fold higher in vegetated compared to bare sediments. (Fig. 3B)." The organic carbon contents are comparable for seagrass and bare soil. Do the result indicate higher susceptibility of the seagrass soil carbon at a higher temperature?

   AR: We agree with the reviewer that this could be an indication for higher susceptibility of seagrass sediment to higher temperatures. We have added some additional information in the discussion section.

   AC: Page 9, line 13-15: *Both CO_2 and CH_4 fluxes were higher in vegetated compared to adjacent bare sediments, indicating elevated remineralization rates in vegetated sediments as well as a higher susceptibility of seagrass sediment to increasing temperatures.*

29) **RC:** Apart from regulation by Seagrass, CH4 and CO2 efflux depend on the redoxcline which has not been highlighted in relation to the abundance of methanogens and methanotrops. In methodology of the incubation experiment it is mentioned that ". . ..the water inside the cores was replaced by fresh seawater from the aquaria leaving a headspace of approx. 5 - 6 cm. . ..". Did this replacement change the redox condition of surface water?

   AR: We thank the reviewer for his/her concern, which is due to insufficient detail in our account of procedures. This replacement was done gently to avoid disturbing the redoxcline. The replacement of the water was done through carefully siphoning the water in the core, retaining 5 mm of water overlaying the corer to avoid disturbing the

redoxcline. Fresh seawater was then also carefully siphoned into the corer. Changing the water overlying the sediment allowed us to start with similar values at the first sampling (T0) to then see how the CO2 and CH4 fluxes were affected over a 24 hours period. Since we used the air from the headspace to determine air-water fluxes, we did not highlight the redoxcline in the water column. The replacement with freshwater would not change the redoxcline relative to that present in the environment, whereas leaving the water that was trapped inside the corers closed and locked could lead to accumulation of products released from the sediment that do not accumulate in the natural environment, where water flows freely and air-sea exchange operates. Hence, removing the water that was contained in closed corers and replacing it with fresh seawater is a standard procedure in sediment core incubations (e.g. Foster and Fullweiller 2019, for a recent paper), necessary to avoid, rather than introduce, artifacts. We now specify how this replacement was done.

AC: Page 4, line: 19-22: *Before measuring fluxes, the water overlying the sediment inside the cores was carefully siphoned until only 5 mm of water remained over the sediment surface and fresh seawater was carefully siphoned in the core, to avoid disturbing the redoxcline, leaving a headspace of approx. 5 - 6 cm, and the cores were closed again with stoppers containing gas tight valves.*

Reference
Foster, S.Q. and Fulweiler, R.W., 2019. Estuarine Sediments Exhibit Dynamic and Variable Biogeochemical Responses to Hypoxia. Journal of Geophysical Research: Biogeosciences, 124(4), pp.737-758.

Discussion
30) RC: This section is inadequate and the observed results need more detailed discussions about the variations CO2 and CH4 fluxes at natural, high temperature and low light conditions. "Similar trends were seen by Garcias-Bonet and Duarte (2017) who reported an increase in CH4 fluxes with increasing organic matter content in Red Sea seagrass sediments." In the present study lower CO2 and CH4 fluxes were recorded from adjacent bare sediments with comparable Organic C content.

AR: We thank the reviewer for his/her comment. We have changed the discussion according to the comments. We based this statement on the fact that the vegetated sediment of S2 had a higher OM content than bare sediments of S2, as well as vegetated and bare sediments in S1. Concurrently, these were the cores with the highest fluxes.

AC: Page 8, line 21-page 9, line 10: *The values reported for CO_2 and CH_4 fluxes varied greatly between the two sites studied here, with higher fluxes in the more organic sediments with higher biomass (S2). CO_2 and CH_4 fluxes were also highly variable over time in the studied site, as the first evaluation of fluxes in the same location delivered rates up to 100-fold above the rates of the second measurement one week later. Hence, organic matter availability along with temperature may account for the large variation in CO_2 and CH_4 fluxes. Additionally, the variability of CO_2 and CH_4 fluxes could also be supported by infaunal species present in the cores that were not recorded in this study. These trends were similar to results reported in previous studies, as a high variability between species and locations was found (cf. Table 1 in Garcias-Bonet and Duarte (2017)).*
Even though there were some differences, carbon, nitrogen and phosphorus concentrations were generally similar, and they didn't seem to have an effect on CO2

and CH4 fluxes. Carbon, nitrogen and phosphorus concentrations were low compared to mean values (Carbon: 33.6 ± 0.31 % DW, nitrogen: 1.92 ± 0.05 % DW, phosphorus: 0.23 ± 0.011 % DW) reported for seagrass leaves by Duarte (1990). Serrano et al. (2018) explains the discrepancy between Red Sea data and global data with the extreme conditions in the Red Sea, such as low nutrient input and high temperatures, as well as a limited data set favoring high carbon stocks in the Mediterranean.

The results presented here add to those by Garcias-Bonet and Duarte (2017) to identify Red Sea seagrass communities as a significant source of CH_4. The presence of seagrass resulted in a higher organic matter supply to the sediments, favoring the presence of methanogens, which led to higher CH_4 fluxes compared to those fluxes supported in bare sediments (Barber and Carlson, 1993; Bahlmann et al., 2015), consistent with the up to 100-fold higher CH_4 fluxes supported by vegetated compared to bare sediments in this study. Additionally, higher fluxes in vegetated cores could be an indicator of direct effects resulting from the presence of seagrass, as vascular plants on land have shown to have varying effects on methane emissions caused by differences in biomass and gross photosynthesis (Öquist and Svensson, 2002).

Similar trends were also seen by Garcias-Bonet and Duarte (2017) who reported an increase in CH_4 fluxes with increasing organic matter content in Red Sea seagrass sediments. They reported organic matter contents in Red Sea seagrass sediments ranging from 2.33 ± 0.07 % (Halodule uninervis) to 12.42 ± 0.23 % (Enhalus acoroides), including a mixed meadow with H. stipulacea and H. uninervis showing a slightly higher organic matter content of 3.51 ± 0.17 % compared to vegetated sediments at S2. Moreover, they found the highest CH_4 fluxes in meadows with the highest biomass, confirming our findings with higher fluxes in study site S2.

Page 9, line 18-23: *However, the fluxes maintained at 25 ˚C showed a net CO_2 uptake with a mean of 464.78 ± 156.6 µmol CO_2 m^{-2} d^{-1} (Table S1), while those reported in a mixed Halodule sp. and Halophila sp. meadow in India showed a net CO_2 release (dry season: $1,190 \pm 1,600$ µmol CO_2 m^{-2} d^{-1}, wet season: $18,400 \pm 8,800$ µmol CO_2 m^{-2} d^{-1}; Banerjee et al., 2018). Both values reported were measured at higher temperatures (dry season: 30 ± 0.68 ˚C, wet season: 27.94 ± 0.72 ˚C, Banerjee et al., 2018) compared to our fluxes measured at 25 ˚C, also indicating that temperature might lead to higher fluxes.*

Page 9, line 26-31: *Mean CH_4 fluxes at in situ temperature (25 ˚C) in vegetated sediments were lower than the mean value of 85.1 ± 27.8 µmol CH_4 m^{-2} d^{-1} reported for other seagrass meadows in the Red Sea (Garcias-Bonet and Duarte, 2017). In contrast, the community exposed to warming reached a maximum average CH_4 flux almost 4-fold higher than the community held at 25 ˚C, and showed a clear increase with warming, relative to sediments held at 25 ˚C. The increase in CH_4 fluxes with warming was consistent with reports from Barber and Carlson (1993) for a Thalassia testudinum community in Florida Bay and Garcias-Bonet and Duarte (2017) for Red Sea seagrass communities, who reported higher CH_4 production rates at higher temperatures.*

31) **RC:** Page 8 Line 24: ". . ..while the CO2 fluxes in vegetated sediments maintained at 25 ËŽC decreased over time." Why it was high initially and decreased gradually? explain.

AR: We thank the reviewer for the comment. The initial higher value might have been a response to the stress due to sample collection and transportation. Even though we allowed the cores time to adapt, this value could still be an indicator for the experienced disturbance. All values measured after more than 5 days of sampling showed negative

values indicating the capacity of seagrass sediments to act as carbon sinks. We added the following information to the discussion section.

AC: Page 9, line 23-25: *An initial high CO2 flux measured on day 2 after sampling could be an indicator for the experienced disturbance due to sample collection and transportation even though we allowed the cores some time to adapt.*

32) **RC:** Line 30: "The presence of seagrass resulted in a higher organic matter supply to the sediments, favoring the presence of methanogens, which led to higher CH4 fluxes compared to those fluxes supported in bare sediments (Barber and Carlson, 1993; Bahlmann et al., 2015), consistent with the up to 100-fold higher CH4 fluxes supported by vegetated compared to bare sediments in this study." In the present study, soil organic C content in vegetated and adjacent bare sediment are comparable but CH4 fluxes are significantly different. Does the results (high emissions at S1 and S2) indicated direct CH4 emission from Seagrass? (pls see:Quist and Svensson, 2002, Vascular plants as regulators of methane emissions from a subarctic mire ecosystem, jgr, 107, NO. D21, 4580 and others) Effect of warming

AR: We thank the reviewer for the comment. We have rearranged the discussion section accordingly and added some additional information:

AC: Page 8, line 34-40: *The results presented here add to those by Garcias-Bonet and Duarte (2017) to identify Red Sea seagrass communities as a significant source of CH4. The presence of seagrass resulted in a higher organic matter supply to the sediments, favoring the presence of methanogens, which led to higher CH4 fluxes compared to those fluxes supported in bare sediments (Barber and Carlson, 1993; Bahlmann et al., 2015), consistent with the up to 100-fold higher CH4 fluxes supported by vegetated compared to bare sediments in this study. Additionally, higher fluxes in vegetated cores could be an indicator of direct effects resulting from the presence of seagrass, as vascular plants on land have shown to have varying effects on methane emissions caused by differences in biomass and gross photosynthesis (Öquist and Svensson, 2002).*

33) **RC:** Page 8, Line 26 : "However, the fluxes maintained at 25 ËŽC were about 3-fold below those reported in a mixed Halodule sp. and Halophila sp. meadow in India (980 μmol CO2 m-2 d-1; Banerjee et al., 2018)." Is this the mean flux (the present value) or the least value recorded or the values represent during the end of the incubation at 25 ËŽC? In the previous sentence it was mentioned as "CO2 fluxes in vegetated sediments maintained at 25 ËŽC decreased over time"

AR: We thank the reviewer for pointing out this error. We have edited the sentence accordingly.

AC: Page 9, line 18-23:
However, the fluxes maintained at 25 ˚C showed a net CO2 uptake with a mean of 464.78 $\pm$ 156.6 µmol CO$_2$ m^{-2} d^{-1} (Table S1), while those reported in a mixed Halodule sp. and Halophila sp. meadow in India showed a net CO2 release (dry season: 1,190 $\pm$ 1,600 µmol CO$_2$ m^{-2} d^{-1}, wet season: 18,400 $\pm$ 8,800 µmol CO$_2$ m^{-2} d^{-1}; Banerjee et al., 2018). Both values reported were measured at higher temperatures (dry season: 30 $\pm$ 0.68 ˚C, wet season: 27.94 $\pm$ 0.72 ˚C, Banerjee et al., 2018) compared to our fluxes measured at 25 ˚C, also indicating that temperature might lead to higher fluxes.

34) **RC:** Page 8, Line 40: "We also reported a 10-fold decline in CH4 fluxes over time for sediment communities maintained at 25 ËŽC, which could be attributable to increased sulfate reduction, reduced CH4 production or a combination of both. Methane is produced under anoxic conditions in marine sediments, yet only a small portion is released, as CH4 production by methanogens is compensated for by CH4 consumption by sulfatereducing bacteria (Barnes and Goldberg, 1976)." The soil redox conditions were not measured in this study. Please show some evidence of enhanced soil anoxicity which may have increased SO4 reduction. What could be the other reason/s of reduced CH4 production.

AR: We thank the reviewer for the comment. We have added more information to this paragraph to improve clarity and address the reviewer's concern.

AC: Page 9, line 34-40: *We also reported a 10-fold decline in CH_4 fluxes over time for sediment communities maintained at 25 ℃, which could be attributable to increased sulfate reduction, reduced CH_4 production or a combination of both. Methane is produced under anoxic conditions in marine sediments, yet only a small portion is released, as CH_4 production by methanogens is compensated for by CH_4 oxidation by sulfate-reducing bacteria (Barnes and Goldberg, 1976). Similar to the trends seen in CO2 fluxes, the decrease in CH_4 fluxes could be attributable to an initial stress response to the disturbance caused by sample collection and transportation. While reduced photosynthetic activity and a decrease in biomass could result in higher CH_4 fluxes (Lyimo et al., 2018), the cores maintained at 25 ℃ might show the effect of healthy conditions.*

Conclusion
35) **RC:** This section may be rewritten after revising the discussion section with few more synthesizing statements.

AR: We thank the reviewer for the comment, we have changed the conclusion accordingly.

AC: Page 11, line 17-27: *In summary, this study reports, for the first time, experimental evidence that warming leads to increased greenhouse gas (CO_2 and CH_4) fluxes in a H. stipulacea meadow in the Red Sea, and it may lead to seagrass meadows shifting from acting as sinks to sources of greenhouse gases. Increased fluxes at higher temperatures can be an indication of higher remineralization rates and a higher susceptibility of vegetated sediments to temperature. The elevated organic matter content, higher biomass and higher plant activity in vegetated sediments led to increased CO_2 and CH_4 fluxes in vegetated compared to bare sediments and a much steeper increase in CO_2 and CH_4 fluxes with warming. In addition, prolonged darkness led to an increase in CO_2 fluxes, while CH_4 fluxes decreased over time, also indicating organic matter to be the driver. However, we also found a high variability in fluxes over time indicating that other factors, such as infaunal species, could play a role as well. While current focus is on conserving blue carbon ecosystems from losses due to deteriorated water quality or mechanical damage, our results show that sublethal warming may also lead to emissions of greenhouse gases from seagrass meadows, contributing to a feedback between ocean warming and further climate change.*

36) **RC:** Figure 2: what does the blue dots represent?

AR: We thank the reviewer for pointing out the missing information, the blue dots represent "Constant temperature, 25 ˚C". We have added the missing information to the graph on page 17.

37) **RC:** Figure 3: . . ... the dashed line indicates line 1:1, and dotted lines show lines 2:1, 4:1 and 8:1. Need to ve detailed.

AR: We thank the reviewer for pointing this out. We used the additional lines to visualize the relationship between vegetated and bare sediments showing that CH_4 fluxes were 3- to 8-fold higher in vegetated compared to bare sediments.

Warming enhances carbon dioxide and methane fluxes from Red Sea seagrass (*Halophila stipulacea*) sediments

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Abstract. Seagrass meadows are autotrophic ecosystems acting as carbon sinks, but they have also been shown to be sources of carbon dioxide (CO_2) and methane (CH_4). Seagrasses can be negatively affected by increasing seawater temperatures, but the effects of warming on CO_2 and CH_4 fluxes in seagrass meadows have not yet been reported. Here, we examine the effect of two disturbances on air-seawater fluxes of CO_2 and CH_4 in Red Sea *Halophila stipulacea* communities compared to adjacent unvegetated sediments using cavity ring-down spectroscopy. We first characterized CO_2 and CH_4 fluxes in vegetated and adjacent unvegetated sediments, and then experimentally examined their response, along with that of the C isotopic signature of CO_2 and CH_4, to gradual warming from 25 ˚C (winter seawater temperature) to 37 ˚C, 2 ˚C above current maximum temperature. In addition, we assessed the response to prolonged darkness, thereby providing insights into the possible role of suppressing plant photosynthesis in supporting CO_2 and CH_4 fluxes. We detected 6-fold higher CO_2 fluxes in vegetated compared to bare sediments, as well as 10- to 100-fold higher CH_4 fluxes. Warming led to an increase in net CO_2 and CH_4 fluxes, reaching average fluxes of $10,422.18 \pm 2,570.12$ µmol CO_2 m^{-2} d^{-1} and 88.11 ± 15.19 µmol CH_4 m^{-2} d^{-1}, while CO_2 and CH_4 fluxes decreased over time in sediments maintained at 25 ˚C. Prolonged darkness led to an increase in CO_2 fluxes but a decrease in CH_4 fluxes in vegetated sediments. These results add to previous research identifying Red Sea seagrass meadows as a significant source of CH_4, while also indicating that sublethal warming may lead to increased emissions of greenhouse gases from seagrass meadows, providing a feedback mechanism that may contribute to further enhance global warming.

1 Introduction

Global warming, as a result of anthropogenic emissions of greenhouse gases, has led to ocean warming by 0.11 ˚C between 1971 to 2010 (IPCC, 2014) with the global mean sea-surface temperature predicted to increase further with additional emissions, depending on emission scenarios (IPCC, 2014). Ocean warming is leading to a shift in species and ecosystem

5   processes (Hoegh-Guldberg and Bruno, 2010), including metabolic processes that are under strong thermal control (Brown et al., 2004; Garcias-Bonet et al., 2018, 2019b).

Ecosystem metabolism can also be a source of greenhouse gases, depending on the metabolic balance of the community, where autotrophic communities [net community production (NCP) > 0] act as a sink for carbon dioxide (CO_2), while heterotrophic communities [net community production (NCP) < 0] act as a source of CO_2 (Duarte et al., 2011). Since

10   respiration rates tend to increase faster with warming than primary production does (Brown et al., 2004; Harris et al., 2006; Regaudie-De-Gioux and Duarte, 2012), warming may lead to typically autotrophic ecosystems, such as seagrass meadows, shifting to net heterotrophic, thereby switching from acting as sinks to sources of CO_2 (Harris et al., 2006). Emissions of metabolic greenhouse gases with ocean warming may provide a feedback mechanism by which anthropogenic emissions of greenhouse gases may lead to warming-dependent emissions by coastal ecosystems, therefore enhancing climate warming.

15   This feedback effect is particularly likely to occur where methane (CH_4) is released, as CH_4 is calculated to have a global warming potential 28 times larger than CO_2 per mol of carbon C emitted (Myhre et al., 2013).

Indeed, CO_2 and CH_4 emissions from some tropical mangrove forests have been calculated to partially offset the capacity of mangroves to act as C sinks (Rosentreter et al., 2018). Whereas the emission of CO_2 and CH_4 from seagrass ecosystems has received far less attention, seagrass ecosystems have been reported to support CH_4 emissions of the order of 1.4 to 401.3

20   μmol CH_4 m^{-2} d^{-1} (cf. Table 1 in Garcias-Bonet and Duarte (2017)). Provided estimates of their global extent of seagrass meadows ranging from a documented 326,000 km^2 (Unsworth et al., 2018) to a predicted 1.6 million km^2 (Jayathilake and Costello, 2018), seagrass meadows may be important, yet hitherto overlooked contributors to CH_4 emissions. Garcias-Bonet and Duarte (2017) reported that seagrasses could contribute to global CH_4 emissions by releasing CH_4 at a rate of 0.09 - 2.7 Tg yr^{-1}, which may increase the contribution of marine global emissions to previously reported global estimates by about 30

25   % (Garcias-Bonet and Duarte, 2017).

Seagrasses are known to be autotrophic ecosystems, acting as C sinks (Duarte et al., 2010) supporting a global burial rate of 27.4 Tg C yr^{-1} (Duarte et al., 2005). They store carbon in their below- and above-ground biomass on a short term, as well as in their sediment on a long-term (Duarte et al., 2005). They account for 10 % of the C storage in ocean sediments even though they only cover 0.2 % of the ocean surface (Duarte et al., 2005; Fourqurean et al., 2012). However, disturbances can

30   lead to the loss of biomass and the emissions of stored C turning blue carbon ecosystems into C sources (Macreadie et al., 2015; Lovelock et al., 2017; Arias-Ortiz et al., 2018) which will ultimately contribute to global emissions intensifying the greenhouse effect. Lyimo et al. (2018) showed that stressors such as shading and grazing led to an increase of CH_4 emissions by seagrass ecosystems by reducing their photosynthetic capacity. Garcias-Bonet and Duarte (2017) reported that CH_4 release from seagrass sediments tended to increase with seawater temperature, and suggested that CH_4 emissions by seagrass

35   ecosystems may be under temperature control in the Red Sea. Indeed, some seagrass ecosystems in the Red Sea have shown to shift from an autotrophic to a heterotrophic state during the warmer summer months, indicating that some seagrass communities might already grow past their thermal optimum (Burkholz et al., 2019a).

The Red Sea ranks as the warmest sea in the world, with summer seawater temperatures reaching 35 ˚C, and is warming at higher rates (0.17 ± 0.07 °C $decade^{-1}$, Chaidez et al., 2017) than those of the global ocean (0.11 °C $decade^{-1}$, Rhein et al.,

40   2013). Provided respiration rates and also CH_4 fluxes in seagrass ecosystems are likely to increase with temperature, seagrass meadows in the Red Sea may be close to shifting from net sinks to net sources of greenhouse gases with further warming. Emission rates are also dependent on organic carbon supply, as high sediment organic matter can promote an

increase in CH_4 production (Sotomayor et al., 1994; Gonsalves et al., 2011) and organic matter released from seagrass photosynthesis may also stimulate CO_2 and CH_4 production in the sediment community. Indeed, sediments in seagrass ecosystems support a 1.7-fold higher organic matter content than surrounding bare sediments, not only due to the slow turn-over of biomass but also due to their ability to trap particles (Kennedy et al., 2010; Duarte et al., 2013).

5   Here, we test the hypothesis that CO_2 and CH_4 fluxes by seagrass communities increase with warming. We do so by experimentally examine the effect of warming and plant activity on air-seawater fluxes of CO_2 and CH_4 in a Red Sea seagrass (*Halophila stipulacea)* community. The tropical seagrass species *Halophila stipulacea* (Forsskål) Ascherson is native to the Indian Ocean and is one of the most common species in the Red Sea (Qurban et al., 2019). It seems to be highly adaptive to various environments, as it is now found as an exotic species in the Mediterranean (Lipkin, 1975) and the

10 Caribbean Sea (Ruiz and Ballantine, 2004), indicating its high resilience to changing conditions (Por, 1971). We first characterize air-seawater fluxes of CO_2 and CH_4 in Red Sea *Halophila stipulacea* communities compared to adjacent unvegetated sediments, and then experimentally examine their response, along with that of the C isotopic signature of CO_2 and CH_4, to gradual warming from 25 ˚C to 37 ˚C. In addition, we assess the response to prolonged darkness, thereby providing insights into the possible role of plant photosynthesis in supporting CO_2 and CH_4 fluxes.

15

2 Material and methods

2.1 Study site and sample collection

Samples were collected at Al Kharar, a lagoon on the Saudi coast of the central Red Sea in February 2018. Two *H. stipulacea* meadows at a depth of 2-3 m, S1 (22°56'46.5"N, 38°52'40.6"E) and S2 (22°54'44.5"N, 38°53'50.9"E), were

20 chosen to represent a range of organic matter content in the sediment, selected to evaluate greenhouse gas fluxes. Moreover, the *H. stipulacea* meadow in the middle of the lagoon (S2) with higher biomass density (Table 1) was chosen as the study site to experimentally assess the role of temperature and darkness in greenhouse gas fluxes. The seagrass and sediment community was sampled using translucent cylindrical PVC cores (26 cm length and 9.5 cm in diameter). The sharpened edge of the core was carefully pushed approximately 10 cm into the sediment with a rubber hammer so that the structure of

25 leaves, roots and sediment stayed intact. A rubber stopper was then placed on top, before the core was carefully pulled out of the sediment without disturbing the structure and another rubber stopper was placed on the bottom of the core. The sediment cores were immediately transported to the laboratory.

2.2 Sediment and plant characterization

30 Once the cores were opened, the first 10 cm of the sediment and the plant biomass from the same cores were collected and dried at 60 ˚C to a constant dry weight. To characterize the two different *H. stipulacea* meadows, sediment and plant biomass samples were then ground to analyze the sediment composition and conduct nutrient analyses. A 50 mL tube was filled with sediment from the first 10 cm and the contents dried at 60 ˚C to a constant dry weight and weighed to determine the sediment bulk density (g sediment cm^{-3}). Organic matter content was analyzed by loss on ignition (LOI, Dean, 1974).

35 Approx. 5 g of dried sediment were placed in a muffle furnace and burned at 450 ˚C for 5 hours. The organic matter content was calculated as:

$$\%OM = \frac{pre-ignition\ weight(g) - post-ignition\ weight\ (g)}{pre-ignition\ weight\ (g)} \times 100 \qquad (1)$$

The carbonate content was estimated using a Pressure Gauge Calcimeter. Approx. 1 g of sample was placed in the calcimeter and the recipient was filled with 10 % hydrochloric acid (HCl). The mass of $CaCO_3$ in the sample (g) was then calculated as

40 follows:

$$m_{CaCO_3} = \frac{p - b}{a \times w} \qquad (2)$$

where p is the pressure recorded (ppm), b is the slope and a the intercept derived from the calibration curve, and w is the exact weight of each sediment sample (g). The percentage of $CaCO_3$ in the sample (% DW) was then calculated using Eq. 3:

$$\%_{CaCO_3} = \frac{m_{CaCO_3}}{w \times 100} \qquad (3)$$

5 Dried sediment and plant samples were digested using USEPA method 3052 and analyzed with nitric acid (HNO_3) and HCl using USEPA method 200.7 following manufacturer instructions. The phosphorus content (% DW) was analyzed using inductively coupled plasma optical emission spectroscropy (ICP-OES) on an Agilent 5110 ICP-OES (Agilent Technologies, Santa Clara, CA, USA). The C and N concentration of both plants and sediments was analyzed after acidification with HCl (Hedges and Stern, 1984), using Flash 2000 Organic Elemental Analyzer (CHNS/O-2, Thermo Fisher Scientic, Waltham,
10 MA, USA). The isotopic signature of ^{13}C in sediment organic matter was analyzed, using cavity ring-down spectroscropy (CRDS G2201-I, Picarro Inc., Santa Clara, CA, USA), from the ^{13}C of CO_2 released by a combustion module (Costech Analytical Technologies Inc., CA, USA) delivering the CO_2 resulting from combusting the sediment organic matter to the CRDS instrument.

15 **2.3 Assessment of carbon dioxide and methane air-seawater fluxes**

In February 2018, triplicate cores from vegetated and adjacent bare (about 5 m from the edge of the seagrass patch) sediments were collected from sites S1 and S2 and transferred to incubation chambers (Percival Scientific Inc., Perry, IA, USA) set at 25 °C and a 12 hours light (up to 70 µmol photons m^{-2} s^{-1}) : 12 hours dark (12 h L : 12 h D) cycle to measure the greenhouse gas (CO_2 and CH_4) fluxes supported by these communities. Before measuring fluxes, the water overlying the
20 sediment inside the cores was carefully siphoned until only 5 mm of water remained over the sediment surface and fresh seawater was carefully siphoned in the core, to avoid disturbing the redoxcline, leaving a headspace of approx. 5 - 6 cm, and the cores were closed again with stoppers containing gas tight valves. The cores were left for one hour to allow for equilibration between the seawater and the headspace air. We then sampled 10 mL of air from each core using a syringe and injected the air sample in a cavity ring-down spectrometer (CRDS; Picarro Inc., Santa Clara, CA, USA) through a small
25 sample isotopic module extension (SSIM A0314, Picarro Inc., Santa Clara, CA, USA), which provided both the partial pressure and the isotopic carbon composition of the CO_2 and CH_4 in the air sample. One sample from each core was taken at the start (T0), after 12 hours of light (T1) and after 12 hours of dark (T2). The daily CO_2 and CH_4 fluxes were calculated from the difference between T0 and T2 taking into account the core surface area (µmol m^{-2} d^{-1}). Before and after each sampling, two standards were measured (A: 750 ppm CO_2, 9.7 ppm CH_4, B: 250.5 ppm CO_2, 3.25 ppm CH_4).

30

2.4 Effect of warming on carbon dioxide and methane air-seawater fluxes

In March 2018, we collected eighteen vegetated and eighteen bare sediment cores from site S2 to evaluate the response of greenhouse gas fluxes to warming. The sampling was performed as described above. The cores were transferred to the Coastal and Marine Resources Core Lab (CMOR, KAUST, Saudi Arabia). Nine vegetated and nine bare sediment cores each
35 were placed in two aquaria with flow-through seawater set at *in situ* temperature (25 °C) and a 12 h L (up to 200 µmol photons m^{-2} s^{-1}): 12 h D cycle. One aquarium was maintained at 25 °C over the entire duration of the experiment to serve as a control for temperature-independent variability in fluxes. The temperature in the second aquarium was increased at a rate of 1 °C day^{-1} to allow for acclimatization of the vegetated and bare cores. CO_2 and CH_4 fluxes were measured at every 2 °C from 25 - 37 °C, with parallel measurements conducted on the cores maintained at 25 °C. After a one day acclimation period
40 at each new temperature, the cores were closed with the stoppers and transferred to incubation chambers (Percival Scientific

Inc., Perry, IA, USA) set at the target temperature for CO_2 and CH_4 flux measurements as described above. After the 24h measurements, the cores were returned to the aquaria. An additional core kept at each of the constant temperature and warming sets was sampled every four days (i.e. at 4 ˚C temperature intervals in the warming treatment) to analyze sediment composition. The cores used for fluxes estimates were opened after the final measurement (20 days since collection) to
5   estimate the plant biomass, analyze the sediment composition at the end of the experiment.

2.5 Effect of darkness on carbon dioxide and methane air-seawater fluxes

In May 2018, six vegetated and six bare sediment cores were collected from site S2 and kept at a constant 25 ˚C with a 24 hours dark cycle. Only during the measurements in the incubators, the cores were exposed to a 12 h L : 12 h D cycle,
10   allowing to compare fluxes with those measured in cores permanently maintained under the 12 h L : 12 h D photoperiod. CO_2 and CH_4 fluxes were measured after the first day of acclimation and then kept in the aquaria until signs of seagrass mortality started to become apparent, which occurred after one week in the dark. CO_2 and CH_4 fluxes were measured at alternate days as detailed above. At the end of the experiment (21 days since collection), the cores were opened and sampled to assess plant biomass, sediment composition.

15

2.6 Measurements of carbon dioxide and methane air-seawater fluxes

The concentration of CO_2 in the seawater after equilibrium was calculated based on the concentration of CO_2 in the headspace (ppm) measured by CRDS according to Sea et al. (2018) and Wilson et al. (2012):

$$[CO_2]_w = 10^{-6}\beta m_a p_{dry} \qquad (4)$$

20   where β is the Bunsen solubility coefficient of CO_2 (mol mL^{-1} atm^{-1}), m_a is the CO_2 concentration measured in the headspace (ppm), and p_{dry} is the atmospheric pressure of dry air (atm). The Bunsen solubility coefficient of CO_2 was calculated using Eq. 5:

$$\beta = H^{cp} \times (RT) \qquad (5)$$

where H^{cp} is the Henry constant (mol mL^{-1} atm^{-1}) calculated using the *marelac* R package (Soetaert et al., 2010). R is the
25   ideal gas constant (0.082057459 atm L mol mL^{-1} K^{-1}) and T is the standard temperature (273.15 K).

The atmospheric pressure of dry air (p_{dry}) was calculated as follows:

$$p_{dry} = p_{wet}(1 - \%H_2O) \qquad (6)$$

where p_{wet} is the atmospheric pressure of wet air. The Boyle's law was applied as gas was collected several times from the same core.

30   The concentration of dissolved CO_2 in seawater before equilibrium was then calculated using Eq. 7:

$$[CO_2]_{aq} = \frac{[CO_2]_w V_w + 10^{-6} m_a V_a}{V_w} \qquad (7)$$

where V_w is the volume of seawater (mL) and V_a is the volume of the headspace (mL). The units were then converted to nM:

$$[CO_2]_{aq} = \frac{10^9 \times p_{dry}[CO_2]_{aq}}{RT} \qquad (8)$$

The daily CO_2 fluxes were calculated from the difference between T0 and T2 taking into account the core surface area (µmol
35   m^{-2} d^{-1}).

Daily CH_4 fluxes were estimated using the same calculations as for the CO_2 fluxes with the exception of the Bunsen solubility coefficient. The Bunsen solubility coefficient was calculated as a function of the seawater temperature and salinity following Wiesenburg and Guinasso (1979). The total CO_2 greenhouse-equivalent fluxes were calculated assuming CH_4 to have a greenhouse potential 28-fold greater than that of CO_2 per mol of C (Myhre et al., 2013).

5

2.7 Isotopic composition of carbon dioxide ($\delta^{13}C$-CO_2) and methane ($\delta^{13}C$-CH_4)

The isotopic signature of CO_2 and CH_4 produced during the incubations was estimated using Keeling plots following Garcias-Bonet and Duarte (2017). $\delta^{13}C$ of CO_2 and CH_4 produced in our incubations was extracted from the intercept of the linear regression between the inverse of the gas concentration (ppm^{-1}) and the isotopic signature measured from the discrete

10   samples in the CDRS instrument.

2.8 Data analysis

The data was analyzed for normality using the Shapiro-Wilk test. Mann-Whitney and t-test were used to test for differences in seagrass and sediment composition between sites and between vegetated and bare sediments, and ANOVA and Kruskal-

15   Wallis test were used to test for differences between vegetated and bare sediments and both sites. To assess differences in greenhouse gas fluxes between different *H. stipulacea* communities, differences in CO_2 and CH_4 fluxes were analyzed between sites and between vegetated and bare sediment by using Kruskal-Wallis test. Trends in the flux between the communities experiencing warming and the ones maintained at 25 ˚C, as well as in the isotopic signature of $\delta^{13}C$-CO_2 and $\delta^{13}C$-CH_4 over time were analyzed by linear regression. When assessing the effect of darkness on greenhouse gas fluxes, the

20   trend of CO_2 and CH_4 fluxes and their isotopic signatures were analyzed by linear regression. The statistical analyses were conducted in PRISM 5 (GraphPad Software, La Jolla, CA, USA) and JMP Pro 13.1.0 (SAS Institute Inc., Cary, NC, USA). The data is openly available from Burkholz et al. (2019b).

3 Results

25   ### 3.1 Seagrass and sediment composition

Carbon, nitrogen (N), and phosphorus (P) concentrations in seagrass leaves were low, but they were 4- to 40-fold higher than vegetated and bare sediment concentrations (Table 1). Seagrass sampled in site S1 had the highest C, N and P concentrations in the leaves, while sediment C and P concentrations differed significantly between sites (ANOVA, $p < 0.05$ and Kruskal-Wallis, $p < 0.001$, respectively), with the highest C and the lowest P concentrations found in the sediment of S2 (Table 1).

30   There were no consistent differences in C, N and P concentration in bare and vegetated sediments (Table 1).

The sediments had high, but variable, carbonate concentrations, which differed between sites (Kruskal-Wallis, $p < 0.0001$; Table 1). The organic matter content was slightly higher in S2 than in S1, in both vegetated (t-test, $p < 0.0001$) and bare (t-test, $p < 0.001$) sediments (Table 1). Sediment bulk density was similar in both S1 and S2 sites, but vegetated sediments in S1 showed significantly lower bulk density compared to bare sediments (t-test, $p < 0.05$; Table 1). Seagrass biomass was

35   significantly higher in S2 compared to S1 (t-test, $p < 0.05$). The isotopic signature of sediment organic carbon ranged across sites from -15.77 ± 0.07 ‰, in vegetated sediments, to -16.36 ± 0.28 ‰, in bare sediments (Table 1). The carbon isotopic signature of seagrass leaves from the same location has been recently reported as -7.96 ± 0.27 ‰ by Duarte et al. (2018).

3.2 Carbon dioxide and methane air-seawater fluxes

The daily CO_2 flux was up to 6-fold higher in vegetated compared to bare sediments and tended to be generally higher in S2 compared to S1, where bare sediments showed net CO_2 uptake, although differences were not significant (Kruskal-Wallis, $p > 0.05$; Fig. 1A). At both sites, S1 and S2, the daily net CH_4 flux was 10- to 100-fold higher in vegetated compared to adjacent bare sediments with generally higher fluxes at S2 (Kruskal-Wallis, $p < 0.01$; Fig. 1B). The total CO_2 greenhouse-equivalent fluxes varied between sites and were higher in the vegetated compared to the bare sediments (Kruskal-Wallis, $p < 0.01$; Fig. 1C).

3.3 Effect of warming on carbon dioxide and methane air-seawater fluxes

The CO_2 fluxes in vegetated sediments increased greatly with warming ($R^2 = 0.38$, $p < 0.001$), but decreased over time when the community was maintained at 25 ˚C ($R^2 = 0.30$, $p < 0.01$; Fig. 2A, Table S1), shifting from sediments showing net CO_2 emission to net CO_2 uptake. Similar responses were observed in the bare sediments, where CO_2 fluxes increased with warming ($R^2 = 0.54$, $p < 0.0001$), while the community tended to shift over time from supporting net CO_2 emission to net CO_2 uptake when the maintained at 25 ˚C (Fig. 2B). The net CO_2 flux, i.e. the difference between the CO_2 fluxes in warming sediments and those at sediments maintained at 25 ˚C, increased significantly with warming in both the vegetated and the bare sediment ($R^2 = 0.74$, $p < 0.05$ and $R^2 = 0.91$, $p < 0.001$, respectively, Fig. 2C).

CH_4 fluxes declined over time when the sediments were maintained at 25 ˚C, both in vegetated ($R^2 = 0.43$, $p < 0.001$, Fig. 2D) and, less strongly, bare sediments ($R^2 = 0.24$, $p < 0.01$; Fig. 2E, Table S2). In contrast, CH_4 fluxes tended to increase with temperature in vegetated (Fig. 2D) and bare (Fig. 2E) sediments gradually warmed from 25 ˚C to 37 ˚C, although it was not significant ($p > 0.05$ and $p > 0.05$, respectively; Table S2). The net CH_4 fluxes, i.e. the difference between the CH_4 fluxes in sediments exposed to warming and those sediments at maintained at 25 ˚C, increased significantly over time (i.e. with warming) in vegetated ($R^2 = 0.69$, $p < 0.05$) but not in bare sediments ($p > 0.05$; Fig. 2F). An outlier in the vegetated sediment at 33 ˚C supporting extreme emissions (CO_2 flux of 55,170 µmol CO_2 m^{-2} d^{-1} and CH_4 flux of 699.8 CH_4 µmol m^{-2} d^{-1}), was observed on day 14 in one of the replicates of the warming treatment where seagrass had died (Fig. 2A and D), and was excluded from the regression analyses reported above.

Despite CO_2 and CH_4 fluxes showing the same response to warming in both types of sediment, vegetated sediments held higher fluxes than bare sediments. The relationship between net CO_2 and CH_4 fluxes in bare vs. vegetated sediments showed that both bare and vegetated communities tended to act as net CO_2 sinks at 25 ˚C, but tended to act as CO_2 sources at warmer temperatures (Fig. 3A), whereas net CH_4 fluxes were 3- to 8-fold higher in vegetated compared to bare sediments. (Fig. 3B). The CH_4/CO_2 ratio declined in the vegetated sediments exposed to warming from 7 to 0.8 %. For CO_2 and CH_4 fluxes in vegetated sediments, the Q10 value for the temperature range 25-37 ˚C was 9 and 1.5, respectively, while the Q10 value for bare sediments was 13.8 and 4.2, respectively.

3.4 Effect of darkness on carbon dioxide and methane air-seawater fluxes

The vegetated sediment shifted over time from showing net CO_2 uptake to net CO_2 emission when maintained in the dark ($R^2 = 0.70$, $p < 0.05$), while the increase in the bare sediment was not significant ($p > 0.05$; Fig. 4A, Table S3). In contrast, when vegetated sediment was maintained at 25 ˚C at a 12 h L : 12 h D photoperiod, the community shifted from net CO_2 emission to net CO_2 uptake (Mann Whitney, $p < 0.05$; Fig. 5A). In bare sediments, CO_2 fluxes showed the same trend in cores maintained at 25 ˚C at a 12 h L : 12 h D photoperiod than under dark conditions (Fig. 5B).

When vegetated sediments were kept in the dark, net CH_4 fluxes decreased 5-fold over time ($R^2 = 0.99$, $p < 0.0001$; Fig. 4B, Table S4). However, the CH_4 fluxes did not differ significantly between vegetated cores maintained at 25 ˚C in the 12 h L : 12 h D photoperiod or in the dark (Mann Whitney, $p > 0.05$), showing the same trend of decreasing CH_4 fluxes (Fig. 5C). In the bare sediment, CH_4 fluxes in sediments kept in the dark were higher than those at 25 ˚C under a 12 h L : 12 h D photoperiod, with significant differences only observed on days 14 and day 20 (Mann Whitney, $p < 0.05$ and $p < 0.05$, respectively; Fig. 5D).

3.5 Isotopic composition of carbon dioxide ($δ^{13}C$-CO_2) and methane ($δ^{13}C$-CH_4)

The isotopic signature of the $δ^{13}C$-CO_2 became heavier with warming in the bare sediment, increasing from -22.36 ± -4.97 ‰ $δ^{13}C$ at 25 ˚C to -9.01 ± 0.98 ‰ $δ^{13}C$ at 37 ˚C ($R^2 = 0.91$, $p < 0.001$), while the other treatments showed similar values over time, ranging from a minimum average of -17.89 ± 1.81 ‰ to a maximum average of -11.55 ± 5.32 ‰ $δ^{13}C$ (Fig. 6A-D).

The isotopic signature of $δ^{13}C$-CH_4 decreased over time in both vegetated and bare sediments, whether they were maintained at constant temperature or experienced warming (Fig. 6E-H). The isotopic signature in the vegetated sediment exposed to warming decreased significantly from -50.8 to -54.06 ‰ ($R^2 = 0.67$, $p < 0.001$).

The $δ^{13}C$ isotopic composition of both CO_2 and CH_4 became heavier over time when the community was kept in the dark (Fig. 7), with a significant increase of $δ^{13}C$-CH_4 in bare sediments ($R^2 = 0.94$, $p < 0.01$; Fig 7D).

4 Discussion

4.1 Carbon dioxide and methane air-seawater fluxes

The values reported for CO_2 and CH_4 fluxes varied greatly between the two sites studied here, with higher fluxes in the more organic sediments with higher biomass (S2). CO_2 and CH_4 fluxes were also highly variable over time in the studied site, as the first evaluation of fluxes in the same location delivered rates up to 100-fold above the rates of the second measurement one week later. Hence, organic matter availability along with temperature may account for the large variation in CO_2 and CH_4 fluxes. Additionally, the variability of CO_2 and CH_4 fluxes could also be supported by infaunal species present in the cores that were not recorded in this study. These trends were similar to results reported in previous studies, as a high variability between species and locations was found (cf. Table 1 in Garcias-Bonet and Duarte (2017)).

Even though there were some differences, carbon, nitrogen and phosphorus concentrations were generally similar, and they didn't seem to have an effect on CO_2 and CH_4 fluxes. Carbon, nitrogen and phosphorus concentrations were low compared to mean values (Carbon: 33.6 ± 0.31 % DW, nitrogen: 1.92 ± 0.05 % DW, phosphorus: 0.23 ± 0.011 % DW) reported for seagrass leaves by Duarte (1990). Serrano et al. (2018) explained the discrepancy between Red Sea data and global data with the extreme conditions in the Red Sea, such as low nutrient input and high temperatures, as well as a limited data set favoring high carbon stocks in the Mediterranean.

The results presented here add to those by Garcias-Bonet and Duarte (2017) to identify Red Sea seagrass communities as a significant source of CH_4. The presence of seagrass resulted in a higher organic matter supply to the sediments, favoring the presence of methanogens, which led to higher CH_4 fluxes compared to those fluxes supported in bare sediments (Barber and Carlson, 1993; Bahlmann et al., 2015), consistent with the up to 100-fold higher CH_4 fluxes supported by vegetated compared to bare sediments in this study. Additionally, higher fluxes in vegetated cores could be an indicator of direct effects resulting from the presence of seagrass, as vascular plants on land have shown to have varying effects on methane emissions caused by differences in biomass and gross photosynthesis (Öquist and Svensson, 2002).

Similar trends were also seen by Garcias-Bonet and Duarte (2017) who reported an increase in CH_4 fluxes with increasing organic matter content in Red Sea seagrass sediments. They reported organic matter contents in Red Sea seagrass sediments ranging from 2.33 ± 0.07 % (*Halodule uninervis*) to 12.42 ± 0.23 % (*Enhalus acoroides*), including a mixed meadow with *H. stipulacea* and *H. uninervis* showing a slightly higher organic matter content of 3.51 ± 0.17 % compared to vegetated

5   sediments at S2. Moreover, they found the highest CH_4 fluxes in meadows with the highest biomass, confirming our findings with higher fluxes in study site S2.

In terms of CO_2 equivalent greenhouse potential, only the bare sediment maintained at 25 ˚C seemed to act as a C sink over the experimental period, while the vegetated sediments, both maintained at 25 ˚C and exposed to warming, acted as sources of greenhouse gases. A sublethal disturbance, such as warming below the lethal threshold, can therefore lead to a shift of

10   seagrass ecosystems from acting as net sinks to net sources of greenhouse gases, as demonstrated experimentally here.

4.2 Effect of warming

Both CO_2 and CH_4 fluxes were higher in vegetated compared to adjacent bare sediments, indicating elevated remineralization rates in vegetated sediments as well as a higher susceptibility of seagrass sediment to increasing

15   temperatures. Vegetated sediments exposed to warming shifted from acting as a CO_2 sink to an increasingly intense source, while the CO_2 fluxes in vegetated sediments maintained at 25 ˚C decreased over time. Warming leads to an increase in both community photosynthesis and respiration, with respiration increasing at a faster rate (Harris et al., 2006) explaining the shift to a CO_2 source in sediments exposed to a thermal stressor. However, the fluxes maintained at 25 ˚C showed a net CO_2 uptake with a mean of 464.78 ± 156.6 µmol CO_2 m^{-2} d^{-1} (Table S1), while those reported in a mixed *Halodule* sp. and

20   *Halophila* sp. meadow in India showed a net CO_2 release (dry season: $1{,}190 \pm 1{,}600$ µmol CO_2 m^{-2} d^{-1}, wet season: $18{,}400 \pm 8{,}800$ µmol CO_2 m^{-2} d^{-1}; Banerjee et al., 2018). Both values reported were measured at higher temperatures (dry season: 30 ± 0.68 ˚C, wet season: 27.94 ± 0.72 ˚C, Banerjee et al., 2018) compared to our fluxes measured at 25 ˚C, also indicating that temperature might lead to higher fluxes. An initial high CO_2 flux measured on day 2 after sampling could be an indicator for the experienced disturbance due to sample collection and transportation even though we allowed the cores some time to

25   adapt.

Mean CH_4 fluxes at *in situ* temperature (25 ˚C) in vegetated sediments were lower than the mean value of 85.1 ± 27.8 µmol CH_4 m^{-2} d^{-1} reported for other seagrass meadows in the Red Sea (Garcias-Bonet and Duarte, 2017). In contrast, the community exposed to warming reached a maximum average CH_4 flux almost 4-fold higher than the community held at 25 ˚C, and showed a clear increase with warming, relative to sediments held at 25 ˚C. The increase in CH_4 fluxes with warming

30   was consistent with reports from Barber and Carlson (1993) for a *Thalassia testudinum* community in Florida Bay and Garcias-Bonet and Duarte (2017) for Red Sea seagrass communities, who reported higher CH_4 fluxes at higher temperatures. Additionally, previous research has shown that methanogenesis has a higher thermal dependence than respiration and photosynthesis (Yvon-Durocher et al., 2014) confirming the trends seen here with increasing fluxes at higher temperatures. We also reported a 10-fold decline in CH_4 fluxes over time for sediment communities maintained at 25 ˚C, which could be

35   attributable to increased sulfate reduction, reduced CH_4 production or a combination of both. Methane is produced under anoxic conditions in marine sediments, yet only a small portion is released, as CH_4 production by methanogens is compensated for by CH_4 oxidation by sulfate-reducing bacteria (Barnes and Goldberg, 1976). Similar to the trends seen in CO_2 fluxes, the decrease in CH_4 fluxes could be attributable to an initial stress response to the disturbance caused by sample collection and transportation. While reduced photosynthetic activity and a degradation in biomass could result in higher CH4

40   fluxes (Lyimo et al., 2018), the cores maintained at 25 ˚C might show the effect of healthy conditions.

Increasing water temperature led to a decrease in the CH_4/CO_2 ratio. While there was ~7 % of sequestered carbon released as CH_4 to the atmosphere in vegetated sediments at 25 ˚C (on day 2), it decreased to ~0.8 % in vegetated sediments at 37 ˚C. In contrast, Banerjee et al. (2018) reported ~1% of carbon being released as CH_4.

The isotopic composition of CO_2 in all treatments showed generally heavier isotopic signatures compared to previous reports of seagrass carbon (average $\delta^{13}C$ value of -7.73 ± 0.11 ‰ for Red Sea seagrass and -7.57 ± 0.15 ‰ for *H. stipulacea* in the Red Sea; Duarte et al., 2018), indicating various organic matter sources such as macroalgae blades (13.38 ± 0.3 ‰), mangrove leaves (26.58 ± 0.13 ‰) and seston (25.43 ± 0.42 ‰; Duarte et al., 2018). However, the mean $\delta^{13}C$ value of Red Sea seagrass sediments was reported to be −13.36 ± 0.4 ‰ (Garcias-Bonet et al., 2019a), similar to the results found in this study. Our chosen study sites were located in an enclosed lagoon with a high abundance of mangrove forests, leading to the conclusion that mangroves might be a major source of organic matter for our study sites. However, a recent study applying stable isotope mixing models found the major contributors to the organic matter in seagrass sediments in the Red Sea to be seagrass leaves and macroalgae blades, with contributions of 43 and 37 %, respectively (Garcias-Bonet et al., 2019a).

The isotopic signature of CO_2 released from bare sediments shifted with warming, suggesting a shift from seston, mangroves and macroalgae as the organic matter supporting respiration to seagrass carbon as the source of CO_2. In the vegetated cores, the isotopic composition of CO_2 stayed rather constant, indicating several sources of organic carbon with no clear shift, regardless of warming.

The isotopic signature of CH_4 in vegetated sediments confirmed its biogenic source as previous reports have shown that the isotopic signature of CH_4 from biogenic sources can range from -40 to -80 ‰, while the isotopic signature of CH_4 from geological and thermogenic sources ranges from -30 to -50 ‰ (Reeburgh, 2014), The isotopic composition of CH_4 in bare sediments was generally at the lower end of this range, with no clear shift with increasing temperature.

The isotopic composition of CH_4 can be determined by the production of CH_4 (methanogenesis) leading to lower $\delta^{13}C$ values and the oxidation of CH_4 (methanotrophy) leading to higher $\delta^{13}C$ values (Whiticar, 1990). Garcias-Bonet and Duarte (2017) reported fluctuations in the isotopic signature of CH_4 in Red Sea seagrass meadows, suggesting an indication for both processes. When exposed to increasing temperatures, we observed a shift to a lighter isotopic signature of CH_4 in vegetated sediments, thereby indicating an increasing CH_4 production by methanogens with warming.

4.3 Effect of prolonged darkness
Communities maintained at 25 ˚C and a 12 h L : 12 h D photoperiod showed continuous net CO_2 uptake, while the communities kept in the dark shifted, as expected, to a heterotrophic state, acting as a CO_2 source. The net CO_2 production corresponded to community respiration rates, while that at 12 h L : 12 h D photoperiod corresponded to the net community production.

We found, however, no effect of prolonged darkness on CH_4 fluxes, suggesting that the elevated CH_4 fluxes in vegetated sediments were not directly supported by fresh photosynthetic products, but rather by the elevated organic matter content in vegetated sediments compared to bare ones. These findings were in contrast to those reported by Lyimo et al. (2018) who found increased CH_4 fluxes under shading indicating that degradation of belowground biomass might have been the key factor related to increased CH_4 fluxes. However, they also reported varying results for different shading intensities, with low intensity having similar fluxes compared to their control group (Lyimo et al., 2018). In contrast, Öquist and Svensson (2002) found that photosynthesis might be regulating methane fluxes in a subarctic peatland ecosystem, with in lower photosynthesis resulting in lower methane fluxes.

4.4 Implications

Reports on greenhouse gas fluxes by seagrass ecosystems are limited (Oremland, 1975; Barber and Carlson, 1993; Alongi et al., 2008; Deborde et al., 2010; Bahlmann et al., 2015; Garcias-Bonet and Duarte, 2017; Banerjee et al., 2018; Lyimo et al., 2018), and no reports had been previously published on how increasing seawater temperatures might affect greenhouse gas fluxes by seagrass ecosystems. Blue carbon ecosystems have shown to turn into C sources when disturbances led to mortality (Macreadie et al., 2015; Lovelock et al., 2017; Arias-Ortiz et al., 2018), consistent with the very large CO_2 and CH_4 fluxes observed in one vegetated sediment where the seagrass died when warmed to 33 ˚C. However, even where seagrass remained alive, warming led to elevated greenhouse fluxes. Additionally, the elevated nutrient and high organic matter stock in seagrass meadows, which supports a 1.7-fold higher organic matter content than surrounding bare sediments, can promote an increase in CO_2 and CH_4 fluxes following disturbance (Gonsalves et al., 2011; Sotomayor et al., 1994). Our results suggest that this stock in seagrass sediments may be remineralized to support net greenhouse gas fluxes at the warmer temperatures reached and with further warming of the Red Sea. Hence, warming may, as other disturbances (Lovelock et al., 2017), shift seagrass ecosystems from net sinks to net sources of greenhouse gases, thereby providing a feedback mechanism that may contribute to further enhance global warming.

5 Conclusion

In summary, this study reports, for the first time, experimental evidence that warming leads to increased greenhouse gas (CO_2 and CH_4) fluxes in a *H. stipulacea* meadow in the Red Sea, and it may lead to seagrass meadows shifting from acting as sinks to sources of greenhouse gases. Increased fluxes at higher temperatures can be an indication of higher remineralization rates and a higher susceptibility of vegetated sediments to temperature. The elevated organic matter content, higher biomass and higher plant activity in vegetated sediments led to increased CO_2 and CH_4 fluxes in vegetated compared to bare sediments and a much steeper increase in CO_2 and CH_4 fluxes with warming. In addition, prolonged darkness led to an increase in CO_2 fluxes, while CH_4 fluxes decreased over time, also indicating organic matter to be the driver. However, we also found a high variability in fluxes over time indicating that other factors, such as infaunal species, could play a role as well. While current focus is on conserving blue carbon ecosystems from losses due to deteriorated water quality or mechanical damage, our results show that sublethal warming may also lead to emissions of greenhouse gases from seagrass meadows, contributing to a feedback between ocean warming and further climate change.

Author contributions

NG-B, CMD and CB designed the project. CB collected the samples and conducted the experiments. NG-B, CMD and CB analyzed the results, CMD and CB wrote the first draft of the manuscript, and all authors contributed substantially to the final manuscript. All authors approved the final submission.

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TABLES

Table 1. Summary of vegetated sediment, bare sediment and seagrass leaves characteristics in the study sites (S1 and S2). NA: Not available.

	S1			S2		
	Vegetated sediment	Bare sediment	Seagrass leaf	Vegetated sediment	Bare sediment	Seagrass leaf
C concentration (% DW)	0.43 ± 0.05	0.41 ± 0.03	17.6 ± 2.72	0.55 ± 0.03	0.52 ± 0.02	15.32 ± 1.48
N concentration (% DW)	0.07 ± 0.01	0.12 ± 0.01	1.06 ± 0.17	0.08 ± 0.002	0.09 ± 0.01	0.94 ± 0.07
P concentration (% DW)	0.03 ± 0.001	0.03 ± 0	0.12 ± 0.01	0.02 ± 0	0.02 ± 0.001	0.11 ± 0.01
Carbonate content (% DW)	91.75 ± 0.56	91.65 ± 0	NA	82.61 ± 0.50	83.63 ± 0	NA
Organic matter (% DW)	2.45 ± 0.09	2.46 ± 0.16	NA	3.26 ± 0.03	2.95 ± 0.04	NA
Bulk density (g cm^{-3})	1.15 ± 0.02	1.28 ± 0.03	NA	1.1 ± 0.07	1.2 ± 0.04	NA
Seagrass biomass (g DW m^{-2})	60.87 ± 1.24	NA	NA	164.66 ± 20.54	NA	NA
Sediment $\delta^{13}C-C_{org}$ (‰)	-15.77 ± 0.07	-15.94 ± 0.1	NA	-15.81 ± 0.13	-16.36 ± 0.28	NA
Seagrass leaf $\delta^{13}C-C$ (‰), extracted from Duarte et al. (2018)			-7.96 ± 0.27			

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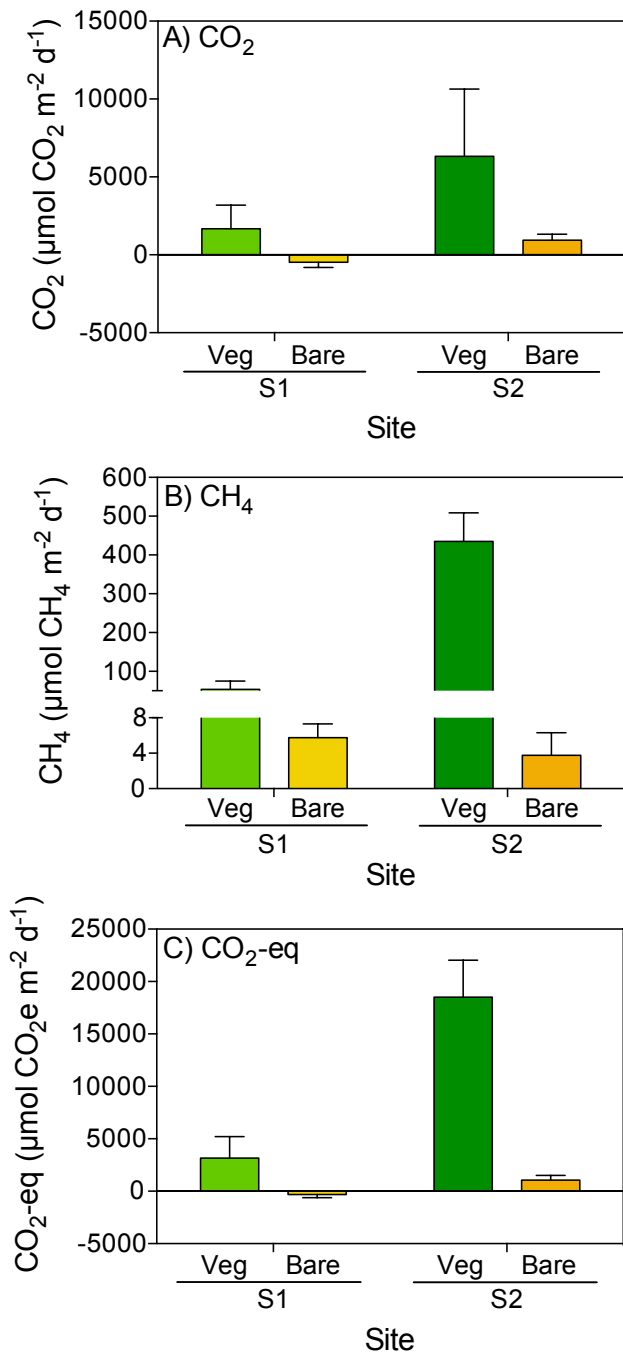
Figure 1: Mean + SE **(A)** CO_2, **(B)** CH_4, **(C)** CO_{2-eq} fluxes in vegetated (green) and adjacent bare (yellow) sediments at two sites (S1 and S2) in the central Red Sea.
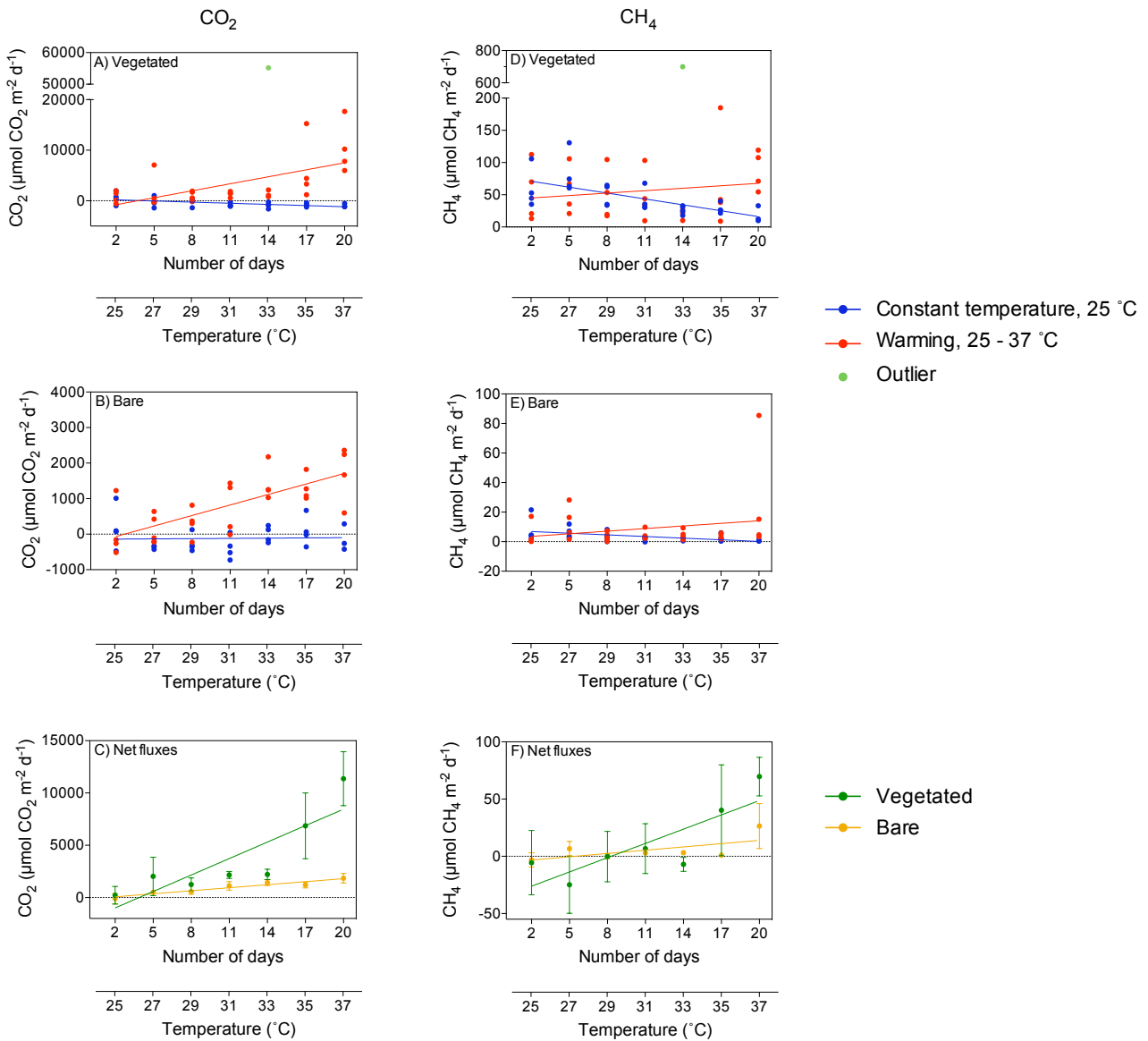
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Figure 2: Mean ± SE CO_2 (left) and CH_4 (right) fluxes in **(A and D)** vegetated and **(B and E)** bare sediments. Symbols indicate each replicate of the community experiencing warming from 25 - 37 ˚C (red) and the community maintained at 25 ˚C (blue) over the experimental period (number of days since the onset of the experiment). An outlier at 33 ˚C in vegetated sediments in shown in green. **(C and F)** Mean ± SE CO_2 (C) and CH_4 (F) net fluxes in vegetated (green) and bare (yellow) sediments over the experimental period (number of days since the onset of the experiment). The second x-axis indicates the experimental temperature for the community exposed to warming from 25 - 37 ˚C. Lines represent a fitted linear equation.
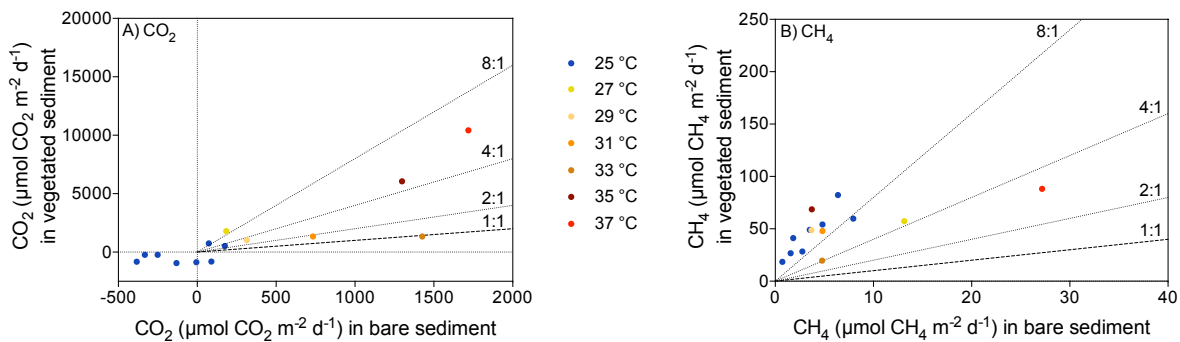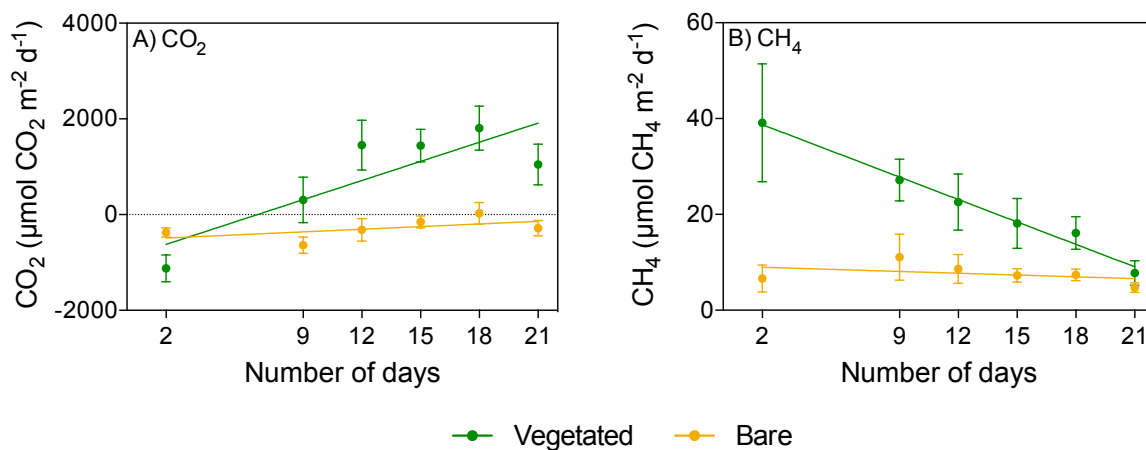
Figure 3: Relationship between vegetated and bare sediments for **(A)** CO_2 and **(B)** CH_4 fluxes. Symbols indicate different temperatures ranging from 25 - 37 °C, the dashed line indicates line 1:1, and dotted lines show lines 2:1, 4:1 and 8:1.

Figure 4: Mean ± SE **(A)** CO_2 and **(B)** CH_4 fluxes in vegetated (green) and bare (yellow) sediments of communities exposed to prolonged darkness over the experimental period (number of days since the onset of the experiment).
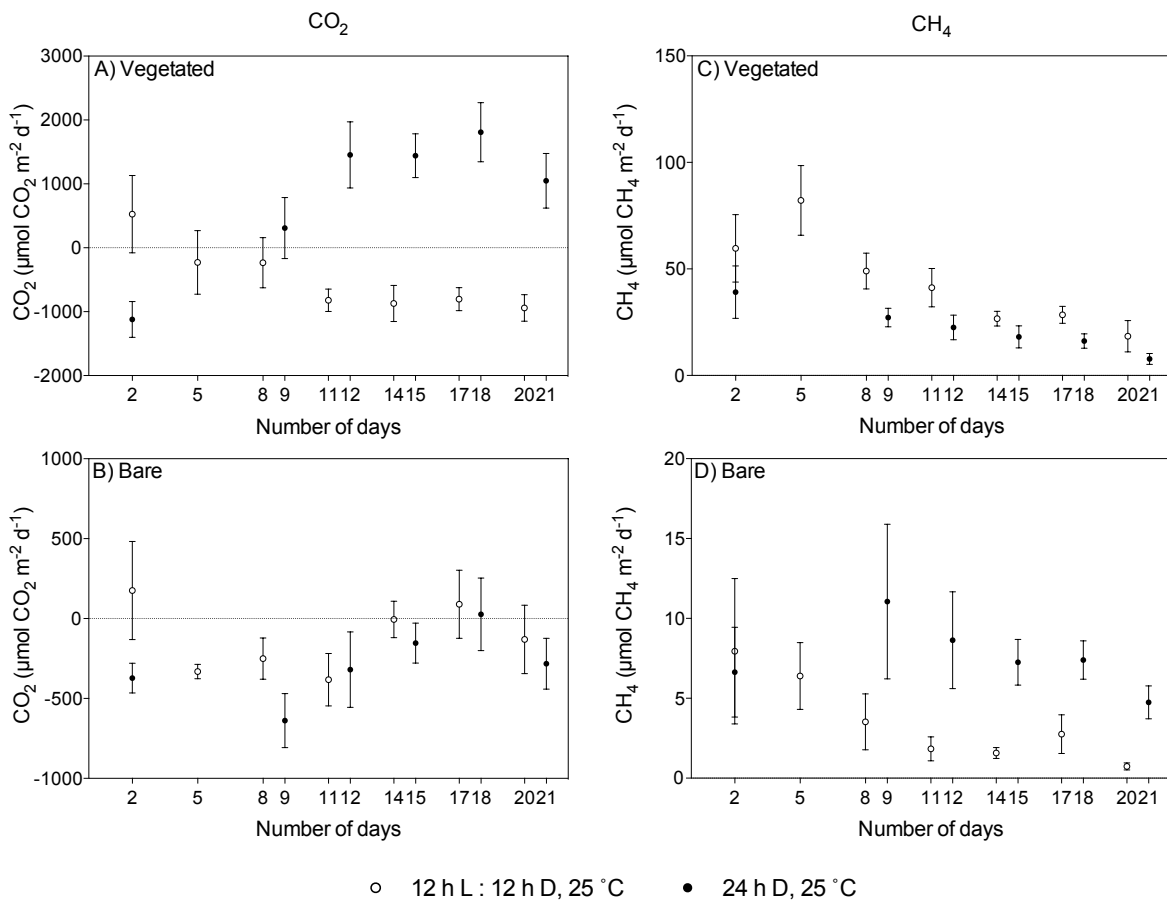
Figure 5: Comparison of mean ± SE CO_2 (left) and CH_4 (right) fluxes in **(A and C)** vegetated and **(B and D)** bare sediments maintained at 25 °C and a 12 h L:12 h D photoperiod (white) and communities kept at 25 °C and a 24 h D period (black) over the experimental period (number of days since the onset of the experiment). Dots indicate mean values and error bars indicate standard error of the mean.
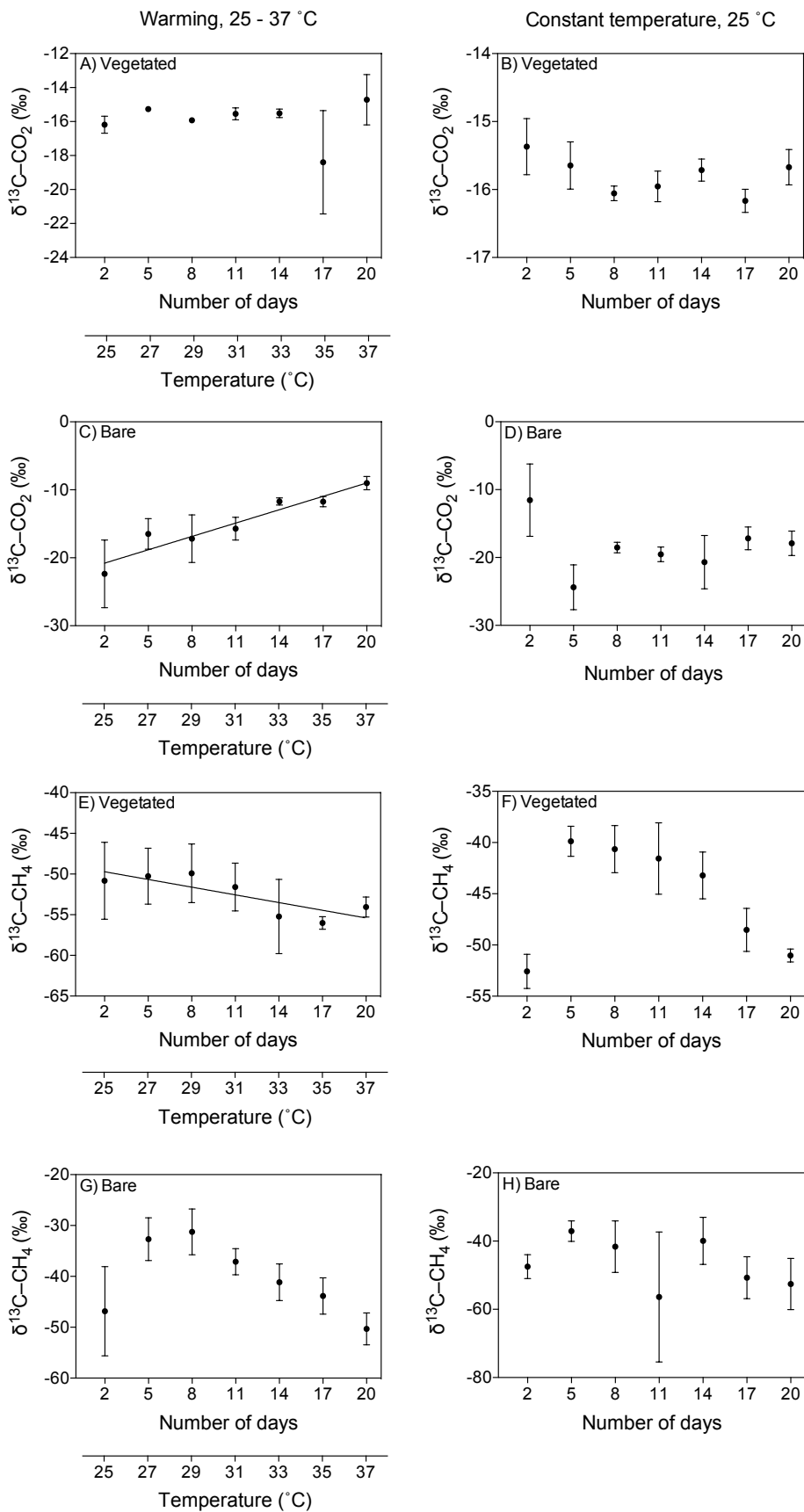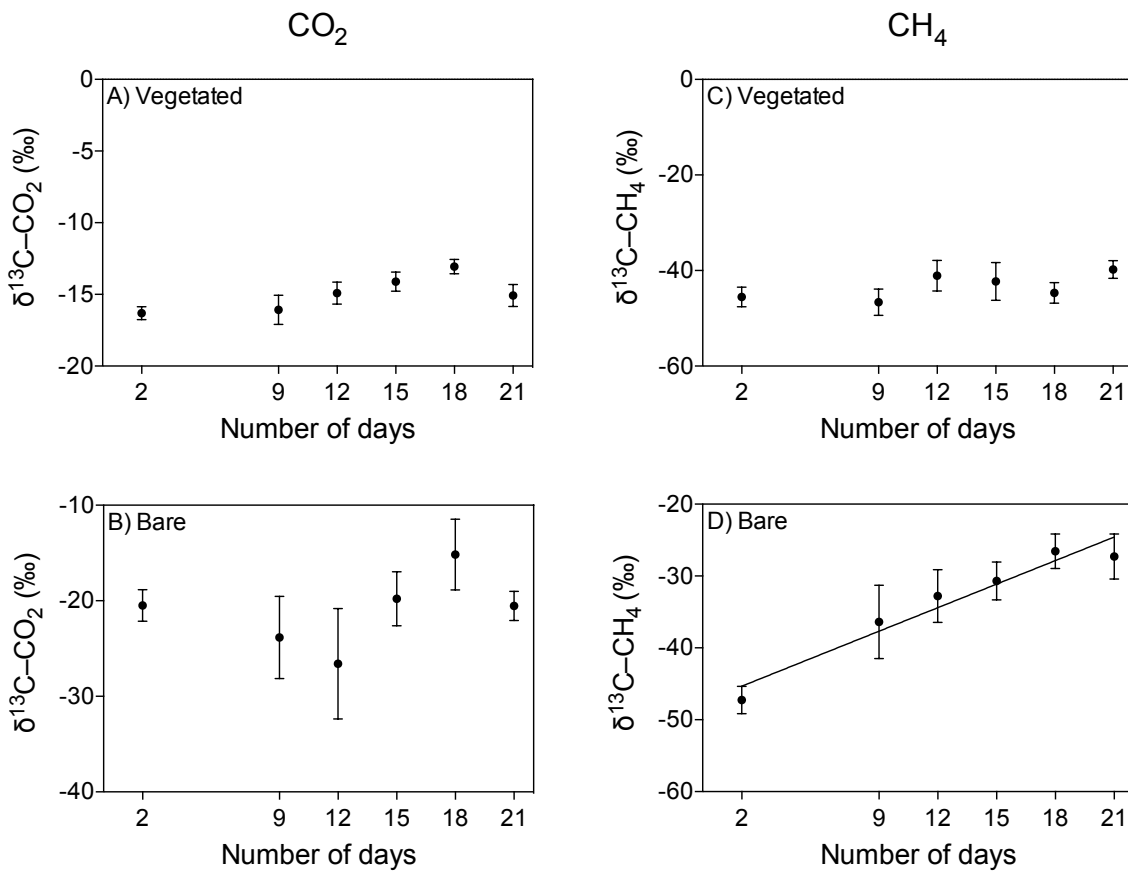
Figure 6: Mean ± SE isotopic signature of CO_2 ($\delta^{13}C$-CO_2) and CH_4 ($\delta^{13}C$-CH_4) in the communities experiencing warming from 25 - 37 ˚C (left) and the communities maintained at 25 ˚C (right). **(A-D)** $\delta^{13}C$-CO_2 is shown for the vegetated (A and B) and bare (C and D) sediments over the experimental period (number of days since the onset of the experiment). **(E-H)**

δ^{13}C-CH$_4$ is shown for the vegetated (E and F) and bare (G and H) sediment over the experimental period. The second x-axis indicates the temperature increase for the community experiencing warming.

5 **Figure 7:** Mean ± SE isotopic signature of CO$_2$ (δ^{13}C-CO$_2$, left) and CH$_4$ (δ^{13}C-CH$_4$, right) in **(A and C)** vegetated and **(B and D)** bare sediments exposed to prolonged darkness over the experimental period (number of days since the onset of the experiment).

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