We thank to referees' critical review and constructive comments regarding our paper. The following list includes the alterations we have made to address the referees' feedback. We believe that the manuscript has been substantially improved following adoption of the valuable suggestions.

Authors' replies to the comments of Referee #1

1) P2L5: "DIC source" should be "C source for their photosynthesis"? Can *Z. marina* also use bicarbonate and/or carbonate as photosynthetic substrates?

1) Author's reply: We have changed the sentence in response to the first part of your comment. (P2L5–6) Also, *Z. marina* can use bicarbonate as a photosynthetic substrate. We have therefore added the following sentences to the Introduction in response to the second part of your comment: "Under normal seawater pH conditions, the bicarbonate ion (HCO_3^-) is the most abundant inorganic carbon species, accounting for nearly 90% of the DIC pool (Plummer and Busenberg, 1982; Zeebe and Wolf-Gladrow, 2001). Some seagrass species indirectly use HCO_3^- under low-CO_2(aq) conditions (Beer et al., 2002; Campbell and Fourqurean, 2013)" (P2L13–16); and "Seagrasses rely largely on aqueous CO_2 [CO_2(aq)] as a carbon source for photosynthesis in nature (Beer and Koch, 1996). Some seagrass species, however, can use bicarbonate ions (HCO_3^-) as a major carbon source (Beer et al., 2002; Beer and Rehnberg, 1997), although there is considerable interspecific variation in HCO_3^- utilization (Campbell and Fourqurean, 2013)." (P2L5–9) Moreover, we have added the following sentence to the Results and Discussion: "*Z. marina* also uses HCO_3^- as a carbon source under low-CO_2(aq) conditions (Beer and Rehnberg, 1997)". (P10L7–8)

2) P2L25: "ratios" should be inserted after "stable carbon isotope"

2) Author's reply: We have inserted "ratios" in response to your comment. (P2L25)

3) P3L5: Needs more careful explanations. The difference of $\delta^{13}C$ values among chemical species in DIC is important in this context. Chemical species in DIC (relative abundance of CO_2 (aq), bicarbonate ion and carbonate ion) are controlled by in situ pH and water temperature. These species typically have distinctive delta 13C values under atmospheric equilibrium. The authors should check the following papers: "Plummer LN, Busenberg E. 1982. The solubilities of calcite, aragonite and vaterite in CO_2-H_2O solutions between 0 and 90°C, and an evaluation of the aqueous model for the system $CaCO_3$-CO_2-H_2O. Geochimica et Cosmochimica Acta

46(6):1011–40."; "Zhang J, Quay PD, Wilbur DO. 1995. Carbon isotope fractionation during gas-water exchange and dissolution of CO_2. Geochimica et Cosmochimica Acta 59(1):107–14."

3) Author's reply: We have added the following sentences in response to your comment: "The chemical species in the carbonate system (CO_2(aq), HCO_3^-, and carbonate ion [CO_3^{2-}]) have distinct $\delta^{13}C$ values, and isotopic fractionations change depending on pH and temperature (Zeebe and Wolf-Gladrow, 2001; Zhang et al., 1995). Because the $\delta^{13}C$ of HCO_3^- (0‰) is isotopically distinct from that of both CO_2(aq) (−9‰) and C_{air} (−8‰) under normal seawater conditions (pH ≈ 8), high $\delta^{13}C$ (>−10‰) in seagrasses shows that they use HCO_3^- as a carbon source because isotopic discrimination during CO_2 assimilation results in $\delta^{13}C$ values that are always higher than those of the carbon sources. Although low $\delta^{13}C$ (<−10‰) in seagrasses could be explained by the assimilation of both ^{13}C-depleted CO_2(aq) and C_{air}, quantification of the contribution of C_{air} is impossible because of the overlap between their $\delta^{13}C$ values." (P3L5–14) In addition to the references suggested, we have also added: Zeebe, R. E. and Wolf-Gladrow, D.: CO_2 in seawater: equilibrium, kinetics, and isotopes, in: Elsevier Oceanography Series 65, edited by: Halpern, D., Elsevier, Amsterdam, p.346, 2001.

4) P3L21-22: "As any ~ calculating $\Delta^{14}C$" should follow "because it is internally corrected by $\delta^{13}C$" and cite Stuiver and Polach (1977)

4) Author's reply: We have made the following changes to the sentence in question in response to your comment: "…by internal correction using $\delta^{13}C$ values eliminates any effects from isotopic fractionation (Stuiver and Polach, 1977)…" (P3L21–22)

5) P3L21: "Furthermore ~ in ecosystems" Unnecessary sentence in this paper

5) Author's reply: We have removed this sentence in response to your comment.

6) P3L18-19: "The age of DIC" is confusing and not a good choice of words. "The ^{14}C age of DIC" is more appropriate, but still unclear. I suggest the authors revise this sentence as "The $\Delta^{14}C$ value of DIC generally differs from that of atmospheric CO_2..."

6) Author's reply: We have changed this sentence as follows in response to your comment: "The $\Delta^{14}C$ of DIC generally differs from that of atmospheric CO_2". (P3L18–19)

7) P3L19-21: "long residence time in the ocean" should be replaced with "longer residence time

of C in the aquatic environment than *** (reference)”

7) Author’s reply: We have changed this sentence as follows in response to your comment: “…because of the longer residence time of carbon in aquatic ecosystems than in the atmosphere (Ishikawa et al., 2014; Stuiver and Braziunas, 1993).” (P3L19–21)

8) P3L24-25: “quantitative evidence of the assimilation of modern C_{air} by the seagrass, *Zostera marina*, by analyzing the $\Delta^{14}C$ values” should be revised as “quantitative evidence that the seagrass *Zostera marina* assimilates modern C_{air}, based on the $\Delta^{14}C$ values”

8) Author’s reply: We have changed this sentence in response to your comment. (P3L24–25)

9) P4L16-17: “screw-cap glass culture bottles” Was the hermeticity of the bottles ensured?

9) Author’s reply: We have changed the sentence as follows: “…500-mL hermetically-sealed glass bottles (Duran bottle; SCHOTT AG, Mainz, Germany)…” (P4L16–17)

10) P5L2-4: Was the surface of *Z. marina* leaves washed? Did the authors see biofilm covering *Z. marina* surface? If it is the case, terrestrial organic matter might be attached to the *Z. marina* surface and provided ^{14}C-enriched C to bulk *Z. marina* samples. Then, negative relationship between $\Delta^{14}C$ of (bulk) *Z. marina* and salinity can be also explained by the river transportation of terrestrial organic matter. That is, contribution of ^{14}C-enriched terrestrial organic matter may be diluted along freshwater-seawater gradient

10) Author’s reply: We washed away both the biofilm and any epiphytes covering the leaves to avoid contamination. We have added the following sentence to the Methods and Materials section of the revised manuscript: “Both the biofilm and epiphytes covering the leaves were gently removed by hands with powder-free groves and washed off using ultrapure water (Milli-Q water; Millipore, Billerica, MA, USA).” (P5L2–4). In addition, we have added the following sentence to the Results and Discussion section in response to your comment regarding the negative relationship between $\Delta^{14}C$ of *Z. marina* and salinity: “Furthermore, the negative relationship between salinity and $\Delta^{14}C_{seagrass}$ cannot be explained by any residual contamination from terrestrial organic carbon on the leaves because the terrestrial POC was ^{14}C-depleted (mean $\Delta^{14}C$ of terrestrial POC, −74.7 ± 23.4‰).” (P8L15–18). We have also added sentences related to the POC sampling procedure to the Material and methods (P5L8–11).

11) P5L7: “plant” should be inserted between “the samples”

11) Author’s reply: We have changed this sentence in response to your comment. (P5L7)

12) P5L14: “ratios” instead of “ratio” and “concentrations” instead of “concentration”

12) Author’s reply: We have changed this sentence in response to your comment. (P5L14)

13) P7L12: I did not understand why and how the authors used GLM. Why was the objective variable the difference between the Δ^{14}C values of the seagrass leaves and those of DIC? Why wasn’t single regression used for each of DIC and seagrass independently?

13) Author’s reply: We used a generalized linear model (GLM) rather than separate regressions for DIC and seagrass because we wanted to examine the difference between Δ^{14}C values in the seagrass leaves and DIC. We have added the following sentences: “These differences provide evidence that the seagrasses assimilate C_{air}. A GLM was suitable for this study because both continuous (salinity) and categorical variables (seagrass leaves or DIC) were used as explanatory variables.” (P7L13–16) In Table 1, the significance ($P < 0.001$) of “Type” (seagrass) indicates that the Δ^{14}C value of the seagrass leaves was significantly higher than that of DIC, showing there is a contribution from C_{air} as a carbon source for the seagrass. For clarification, we have added model equations to Fig. 2a: $\Delta^{14}C_{DIC} = -1.78 \times \text{Salinity} + 4.40$, and $\Delta^{14}C_{seagrass} = -1.78 \times \text{Salinity} + (4.40 + 7.34)$.

14) P5L13: Were δ^{13}C values of plants measured by EAIRMS whereas δ^{13}C values of DIC measured by AMS? If so, provide a brief note that typical AMS is not optimized for δ^{13}C measurements. A great care should be taken to compare δ^{13}C values determined by EAIRMS and AMS. At least, the authors can check the difference between δ^{13}C values of plants measured by EAIRMS and those by AMS. How much different were they?

14) Author’s reply: The analytical precision of AMS was within 0.7‰ for δ^{13}C and the precision of IRMS was 0.2‰ for δ^{13}C. Thus, IRMS is more suitable for δ^{13}C measurements than AMS. However, as you point out, we must acknowledge that Δ^{14}C was calculated from δ^{13}C measured with IRMS, because different individual subsamples were used for each analysis in this study (e.g., the differences between δ^{13}C by AMS and IRMS ranged from 0.1‰ to 3‰). In this version of the manuscript, we recalculated Δ^{14}C from δ^{13}C measured with AMS to avoid errors caused by using different individual subsamples. We have changed the relevant sentences in the

Materials and Methods (P5L14–P6L9), the isotopic signatures (Δ^{14}C and δ^{13}C of seagrass), and the carbon-source mixing model results. Our recalculation shows that the contribution of C_{air} (mean, 17%) is lower than that in the previous version of the manuscript (22%) but the general conclusion (i.e., that *Z. marina* significantly assimilates C_{air}) is robust (P8L21–24).

15) P7L21: "at each of four stations" should be inserted before "as follows"?

15) Author's reply: We have revised this sentence in response to your comment. (P7L21)

16) P8L3-4: The sentence "Δ^{14}C DIC was calculated from the best GLM (Table 1)." should be revised as "As DIC and *Z. marina* were not collected from the same stations, the Δ^{14}C DIC value as a C source of *Z. marina* in each station was estimated from the best GLM (Table 1)."

16) Author's reply: We have added the following sentences: "Because DIC taken up by seagrasses is a mixture of DIC from two sources (terrestrial and oceanic) each having distinct Δ^{14}C values, it is reasonable to use salinity as a proxy for the extent of mixing of these two sources as well as for the salinity gradient-based comparison between Δ^{14}C of DIC and seagrass (Table 1). This comparison was therefore possible even though DIC and *Z. marina* samples were not necessarily collected from the same stations (Fig. 1)." (P7L7–12) We have also changed the following sentence in response to your comment: "The Δ^{14}C values of DIC as the carbon source for *Z. marina* in the mixing model were estimated from the best GLM (Table 1)." (P8L3–4)

17) P8L19: Insert space between "theΔ^{14}C"

17) Author's reply: We have modified this sentence in response to your comment. (P8L19)

18) P8L24-P9L4: "As mean ~ sampling sites" Unclear sentence

18) Author's reply: We have changed this sentence as follows in response to your comment: "The contribution of C_{air} as a carbon source varied greatly even between samples from the same station (Fig. 2b). Because we did not determine the exposure time of each shoot in this study, we are unable to quantify any relationship between the contribution of C_{air} and air exposure time; however, the exposure time could mediate the assimilation of C_{air} (Clavier et al., 2011)." (P8L24–P9L4)

19) P9L10: “Nevertheless” should be replaced with “In any case”

19) Author’s reply: We have changed this sentence in response to your comment. (P9L10)

20) P10L2: “In particular isotopic fractionation” Cite Stuiver and Polach (1977) here

20) Author’s reply: We have added the appropriate citation in response to your comment. (P10L2)

21) P10L6-20: “As the ~ C_{air} (-8 ‰)” These values are determined by a certain combination of $\delta^{13}C$ of atmospheric CO_2, pH and water temperature with assumption that DIC equilibrates with atmospheric CO_2. If pH and water temperature data are available, relative abundance and isotopic composition of each C species can be estimated. At least provide more detailed explanations with appropriate citations as I suggested in Introduction

21) Author’s reply: We have added Fig. 2d in response to your comment. We have modified the sentences in question as follows: “As the $\delta^{13}C$ of HCO_3^- was isotopically distinct from $\delta^{13}C$ of both $CO_2(aq)$ and C_{air} (Fig. 2d) and as *Z. marina* also uses HCO_3^- as a carbon source under low-$CO_2(aq)$ conditions (Beer and Rehnberg, 1997), the $\delta^{13}C$ of the seagrass should change depending on the contribution of HCO_3^- as a carbon source (Campbell and Fourqurean, 2009; Raven et al., 2002). However, it is not possible to distinguish the contribution of C_{air} from that of other carbon sources because the $\delta^{13}C$ of C_{air} overlapped those of both HCO_3^- and $CO_2(aq)$ (Fig. 2d). Furthermore, $\delta^{13}C$ of both HCO_3^- and $CO_2(aq)$ change through mixing between low-$\delta^{13}C$ river water and high-$\delta^{13}C$ seawater in brackish areas (Fig. 2d). In any case, there are large uncertainties when using $\delta^{13}C$ to quantitatively estimate the contribution of C_{air} as a carbon source because the isotopic fractionation that occurs in the steps between the carbon source and organic plant compounds changes depending on the photosynthetic rate (Raven et al., 2002). The radiocarbon isotopic approach can avoid the uncertainties derived from both the contribution of HCO_3^- as a carbon source and isotopic fractionation in carbon assimilation.” (P10L6–20) We have also added the related sentence: “The samples for measuring DIC concentration and TA were collected into 250-mL Duran bottles (SCHOTT AG), which were poisoned with saturated mercuric chloride solution (200 µL per bottle).” (P4L19–21) and a new subsection: “2.3 Carbonate system analysis” (P6L11–P7L4) to the Material and Methods.

22) P10L12-14: “seagrass with isotopic signatures” Unclear sentence. Revise

22) Author's reply: We have changed this sentence as follows in response to your comment: "…the $\delta^{13}C$ of the seagrass should change depending on the contribution of HCO_3^- as a carbon source (Campbell and Fourqurean, 2009; Raven et al., 2002)." (P10L8–10)

23) Table 1: What is "Category (seagrass)"? Again, why was GLM used?

23) Author's reply: "Category (seagrass)" indicates the difference between the intercept of the DIC model and that of the seagrass model. The significance ($P < 0.001$) of "Category (seagrass)" indicates that the $\Delta^{14}C$ values of the seagrass leaves were significantly higher than that of DIC. A GLM was used because it can estimate the model equation and examine the significant differences simultaneously.

24) Fig. 2 (a): Provide regression formula for both DIC and seagrass

24) Author's reply: We have added model equations to Fig. 2a.
$\Delta^{14}C_{DIC} = -1.78 \times \text{Salinity} + 4.40$; $\Delta^{14}C_{seagrass} = -1.78 \times \text{Salinity} + (4.40 + 7.34)$.

25) Fig. 2 (c): Was the relationship between $\delta^{13}C$ and salinity significant?

25) Author's reply: Yes, this and the other relationships were significant. We have added the following sentence: "There were significant correlations between salinity and $\delta^{13}C$ of DIC, HCO_3^-, $CO_2(aq)$ and the seagrass (Pearson's correlation coefficient: $P < 0.001$; Fig. 2c, d)." (P10L5–6)

Authors’ replies to the comments of Referee #2

1) P2L6-9: Should acknowledge that HCO_3^- is also a viable carbon source, along with transport mechanisms associated with its use.

1) Author’s reply: We have added the following sentences in response to your comment: “Under normal seawater pH conditions, the bicarbonate ion ($HCO_3^−$) is the most abundant inorganic carbon species, accounting for nearly 90% of the DIC pool (Plummer and Busenberg, 1982; Zeebe and Wolf-Gladrow, 2001). Some seagrass species indirectly use $HCO_3^−$ under low-CO_2(aq) conditions (Beer et al., 2002; Campbell and Fourqurean, 2013), using one or both of the following suggested mechanisms: (1) extracellular dehydration of $HCO_3^−$ into CO_2(aq) via membrane-bound enzymes (Beer and Rehnberg 1997); or (2) electrogenic proton (H^+) extrusion into an boundary layer on the leaf surface, facilitating $HCO_3^−/H^+$ cotransport (Hellblom et al. 2001).” (P2L13–20)

2) P4L22: Why the difference in sites between the DIC sampling stations and the *Z. marina* stations?

2) Author’s reply: We have added the following sentence as explanation: “Because DIC taken up by seagrasses is a mixture of DIC from two sources (terrestrial and oceanic) each having distinct $\Delta^{14}C$ values, it is reasonable to use salinity as a proxy for the extent of mixing of these two sources as well as for the salinity gradient-based comparison between $\Delta^{14}C$ of DIC and seagrass (Table 1). This comparison was therefore possible even though DIC and *Z. marina* samples were not necessarily collected from the same stations (Fig. 1).” (P7L7–12).

3) P5L1: How was this determined?

3) Author’s reply: We have added the following sentence to explain how biomass was determined: “The aboveground wet-weight biomass of the seagrass, estimated from randomly thrown quadrats ($0.0625\ m^2$), ranged from 400 to 4300 $g\ m^{−2}$.” (P4L23–P5L1)

4) P4L13: State number of independent samples per station both for DIC samples and seagrass biomass.

4) Author’s reply: We have added the following sentences: “At each station, one water sample was collected…” (P4L13) and “Three or four independent samples of seagrass leaves were

collected at each station.” (P5L1–2)

5) P5L2-4: Any epiphyte loading on the seagrass leaf surface?

5) Author’s reply: We washed the leaves of both biofilm and epiphytes to avoid contamination. We have added the following sentence: “Both the biofilm and epiphytes covering the leaves were gently removed by hands with powder-free groves and washed off using ultrapure water (Milli-Q water; Millipore, Billerica, MA, USA).” (P5L2–4).

6) P8L22: Please clarify where 46% C_{air} contribution comes from? This value seems rather high. While carbon fixation clearly occurs during emersion, prior work has suggested reduced maximal photosynthetic rates during air exposure (Clavier 2011), particularly in cases of desiccation (Leuschner et al 1998). Furthermore, Fig 2b. displays rather high within station variation on the relative contribution of C_{air}, to what might you attribute such variation?

6) Author’s reply: The value of 46% was the maximum from all samples. For clarification, we have shown the range of the C_{air} contribution (P1L19, P8L22). The estimated values have been modified in this revision of the manuscript as the result of a recalculation (please see our response to comment 14 from Referee #1). We have added the following sentences in response to your comment: “Our high estimate of the C_{air} contribution (mean, 17%) was unexpected because prior works suggest that photosynthetic rates of seagrasses in intertidal zones decrease during air exposure (Clavier, 2011), particularly in cases of desiccation (Leuschner et al., 1998). However, the leaves of subtidal seagrass are never desiccated because of the presence of the thin film of water, which reduces the negative effects of air exposure (i.e., desiccation).” (P10L24–P11L4) As you point out, there is large variation in the C_{air} contribution, even between samples from the same station. We believe that this variation results from the variation in exposure time. We have added the following sentences: “The contribution of C_{air} as a carbon source varied greatly even between samples from the same station (Fig. 2b). Because we did not determine the exposure time of each shoot in this study, we are unable to quantify any relationship between the contribution of C_{air} and air exposure time; however, the exposure time could mediate the assimilation of C_{air} (Clavier et al., 2011).” (P8L24–P9L4)

7) P10L6-10: Citations statements are primarily derived from interspecific distinctions. Given that you’re comparing the same species, how might salinity gradients influence resultant $\delta^{13}C$ values? What about terrestrially derived sources of isotopically light $\delta^{13}C$ from the decomposition of organic matter.

7) Author’s reply: As you point out, the decomposition of terrestrially-derived organic carbon affects the positive relationship between salinity and $\delta^{13}C$ of seagrass. However, DIC released from the decomposed terrestrial organic matter should be reflected in the $\delta^{13}C$ values of bulk DIC. We have added the following sentence regarding the influence of salinity: “Furthermore, $\delta^{13}C$ of both HCO_3^- and CO_2(aq) change through mixing between low-$\delta^{13}C$ river water and high-$\delta^{13}C$ seawater in brackish areas (Fig. 2d).” (P10L12–14)

8) P10L6-10: Without detailed data from laboratory incubation, I find these conclusions difficult to make given the reasons that you have already described in regards to $\delta^{13}C$ isotope analysis. There appears to be many relevant citations missing from the references. I suggest the authors incorporate additional studies, and provide a more comprehensive discussion of this topic.

8) Author’s reply: We have added Fig. 2d in response to your comment. We have modified the sentences in question as follows and moved them to the Introduction: “Because the $\delta^{13}C$ of HCO_3^- (0‰) is isotopically distinct from that of both CO_2(aq) (−9‰) and C_{air} (−8‰) under normal seawater conditions (pH $\approx$ 8), high $\delta^{13}C$ (>−10‰) in seagrasses shows that they use HCO_3^- as a carbon source because isotopic discrimination during CO_2 assimilation results in $\delta^{13}C$ values that are always higher than those of the carbon sources. Although low $\delta^{13}C$ (<−10‰) in seagrasses could be explained by the assimilation of both ^{13}C-depleted CO_2(aq) and C_{air}, quantification of the contribution of C_{air} is impossible because of the overlap between their $\delta^{13}C$ values.” (P3L8–14) We have added the following sentences to the Results and Discussion: “As the $\delta^{13}C$ of HCO_3^- was isotopically distinct from $\delta^{13}C$ of both CO_2(aq) and C_{air} (Fig. 2d) and as *Z. marina* also uses HCO_3^- as a carbon source under low-CO_2(aq) conditions (Beer and Rehnberg, 1997), the $\delta^{13}C$ of the seagrass should change depending on the contribution of HCO_3^- as a carbon source (Campbell and Fourqurean, 2009; Raven et al., 2002). However, it is not possible to distinguish the contribution of C_{air} from that of other carbon sources because the $\delta^{13}C$ of C_{air} overlapped those of both HCO_3^- and CO_2(aq) (Fig. 2d). Furthermore, $\delta^{13}C$ of both HCO_3^- and CO_2(aq) change through mixing between low-$\delta^{13}C$ river water and high-$\delta^{13}C$ seawater in brackish areas (Fig. 2d).” (P10L6–14)

Authors' replies to the comments of Referee #3

1) P9L10-11: The comments about surface water Δ^{14}C-DIC seem like they could be a fairly significant over-simplification: what about the seasonal role of currents with markedly different Δ^{14}C, e.g. to the south the dynamics of the Oyashio and Tsugaru Warm Current (Kuroshio) can lead to variation in Δ^{14}C-DIC in surface waters that covers the range of values observed in this study. The potential role of seasonal variability in Δ^{14}C-DIC needs to be better explored – for instance could oceanic intrusion perhaps explain the Δ^{14}C variations in seagrass leaves independent of the hypothesized utilization of atmospheric CO_2?

1) Author's reply: As you point out, the seasonal change of oceanic context (e.g., currents) could affect the application of our approach. We have added the following sentences to address this issue: "However, the seasonal dynamics of $\Delta^{14}C_{DIC}$ could affect the application of this approach because it is only applicable when the Δ^{14}C values for endmembers (seawater DIC, freshwater DIC, and C_{air}) are distinct (not overlapping) as they were in May and July 2014 during this study. We could not use the Δ^{14}C approach to quantify the C_{air} contribution in September or November 2014 in Furen Lagoon because the $\Delta^{14}C_{DIC}$ of seawater increased to near $\Delta^{14}C_{air}$ and there was overlap between the two (Fig. 3). The overlapping in the range of values, induced by variations in the $\Delta^{14}C_{DIC}$ of seawater, likely caused by the dynamics of the Oyashio (mean $\Delta^{14}C_{DIC}$, −41‰; Aramaki et al., 2001) and the Soya warm current ($\Delta^{14}C_{DIC}$ > 50‰; Aramaki et al., 2007) (Fig. 1). The variation in $\Delta^{14}C_{DIC}$ of seawater could also be affected by seasonal stratification via regulation of the upwelling of low-Δ^{14}C bottom water. The applicability of the Δ^{14}C technique to other areas will depend on the Δ^{14}C dynamics of endmembers." (P9L11–22)

We have also added the following two references to the reference list:

Aramaki, T., Watanabe, S., Kuji, T., and Wakatsuchi, M.: The Okhotsk-Pacific seawater exchange in the viewpoint of vertical profiles of radiocarbon around the Bussol' Strait, Geophys. Res. Lett., 28, 3971–3974, 2001.

Aramaki, T., Senjyu, T., Togawa, O., Otosaka, S., Suzuki, T., Kitamura, T., Amano, H., and Volkov, Y. N.: Circulation in the northern Japan Sea studied chiefly with radiocarbon, Radiocarbon, 49, 915–924, 2007.

2) Another major issue in the context of the potential seasonal variation in Δ^{14}C of the DIC in an oceanographic context (as above) is the leaf turnover time: what is the turnover time of the leaf

carbon, i.e. what season does the tissue sampling reflect, and does this change spatially into the lagoon?

2) Author's reply: We have added the following sentence in response to your comment: "The $\Delta^{14}C_{seagrass}$ could reflect $\Delta^{14}C_{DIC}$ from May to July because *Z. marina* leaves start to grow in early May at the study site, with the turnover time of leaves being 30–90 days (mean, 60 days; Hosokawa et al., 2009)." (P8L13–15)

3) A location map is needed, showing the sampling sites and the location of the bay in relation to the open ocean etc. All of this is very important for the readers' interpretation, especially given the possible seasonal influence of ocean current dynamics on $\Delta^{14}C$ of the DIC as above.

3) Author's reply: We have added a location map (Fig. 1) and the appropriate text regarding this map and sampling locations (P4L13, P4L22, P5L9).

4) Abstract; P1L19: What does the 46 % refer to if the mean is 22 %?

4) Author's reply: The value of 46% was the maximum for all samples. For clarification, we have included the range of the C_{air} contribution (P1L19, P8L21–22). The estimated values have been modified as a result of recalculation (please see our response to comment 14 from Referee #1).

5) P2L1: Second "their" seems superfluous.

5) Author's reply: We have removed this word in response to your comment.

6) P2L21: If the diffusion rate of CO_2 is lower in water, how does a water layer promote CO2 uptake? A layer of water would seem to reduce uptake by limiting diffusion.

6) Author's reply: We argue that CO_2 uptake is promoted under conditions with a thin layer or film of water on the leaf surface during low tide, in contrast to a thick water layer when leaves are submerged during high tide. We have modified the sentence in question as follows for clarification: "During low tide, air-exposed aquatic macrophytes have a thin film of water between the air and their leaves, which promotes the uptake of C_{air}, in contrast to high tide, when there is a thick water layer inhibiting the uptake of C_{air} (Ji and Tanaka, 2002)." (P2L21–24)

7) P4L16: The use of “dispensed” here is strange.

7) Author’s reply: We have replaced “dispensed” with “collected”. (P4L16)

8) P9L10-11: The application of the technique here, and certainly other areas of the Pacific, depends on much more thorough understanding of $\Delta^{14}C$ dynamics in response to oceanic forcing.

8) Author’s reply: As you point out, the utility of the approach depends on a much more thorough understanding of $\Delta^{14}C$ dynamics. We have added the following sentence: “The applicability of the $\Delta^{14}C$ technique to other areas will depend on the $\Delta^{14}C$ dynamics of endmembers.” (P9L21–22)

9) P11L10: It could also be argued that a more thorough oceanographic context is required to adequately interpret tracers like $\Delta^{14}C$ in this context.

9) Author’s reply: We have added the following sentences in response to your comment: “Other applications may include determining the origin of the DIC source (e.g., terrestrial or oceanic) in deeper seagrass systems. However, adequate determinations will require separation and stability in the endmember values (e.g., in oceanographic contexts and in the dynamics of $\Delta^{14}C$ in coastal waters).” (P11L12–15)

Radiocarbon isotopic evidence for assimilation of atmospheric CO_2 by the seagrass *Zostera marina*

K. Watanabe[1] and T. Kuwae[1]

[1]{Coastal and Estuarine Environment Research Group, Port and Airport Research Institute, 3-1-1 Nagase, Yokosuka 239-0826, Japan}

Correspondence to: K. Watanabe (watanabe-ke@ipc.pari.go.jp)

Abstract

Submerged aquatic vegetation takes up water-column dissolved inorganic carbon (DIC) as a carbon source across its thin cuticle layer. It is expected that marine macrophytes also use atmospheric CO_2 when exposed to air during low tide, although assimilation of atmospheric CO_2 has never been quantitatively evaluated. Using the radiocarbon isotopic signatures ($\Delta^{14}C$) of the seagrass *Zostera marina*, DIC and POC, we show quantitatively that *Z. marina* takes up and assimilates atmospheric modern CO_2 in a shallow coastal ecosystem. The $\Delta^{14}C$ values of the seagrass (−40‰ to −10‰) were significantly higher than those of aquatic DIC (−46‰ to −18‰), indicating that the seagrass uses a ^{14}C-rich carbon source (atmospheric CO_2, +17‰). A carbon-source mixing model indicated that the seagrass assimilated 0–40% (mean, 17%) of its inorganic carbon as atmospheric CO_2. CO_2 exchange between the air and the seagrass might be enhanced by the presence of a very thin film of water over the air-exposed leaves during low tide. Our radiocarbon isotope analysis, showing assimilation of atmospheric modern CO_2 as an inorganic carbon source, improves our understanding of the role of seagrass meadows in coastal carbon dynamics.

1 Introduction

Submerged aquatic vegetation assimilates dissolved inorganic carbon (DIC) from the water column as a carbon source. Seagrasses take up DIC across their thin cuticle layer (Hemminga and Duarte, 2000), as their leaves lack stomata despite being angiosperms (Larkum and Den Hartog, 1989). An alternative carbon source, atmospheric CO_2 (C_{air}), cannot directly reach seagrasses when they are completely submerged; however, seagrasses can take up C_{air} when their leaves are exposed to air during low tide (Leuschner and Rees, 1993; Clavier et al., 2011; Jiang et al., 2014). Seagrasses rely largely on aqueous CO_2 [CO_2(aq)] as a carbon source for photosynthesis in nature (Beer and Koch, 1996). Some seagrass species, however, can use bicarbonate ions (HCO_3^-) as a major carbon source (Beer et al., 2002; Beer and Rehnberg, 1997), although there is considerable interspecific variation in HCO_3^- utilization (Campbell and Fourqurean, 2013). As CO_2(aq) is in limited supply under normal seawater conditions (pH ≈ 8), comprising only 1% (roughly 10–15 μmol L^{-1}) of the DIC pool, photosynthesis in seagrasses under high light conditions is frequently limited by carbon availability (Zimmerman et al., 1995; Invers et al., 2001; Campbell and Fourqurean, 2013). Under normal seawater pH conditions, the bicarbonate ion (HCO_3^-) is the most abundant inorganic carbon species, accounting for nearly 90% of the DIC pool (Plummer and Busenberg, 1982; Zeebe and Wolf-Gladrow, 2001). Some seagrass species indirectly use HCO_3^- under low-CO_2(aq) conditions (Beer et al., 2002; Campbell and Fourqurean, 2013), using one or both of the following suggested mechanisms: (1) extracellular dehydration of HCO_3^- into CO_2(aq) via membrane-bound enzymes (Beer and Rehnberg 1997); or (2) electrogenic proton (H^+) extrusion into an boundary layer on the leaf surface, facilitating HCO_3^-/H^+ cotransport (Hellblom et al. 2001).

Diffusion of CO_2 in water is much slower than that in air. During low tide, air-exposed aquatic macrophytes have a thin film of water between the air and their leaves, which promotes the uptake of C_{air}, in contrast to high tide, when there is a thick water layer inhibiting the uptake of C_{air} (Ji and Tanaka, 2002). Previous studies have shown the possibility of C_{air} uptake by seagrasses by using evidence from stable carbon isotope ratios

($\delta^{13}C$) in seagrasses and the two carbon sources (DIC and C_{air}) (Clavier et al., 2011; Cooper and McRoy, 1988; Raven et al., 2002). However, the ^{13}C method has considerable uncertainty because in addition to the source of carbon, the $\delta^{13}C$ values of seagrasses are also determined by other factors such as the chemical species of DIC [$CO_2(aq)$ or HCO_3^-] and the primary production rate. The chemical species in the carbonate system ($CO_2(aq)$, HCO_3^-, and carbonate ion [CO_3^{2-}]) have distinct $\delta^{13}C$ values, and isotopic fractionations change depending on pH and temperature (Zeebe and Wolf-Gladrow, 2001; Zhang et al., 1995). Because the $\delta^{13}C$ of HCO_3^- (0‰) is isotopically distinct from that of both $CO_2(aq)$ (−9‰) and C_{air} (−8‰) under normal seawater conditions (pH ≈ 8), high $\delta^{13}C$ (>−10‰) in seagrasses shows that they use HCO_3^- as a carbon source because isotopic discrimination during CO_2 assimilation results in $\delta^{13}C$ values that are always higher than those of the carbon sources. Although low $\delta^{13}C$ (<−10‰) in seagrasses could be explained by the assimilation of both ^{13}C-depleted $CO_2(aq)$ and C_{air}, quantification of the contribution of C_{air} is impossible because of the overlap between their $\delta^{13}C$ values.

The natural abundance of radiocarbon (^{14}C) has recently been used to assess food web structures (Ishikawa et al., 2014) and the origin and components of organic-matter pools (Goñi et al., 2013), as carbon sources have specific ^{14}C concentrations ($\Delta^{14}C$). The $\Delta^{14}C$ of inorganic carbon also has specific values depending on the source, such as DIC or C_{air}. The $\Delta^{14}C$ of DIC generally differs from that of atmospheric CO_2 because of the longer residence time of carbon in aquatic ecosystems than in the atmosphere (Ishikawa et al., 2014; Stuiver and Braziunas, 1993). The calculation of $\Delta^{14}C$ by internal correction using $\delta^{13}C$ values eliminates any effects from isotopic fractionation (Stuiver and Polach, 1977), so the $\Delta^{14}C$ values of seagrasses are determined only by the two inorganic carbon sources. This study is the first to show quantitative evidence that the seagrass *Zostera marina* assimilates modern C_{air}, based on the $\Delta^{14}C$ values of the seagrass and two carbon sources.

2 Material and methods

2.1 Field surveys

Field surveys were conducted in 2014 during the growing season of *Z. marina* (May, July, September and November) in Furen Lagoon, Japan (Fig. 1; 43°19′46.5″N, 145°15′27.8″E). The lagoon is covered by ice from December to April. Furen Lagoon is brackish (salinity, ~30) and the northern part of the lagoon receives freshwater from the Furen, Yausubetsu, and Pon-Yausubetsu Rivers. The lagoon is covered by large seagrass meadows (67% of the total area) dominated by *Z. marina*. The offshore of the lagoon (Sea of Okhotsk) is influenced by the dynamics of both the Oyashio and the Soya warm current. Surface water samples (depth, 0.1 m) for DIC (concentration and isotopic signatures) and total alkalinity (TA) in the water column were collected from a research vessel along the salinity gradient at seven stations in the lagoon (Fig. 1; stations F1–F7). At each station, one water sample was collected for measuring DIC and TA and the salinity of the surface water was recorded with a conductivity-temperature sensor (COMPACT-CT; JFE Advantech, Nishinomiya, Japan). The samples for isotopic analysis of DIC were collected into 500-mL hermetically-sealed glass bottles (Duran bottle; SCHOTT AG, Mainz, Germany), which were poisoned by adding saturated mercuric chloride solution (400 µL per bottle) to prevent changes in DIC due to biological activity. The samples for measuring DIC concentration and TA were collected into 250-mL Duran bottles (SCHOTT AG), which were poisoned with saturated mercuric chloride solution (200 µL per bottle). Seagrass (*Z. marina*) leaves were collected at four stations covered by *Z. marina* meadows (Fig. 1; stations F3, F4, F8 and F9) along the salinity gradient. The stations were located in subtidal zones (mean water depth, 0.83–1.12 m). The aboveground wet-weight biomass of the seagrass, estimated from randomly thrown quadrats

(0.0625 m^2), ranged from 400 to 4300 g m^{-2}. Three or four independent samples of seagrass leaves were collected at each station. Both the biofilm and epiphytes covering the leaves were gently removed by hands with powder-free groves and washed off using ultrapure water (Milli-Q water; Millipore, Billerica, MA, USA). To estimate the $\Delta^{14}C$ of C_{air}, leaves of a terrestrial plant (giant reed, *Phragmites australis*) were collected near the lagoon. Plant samples were freeze-dried and subsamples were homogenized. To remove carbonate, the plant samples were acidified with 1 N HCl and dried again.

Water samples for the isotopic analysis of terrestrial particulate organic carbon (POC) were collected at three riverine stations (Fig. 1; stations R1–R3). Samples for POC were obtained by filtration (approximately 1 L) onto pre-combusted (450 °C for 2 h) glass-fiber filters (GF/F, Whatman, Maidstone, Kent, UK).

2.2 Carbon isotope analysis

We determined the stable carbon isotope ratios ($\delta^{13}C$) and radiocarbon concentrations ($\Delta^{14}C$) of seagrass leaves, terrestrial plant leaves, DIC samples and POC samples. Prior to $\Delta^{14}C$ and $\delta^{13}C$ measurements, samples were subjected to graphite purification as follows. DIC samples for $\Delta^{14}C$ and $\delta^{13}C$ analysis were acidified ($pH < 2$) with H_3PO_4 and sparged using ultra-high purity mixed N_2/H_2 gas. The powdered plant leaves and POC samples for $\Delta^{14}C$ and $\delta^{13}C$ analysis were combusted in an elemental analyzer (either a Euro EA3000, EuroVector, Milan, Italy; or a Flash 2000, Thermo Fisher Scientific, Inc., Waltham, Massachusetts, USA). For each process, the CO_2 evolved was collected cryogenically and purified in a vacuum line. The purified CO_2 was then reduced to graphite using hydrogen and an iron catalyst at 650 °C for 10 h. The ^{13}C and ^{14}C concentrations were measured using an accelerator mass spectrometer

(AMS). The AMS results are reported as $\Delta^{14}C$ (‰) values (Stuiver and Polach, 1977) as follows:

$$\Delta^{14}C\ (‰) = \delta^{14}C - 2(\delta^{13}C + 25)(1 + \delta^{14}C/1000). \qquad (1)$$

The $\Delta^{14}C$ values were corrected by the radioactive decay of an international standard (oxalic acid) since AD 1950 (Stuiver and Polach, 1977). The $\delta^{13}C$ values are reported relative to Vienna Pee Dee Belemnite. $\delta^{13}C$ data were corrected using an internal standard. The analytical precision of the AMS was within 0.7‰ for $\delta^{13}C$ and 3‰ for $\Delta^{14}C$.

2.3 Carbonate system analysis

DIC concentration and TA were determined on a batch-sample analyzer (ATT-05; Kimoto Electric, Osaka, Japan). The precision of the analyses was 4 μmol L^{-1} for DIC and 3 μmol L^{-1} for TA. The concentrations of $CO_2(aq)$, HCO_3^-, and CO_3^{2-} were estimated using chemical equilibrium relationships and the TA and DIC concentrations of the water samples (Zeebe and Wolf-Gladrow, 2001). The $\delta^{13}C$ values of $CO_2(aq)$ ($\delta^{13}C_{CO_2(aq)}$) and HCO_3^- ($\delta^{13}C_{HCO_3^-}$) were calculated as follows (Zeebe and Wolf-Gladrow, 2001; Zhang et al., 1995):

$$\delta^{13}C_{HCO_3^-} = \delta^{13}C_{DIC} - ([\varepsilon_{db} \times [CO_2(aq)] + \varepsilon_{cb} \times [CO_3^{2-}])/[DIC], \qquad (2)$$

$$\delta^{13}C_{CO_2(aq)} = \delta^{13}C_{HCO_3^-} + \varepsilon_{db}, \qquad (3)$$

$$\varepsilon_{db} = \varepsilon(CO_2(aq) - HCO_3^-) = -9866/T + 24.12\ (‰), \qquad (4)$$

$$\varepsilon_{cb} = \varepsilon(CO_3^{2-} - HCO_3^-) = -867/T + 2.52\ (‰), \qquad (5)$$

where [CO_2(aq)], [CO_3^{2-}], and [DIC] are the concentrations of CO_2(aq), CO_3^{2-} and DIC, respectively; T is water temperature (K); and ε_{db} and ε_{cb} are factors for the isotopic fractionation between CO_2(aq) and HCO_3^-, and between CO_3^{2-} and HCO_3^-, respectively.

2.4 Data analysis

Because DIC taken up by seagrasses is a mixture of DIC from two sources (terrestrial and oceanic) each having distinct $\Delta^{14}C$ values, it is reasonable to use salinity as a proxy for the extent of mixing of these two sources as well as for the salinity gradient-based comparison between $\Delta^{14}C$ of DIC and seagrass (Table 1). This comparison was therefore possible even though DIC and *Z. marina* samples were not necessarily collected from the same stations (Fig. 1). A general linear model (GLM) was used to examine the differences between the $\Delta^{14}C$ values of the seagrass leaves and those of DIC in May and July 2014. These differences provide evidence that the seagrasses assimilate C_{air}. A GLM was suitable for this study because both continuous (salinity) and categorical variables (seagrass leaves or DIC) were used as explanatory variables. We selected salinity, category (seagrass leaves or DIC), and their interaction (salinity × category) as the explanatory variables (Table 1). We used Akaike's Information Criterion (AIC) to select the most parsimonious model.

The relative contribution of C_{air} to assimilated seagrass carbon was calculated by a two-carbon-source mixing model using the $\Delta^{14}C$ values of DIC ($\Delta^{14}C_{DIC}$), C_{air} ($\Delta^{14}C_{air}$), and the seagrass ($\Delta^{14}C_{seagrass}$) at each of four stations as follows:

$$C_{air}\ (\%\ \text{contribution}) = (\Delta^{14}C_{seagrass} - \Delta^{14}C_{DIC})/(\Delta^{14}C_{air} - \Delta^{14}C_{DIC}) \times 100. \qquad (6)$$

$\Delta^{14}C_{air}$ was estimated from the $\Delta^{14}C$ value of the sampled terrestrial plants ($\Delta^{14}C = +17.2‰$). The $\Delta^{14}C$ values of DIC as the carbon source for *Z. marina* in the mixing model were estimated from the best GLM (Table 1).

3 Results and discussion

Our radiocarbon isotopic analysis shows quantitatively that the seagrass *Z. marina* uses C_{air} in a shallow lagoon (Fig. 2a and Table 1). The GLM strongly highlights the effect of salinity on the $\Delta^{14}C$ of DIC and the seagrass in May and July 2014 (Table 1; GLM, $P < 0.001$). Our results indicate that the changes in $\Delta^{14}C_{DIC}$ are regulated mostly by mixing between high-$\Delta^{14}C$ river water and low-$\Delta^{14}C$ seawater: the seagrass uses aquatic DIC as the main carbon source, as expected from previous studies (Hemminga and Duarte, 2000; Invers et al., 2001; Campbell and Fourqurean, 2013). The $\Delta^{14}C_{seagrass}$ could reflect $\Delta^{14}C_{DIC}$ from May to July because *Z. marina* leaves start to grow in early May at the study site, with the turnover time of leaves being 30–90 days (mean, 60 days; Hosokawa et al., 2009). Furthermore, the negative relationship between salinity and $\Delta^{14}C_{seagrass}$ cannot be explained by any residual contamination from terrestrial organic carbon on the leaves because the terrestrial POC was ^{14}C-depleted (mean $\Delta^{14}C$ of terrestrial POC, −74.7 ± 23.4‰).

The model also reinforced our observations that $\Delta^{14}C_{seagrass}$ was higher than $\Delta^{14}C_{DIC}$ (Fig. 2a and Table 1; GLM, $P < 0.001$). This shows that the seagrass assimilates ^{14}C-rich C_{air} ($\Delta^{14}C$ around 17‰). The two-carbon-source mixing model indicated that the seagrass assimilated 0–40% (mean ± SD, 17 ± 12%) of its inorganic carbon as C_{air}; the contribution was 20 ± 12% in the low-salinity zone (salinity, 12–15) and 13 ± 12% in the high-salinity zone (salinity, 25–29) (Fig. 2b). The contribution of C_{air} as a carbon source varied greatly even between samples from the same station (Fig. 2b). Because we did not determine the exposure time of each shoot in this study, we are unable to quantify any relationship between the contribution of C_{air} and air exposure time; however, the exposure time could mediate the assimilation of C_{air} (Clavier et al., 2011).

As $\Delta^{14}C_{DIC}$ was significantly lower than $\Delta^{14}C_{air}$, the contribution of C_{air} can be determined for May and July 2014 (Fig. 2a). This radiocarbon isotopic approach would be useful in the high latitudes of the Pacific Ocean where surface seawater is ^{14}C-depleted ($\Delta^{14}C_{DIC} < 0‰$) (Talley, 2007). In contrast, the $\Delta^{14}C_{DIC}$ in surface seawater is generally higher than $\Delta^{14}C_{air}$ in other regions of the Pacific Ocean because of bomb-derived ^{14}C (Talley, 2007).

In any case, the $\Delta^{14}C$ approach is potentially applicable to other regions by using the $\Delta^{14}C$ gradient. However, the seasonal dynamics of $\Delta^{14}C_{DIC}$ could affect the application of this approach because it is only applicable when the $\Delta^{14}C$ values for endmembers (seawater DIC, freshwater DIC, and C_{air}) are distinct (not overlapping) as they were in May and July 2014 during this study. We could not use the $\Delta^{14}C$ approach to quantify the C_{air} contribution in September or November 2014 in Furen Lagoon because the $\Delta^{14}C_{DIC}$ of seawater increased to near $\Delta^{14}C_{air}$ and there was overlap between the two (Fig. 3). The overlapping in the range of values, induced by variations in the $\Delta^{14}C_{DIC}$ of seawater, likely caused by the dynamics of the Oyashio (mean $\Delta^{14}C_{DIC}$, −41‰; Aramaki et al., 2001) and the Soya warm current ($\Delta^{14}C_{DIC} > 50‰$; Aramaki et al., 2007) (Fig. 1). The variation in $\Delta^{14}C_{DIC}$ of seawater could also be affected by seasonal stratification via regulation of the upwelling of low-$\Delta^{14}C$ bottom water. The applicability of the $\Delta^{14}C$ technique to other areas will depend on the $\Delta^{14}C$ dynamics of endmembers.

Our $\Delta^{14}C$ analysis considerably reduces the limitations and uncertainties of conventional methods such as that using only $\delta^{13}C$ (Clavier et al., 2011; Cooper and McRoy, 1988; Raven et al., 2002). In particular, the use of $\Delta^{14}C$ has the advantage of avoiding effects of isotopic fractionation (Stuiver and Polach, 1977); the use of $\delta^{13}C$ does not and therefore generates large uncertainties. The $\delta^{13}C$ of the seagrass was low (−14.0 ± 2.4‰) in the low-salinity zone (salinity, 12–15) and high (−8.8 ± 1.9‰) in the high-salinity zone (salinity, 25–29) (Fig. 2c). There were significant correlations between salinity and $\delta^{13}C$ of DIC, HCO_3^-, $CO_2(aq)$ and the seagrass (Pearson's correlation coefficient: $P < 0.001$; Fig. 2c, d). As the $\delta^{13}C$ of HCO_3^- was isotopically distinct from $\delta^{13}C$ of both $CO_2(aq)$ and C_{air} (Fig. 2d) and as *Z. marina* also uses HCO_3^- as a carbon source under low-$CO_2(aq)$ conditions (Beer and Rehnberg, 1997), the $\delta^{13}C$ of the seagrass should change depending on the contribution of HCO_3^- as a carbon source (Campbell and Fourqurean, 2009; Raven et al., 2002). However, it is not possible to distinguish the contribution of C_{air} from that of other carbon sources because the $\delta^{13}C$ of C_{air} overlapped those of both HCO_3^- and $CO_2(aq)$ (Fig. 2d). Furthermore, $\delta^{13}C$ of both HCO_3^- and $CO_2(aq)$ change through mixing between low-$\delta^{13}C$ river water and high-$\delta^{13}C$ seawater in brackish areas (Fig. 2d).

In any case, there are large uncertainties when using $\delta^{13}C$ to quantitatively estimate the contribution of C_{air} as a carbon source because the isotopic fractionation that occurs in the steps between the carbon source and organic plant compounds changes depending on the photosynthetic rate (Raven et al., 2002). The radiocarbon isotopic approach can avoid the uncertainties derived from both the contribution of HCO_3^- as a carbon source and isotopic fractionation in carbon assimilation.

The seagrass leaves assimilated C_{air} when exposed to air during low tide (Fig. 4). CO_2 exchange between the air and water would occur at the very thin film of water on the air-exposed seagrass leaves (Fig. 4c), likely enhancing the passive uptake of C_{air} by diffusion. Our high estimate of the C_{air} contribution (mean, 17%) was unexpected because prior works suggest that photosynthetic rates of seagrasses in intertidal zones decrease during air exposure (Clavier, 2011), particularly in cases of desiccation (Leuschner et al., 1998). However, the leaves of subtidal seagrass are never desiccated because of the presence of the thin film of water, which reduces the negative effects of air exposure (i.e., desiccation).

The net ecosystem production of seagrass meadows is a key factor determining whether they are sinks or sources of C_{air} (Maher and Eyre, 2012; Tokoro et al., 2014; Watanabe and Kuwae, 2015). Previously, however, such an exchange of CO_2 has been thought to occur only via the air–water interface with subsequent exchange with seagrasses as DIC. This study using radiocarbon isotope analysis demonstrates the assimilation of modern C_{air} by seagrass. Moreover, our radiocarbon isotopic approach has potential for application to other photoautotrophs living near the air–water interface, such as intertidal macroalgae and amphibious macrophytes. Other applications may include determining the origin of the DIC source (e.g., terrestrial or oceanic) in deeper seagrass systems. However, adequate determinations will require separation and stability in the endmember values (e.g., in oceanographic contexts and in the dynamics of $\Delta^{14}C$ in coastal waters). The relative contribution of gas exchange via the air–seagrass water film to the total exchange is still unknown. To understand the role of seagrass meadows in the global carbon cycle, it will be necessary in future studies to precisely measure CO_2 exchanges at both the air–water and air–seagrass water-film interfaces.

Author contribution

K.W. and T.K. designed this study, K.W. carried out the field surveys and analyzed the data, and K.W. and T.K. wrote the manuscript.

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Table 1. Coefficients (median ± standard error) and significance levels for the general linear models (GLMs) examined for samples collected in May and July 2014. AIC, Akaike information criterion.

Variable	**Best model (AIC = 288.33)**		**Full model (AIC = 290.29)**	
	Coefficient	***P***	**Coefficient**	***P***
Salinity	−1.78 ± 0.12	<0.001	−1.76 ± 0.18	<0.001
Category (seagrass)	7.34 ± 2.00	<0.001	8.23 ± 4.89	n.s.
Salinity × category			−0.05 ± 0.25	n.s.
(Intercept)	4.40 ± 2.59	n.s.	3.97 ± 3.36	n.s.

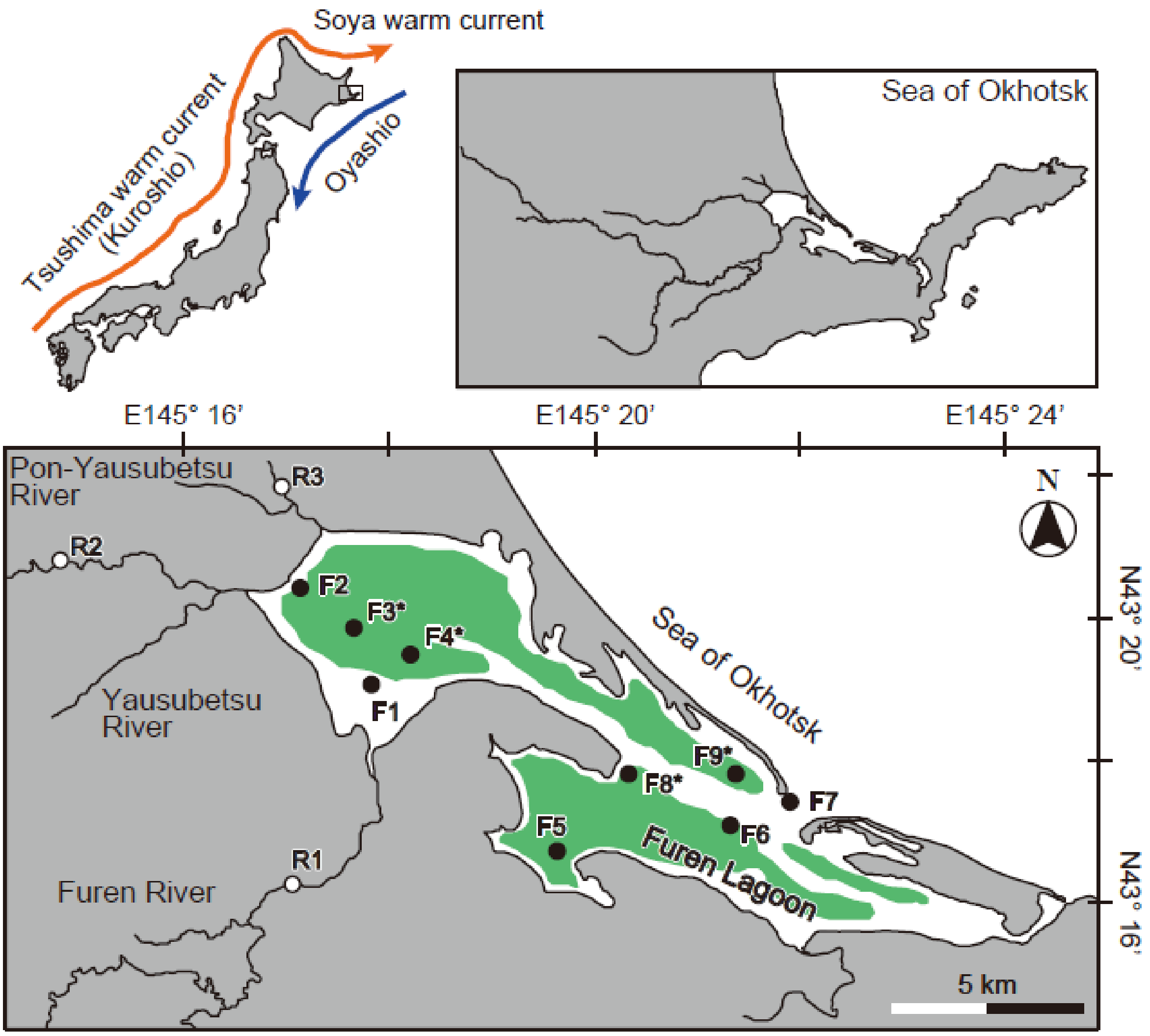

Figure 1. Location of Furen Lagoon and sampling stations. The area offshore of Furen Lagoon is affected by both the Oyashio and the Soya warm current. The northern part of the lagoon receives freshwater from the Furen, Yausubetsu, and Pon-Yausubetsu Rivers. Closed circles show lagoon stations. Water samples for DIC were collected at stations F1–F7. Seagrass samples were collected at stations F3, F4, F8 and F9 (marked with *). POC samples were collected at stations R1–R3. The green-shaded areas indicate seagrass meadows.

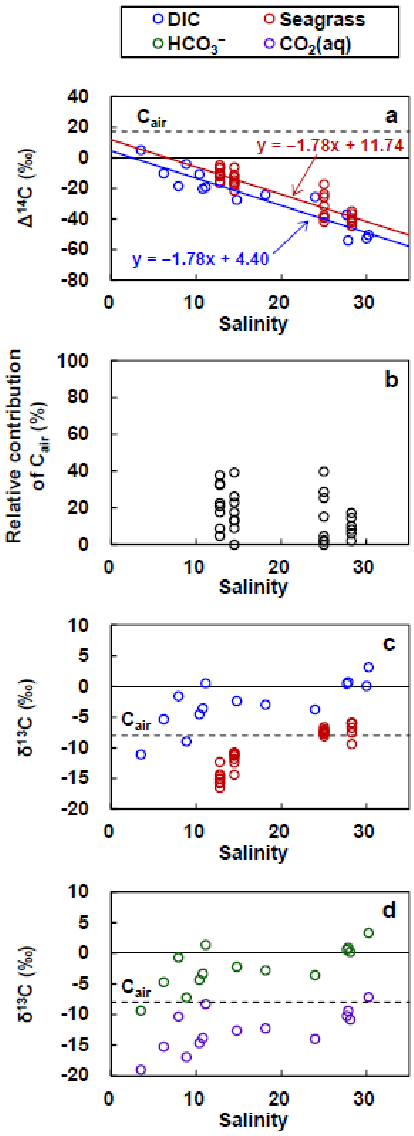

Figure 2. **(a)** Spatial distribution of the $\Delta^{14}C$ values of dissolved inorganic carbon (DIC) (blue open circles) and seagrass (red open circles) along the salinity gradient in May and July 2014 in Furen Lagoon, Japan. Blue and red solid lines represent the best fitting model of all general linear models (GLMs) examined for DIC and seagrass, respectively. **(b)** Spatial distribution of the relative contribution of C_{air} to total inorganic carbon assimilated by seagrass along the salinity gradient, as calculated by the two-carbon-source mixing model. **(c)** Spatial distribution of the $\delta^{13}C$ values of DIC (blue open circles) and seagrass (red open circles) along the salinity gradient. **(d)** Spatial distribution of the $\delta^{13}C$ values of bicarbonate ion (HCO_3^-) (green open circles) and aqueous CO_2 [CO_2(aq)] (purple open circles) along the salinity gradient. The dashed line indicates the isotopic signature of atmospheric CO_2 (C_{air}).

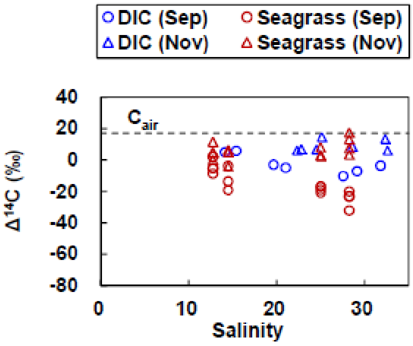

Figure 3. Spatial distribution of the Δ^{14}C values of dissolved inorganic carbon (DIC) (blue) and seagrass (red) along the salinity gradient in September (open circles) and November (open triangles) 2014 in Furen Lagoon, Japan. The dashed line indicates the Δ^{14}C of atmospheric CO_2 ($\Delta^{14}C_{air}$).

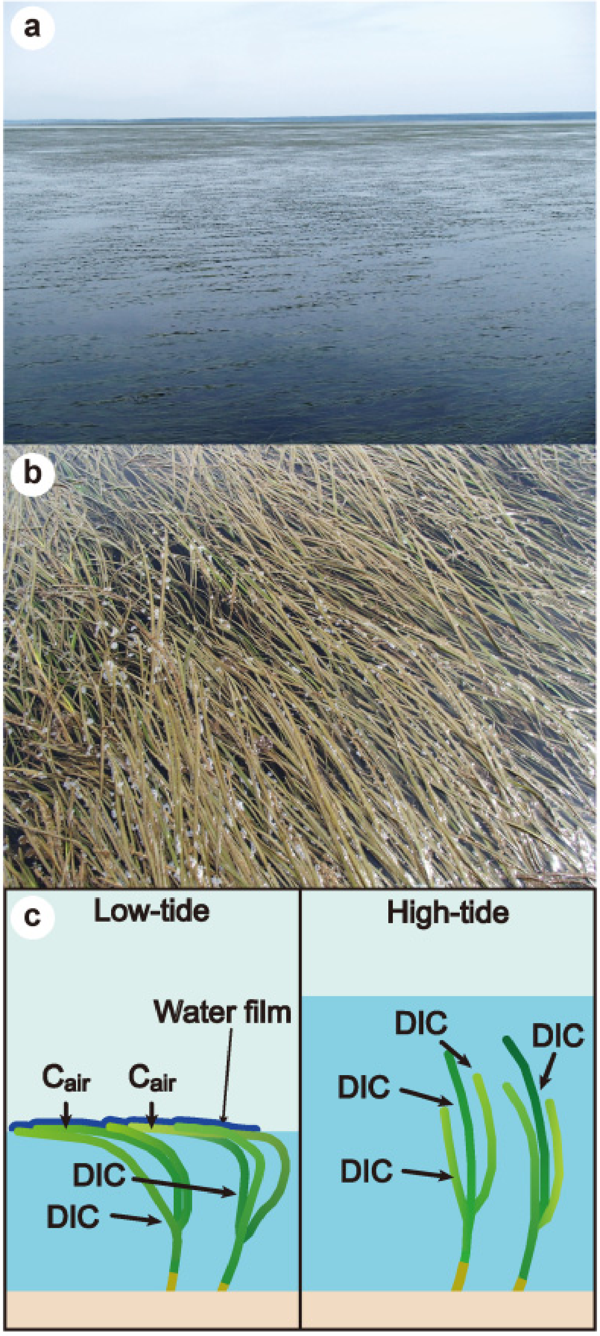

Figure 4. **(a)** Distant and **(b)** close-up views of the seagrass leaves exposed to the air during low tide in Furen Lagoon, Japan. **(c)** Conceptual diagram of the uptake of atmospheric CO_2 (C_{air}) across the surface-water film on the seagrass leaves during low tide (left), and the uptake of DIC during high tide (right).