Carbon sink services for tropical coastal seagrass are far lower than anticipated when accounting for black carbon

John B. Gallagher[1,2,3], Chuan Chee Hoe[4] Yap Tzuen-Kiat[3], and Farahain W[3]

[1]Centre for Marine and Coastal studies, Universiti Sains Malaysia, 11800, Pinang, Malaysia

[2] Institute for Marine and Antarctic Studies, University of Tasmania, 7000, Tasmania, Australia

[3] Borneo Marine Research Institute, Universiti Malaysia Sabah, 88400, Sabah, Malaysia

[4] Faculty of Science and Natural Resources, Universiti Malaysia Sabah, 88400, Sabah, Malaysia

Key words: pyrogenic carbon, blue carbon, seagrass, sediments, tropical

Valuing the sedimentary ‘blue carbon’ stocks of seagrass meadows in mitigating greenhouse gas emissions requires the exclusion of allochthonous recalcitrant forms, such as black carbon (BC) from the stock assessment. Regression models constructed across a tropical estuary predicted that carbon sinks within the more abundant sandy meadows of coastal bays likely support a significant but modest BC fraction. We tested the prediction by measuring BC fractions of total organic carbon (TOC) across three coastal meadows of the same region. One patchy meadow was located close to a major urban centre while the remaining two continuous meadows where contained in separate open embayments of a rural marine park, differing in fetch and species. In all cases, the BC/TOC fractions were significantly greater than predicted constituting a major component of the organic carbon content, 28% ± 1.6, and 26% ± 4.9 to 36% ± 1.5 (±95% confidence intervals) for urban and marine park meadows respectively. The higher BC/TOC fractions were explained by site-specific variability in BC atmospheric supply, patchy coverage, and a presumed increase in the loss of seagrass litter, as determined by the canopy height and proximity to the meadows exposed edge.

Introduction

The realisation that anthropogenic emissions of CO_2 is effecting climate change has highlighted the importance of quantifying and managing existing sedimentary organic carbon stocks, buried and protected from remineralisation. Lately, there has been a focus on ‘blue carbon’ reservoirs. These ecosystems are the seagrass, saltmarsh, mangrove, and macro-algae (1, 2). Of the four, seagrass ecosystems remain better placed to augment their organic carbon stocks. Coastal seagrass meadows filter out organic detritus washed out across intertidal and terrestrial landscapes and sequester them within their sediments (3), which would otherwise be mineralised across the continental shelf (4).

Chew and Gallagher (5), however, challenged the traditional biogeochemistry mass balance concept of carbon storage. They argued that because recalcitrant organic carbon produced outside an ecosystem does not require protection from remineralisation, then their presence within sediments cannot be counted as a burial service in the mitigation of greenhouse gas emissions. Black carbon (BC) is an example of an ‘allochthonous recalcitrant’. It is formed during the incomplete combustion of biomass and fossil fuels, of which SE Asia is a global hotspot (6). Its supply to seagrass meadow sediments can be both through atmospheric deposition and with soil washout (5). However, the black carbon content of coastal seagrass sediments is unknown. Nonetheless, estimates of its importance to the total organic carbon content (TOC) have been made from a tropical estuarine system, of around 18 ± 3% (±95% confidence interval) within tropical regions located around Sabah (Malaysia) (5). While the BC/TOC fraction was significant, if not moderate, the equivalence may have be confounded. Within the confines of a tide–dominated estuary, the BC fraction could be reduced by a sizeable fraction, due to the lost seagrass litter returned on the flood tide. Contrast this with coastal seagrass meadows, which lose a large fraction of its litter to the coastal shelf across the whole meadow or close to their exposed boundary (7-9). It is also plausible that the narrow entrance could restrict BC supply from coastal bare sediments by persistent onshore winds (Monsoons). Taken together, these two factors could inflate coastal seagrass sedimentary BC/TOC fractions over that of their sandier estuarine analogues. This study sets out to test the prediction and the possible confounding factors by measuring the surface sedimentary BC and TOC contents across three subtidal (0.5-1 m) tropical seagrass meadows and adjacent bare sediments of same region.

Materials and Methods

The study was conducted within the rural Tun Mustapha Marine Park, and the urban Sepanggar Bay, which contains a major shipping port. Both locations are in North Borneo (Sabah,Malaysia) (electronic supplementary material, figure S1). The two Marine Park seagrass meadows Limau-Limauan (LL) and Bak-Bak (BB) supported continuous meadows. The BB meadow, contained a mix of smaller canopy pioneer species, *Cymodocea rotundata* and *Halodule pinifolia*, consistent with a relatively more energetic environ, over that of the LL meadow, dominated by a large leafed climax species, *Enhalus acoroides* (10). In contrast, the Sepanggar Bay meadow near ODEC beach (OD) was patchy and reminiscent of a degraded system. The meadow supported a mixed bed species of mainly pioneer forms, *Cymodocea serrulata*, *Halodule uninervis*, and *Halophila ovalis*, with only isolated small stands of *E. acroides*.

Across each meadow, the first 1 cm of sediment was taken haphazardly within a 25 cm^2 quadrat for BC and TOC contents. Quadrats were laid down every 5 m along two parallel 50 m transects perpendicular to the exposed boundary of a prevailing Monsoon

(Supplementary Figure S1). Along with BC and TOC, a range of sedimentological and seagrass biological variables were also measured within each quadrat (table 1). Samples of bare sediments were also taken for BC and TOC contents. The sites were selected away from adjacent shallow banks of coral rubble, and windward to the prevailing Monsoon, along with an additional 10 samples along the central channel adjacent to seagrass meadows of Salut–Mengkabong estuary. For details of sample treatment, sediment particle size distribution and analysis of TOC and BC as measured using a gravimetric chemo-thermal oxidation protocol can be found elsewhere (5). All statistical analysis, ANOVA, ANCOVA, median and quartiles and SE, were calculated in PAST™ after confirming normality of data distributions.

Results

Overall, BC represented a significantly larger fraction of the TOC than was found across the upper silty/mud and lower silty/sand sediments of the estuary Salut–Mengkabong (figure 1). Furthermore, it appeared that the difference was also reflected in the BC/TOC fractions across their adjacent bare sediments. For BB and LL, their BC/TOC variability was not reflected in smaller TOC contents found across transects closer to the exposed edge of their meadows (figure 2a). That is to say, there was a similar linear response of BC to increases in TOC across the BB and LL meadows, and both linear responses supported near zero intercepts (figure 2b). Although, it should be noted, that there was a greater difference in the mean TOC between the transects of the larger canopy LL meadow over that of BB (figure 2a), for similar coverages (table 1). Furthermore, BB had on average 2.4 times higher sedimentary TOC contents than LL, which was not reflected in a higher silt/clay fraction (table 1). In contrast, there was no differences for both the average sedimentary TOC and BC between the inner and exposed transects of the patchy meadow at OD. Instead, most of the variance was contained across the transect's TOC resulting in a relatively invariant response with BC content (figure 2b). It should also be noted that the mean particle sizes within the patch stands at OD were much greater and not smaller than found in adjacent bare patches of the meadow of 8.1µm ± 2.4 and 107.5µm ± 19.0 (±95% CI) respectively (analysed from electronic supplementary material, table S1).

Discussion

As expected, the sedimentary TOC content was less along the outer more exposed transects for both LL and BB meadows. We believe that falling rates of resuspension and subsequent oxidisation closer to the exposed meadows edge is not a likely explanation (4). There was a near doubling of seagrass coverage, and presumably their root's ability to bind sediments (11), across the inner transect of BB, and not for LL (table 1). Loss of TOC by resuspension would then result in greater and not smaller differences in sedimentary TOC contents between inner and outer transects of BB over that of LL (figure 2a). Neither can contributions of BC from adjacent bare sediments explain the data patterns. Firstly, net deposition of these sediments is likely to be greater across the inner transects, as turbulence is increasingly attenuated (12). This should reduce and not increase the inner transects TOC contents. Secondly, a model that describes increases in BC with TOC, which converges towards a positive TOC intercept close to its origin, is more consistent with additional organic carbon not associated with BC. A more likely alternative for the inter and intra meadow differences in TOC is a greater reduction in turbulence and loss of litter across the meadow, by the larger LL canopy species (12) (table 1).

The OD meadow variance in both TOC, its relationship to BC and sedimentology appears to illustrate a separate circumstance over the more continuous and rural meadows. The larger mean sediment particle sizes within the patch stands over the bare regions of the OD meadow (see Results section), would imply a seemingly inconsistent greater and not smaller amount of turbulence within the canopy. This has been reported or similar small patchy distributions, where the increased amount of turbulence comes from the less restrictive movement of the seagrass canopy (13). How this affected the variance was unclear. Nonetheless, the relative high TOC, possibly the result of a more eutrophic polluted environ may have tempered increases in BC/TOC fraction. Either way, the invariance of BC with TOC suggests that the supply of BC was ostensibly over a larger scale, consistent with atmospheric deposition (5).

Conclusion

The study demonstrated that BC, an allochthonous recalcitrant form, can represent a major fraction of the sediment content of coastal seagrass meadows and lead to significant overestimates of their carbon sink services. Furthermore, it appears that the size of seagrass canopy species and not coverage maybe a better predictor of the extent of the BC contribution to the sedimentary TOC than the an expected increase in the amount of BC emitted for a urban environ, when covariant with eutrophication. We thus, recommend we move forward away from a simple mass balance approach to one that includes stability and origin by incorporating the concept of allochthonous recalcitrance.

Data accessibility. Supporting data and figures can be found in the electronic supplementary material

Author contributions. All the authors assisted in fieldwork and analysis of the samples. J.B.G. conceived the program and led the writing of the manuscript. C.C.H. compiled the supplemental material, and the statistical analysis set within Table 1. All the authors approve the final version of the manuscript and agree to be accountable for all aspects of the manuscript.

Competing interests. We declare we have no competing interests

Funding. Provided by Sabah Park's Tun Mustapha Park Scientific Expedition (SDK0006-2017), and from the Ministry of Science Technology and Innovation (FRGS0424-SG-1/2015).

Figure 1. The BC/TOC fractions for seagrass sediments of upper (SMU), and lower (SML) Salut–Mengkabong Estuary, the coastal seagrass meadows at ODEC beach Sepanggar Bay (OD), Bak-Bak (BB) and Limau-Limauan (LL). BSM, BOD and BLB are the fraction from bare sediments outside of the meadows within the estuary, OD, and LL and BB (combine) respectively. The box plot represents the median, 25% and 75% quartiles, 95% cofidence limits and outliers. Data for SMU and SML was compiled from Supplementary material (5) in accordance to Open Access licence http://creativecommons.org/licenses/by/4.0/.

Figure 2. The upper graph **a,** shows the total organic carbon content (TOC) and black carbon (BC) contents of ODEC beach in Sepanggar Bay(OD), Bak Bak (BB), and Limau Limauan (LL), average across their inner and outer meadow transects. The error bars represent their 95% confidence limits. The lower graph **b,** are the ordinary least squares regressions for BC with TOC. Significant differences between transect TOC and BC means could be found for LL ($P < 0.05$, $P < 0.05$) and BB ($P < 0.07$, $P < 0.05$) respectively. The probablity of the regression intercepts and slopes between BB and LL are being the same was statistically significant (ANCOVA $P > 0.38$).

Table 1. Mean and standard errors of TOC and BC surface sediment contents (as dry mass), along with their seagrass canopy and sediment parameters for the three Sabahan seagrass meadows (Malaysia).

Seagrass meadow	**n**	**TOC (%)**	**BC (%)**	**BC/TOC (%)**	**Coverage (%)**	**Canopy (cm)**	**Particle Size (µm)**	**Silt/clay (%)**
ODEC Beach	22	1.07 ± 0.04	0.29 ± 0.01	27.97 ± 0.76	10 ± 3	5.8 ± 1.7	110.22 ± 3.97	8.98 ± 0.96
Bak-Bak	22	0.71 ± 0.02	0.26 ± 0.01	35.66 ± 0.74	42 ± 6	3.8 ± 0.6	132.30 ± 1.83	4.09 ± 0.18
Limau-Limauan	22	0.30 ± 0.04	0.08 ± 0.02	26.13 ± 2.37	33 ± 5	11.5 ± 1.3	74.82 ± 4.65	17.14 ± 2.95

References

1. McLeod E, Chmura GL, Bouillon S, Salm R, Björk M, Duarte CM, et al. A blueprint for blue carbon: Toward an improved understanding of the role of vegetated coastal habitats in sequestering CO 2. Frontiers in Ecology and the Environment. 2011;9(10):552-60.

2. Hill R, Bellgrove A, Macreadie PI, Petrou K, Beardall J, Steven A, et al. Can macroalgae contribute to blue carbon? An Australian perspective. Limnology and Oceanography. 2015;60(5):1689-706.

3. Kennedy H, Beggins J, Duarte CM, Fourqurean JW, Holmer M, Marba N, et al. Seagrass sediments as a global carbon sink: Isotopic constraints. Global Biogeochemical Cycles. 2010;24.

4. Cathalot C, Rabouille C, Tisnérat-Laborde N, Toussaint F, Kerhervé P, Buscail R, et al. The fate of river organic carbon in coastal areas: A study in the RhÔne River delta using multiple isotopic (δ13C, δ14C) and organic tracers. Geochimica Et Cosmochimica Acta. 2013;118:33-55.

5. Chew ST, Gallagher JB. Accounting for black carbon lowers estimates of blue carbon storage services. Scientific reports. 2018;8(1):2553.

6. Gaveau DLA, Salim MA, Hergoualc'h K, Locatelli B, Sloan S, Wooster M, et al. Major atmospheric emissions from peat fires in Southeast Asia during non-drought years: evidence from the 2013 Sumatran fires. Scientific reports. 2014;4:6112.

7. Chiu S-H, Huang Y-H, Lin H-J. Carbon budget of leaves of the tropical intertidal seagrass Thalassia hemprichii. Estuarine, Coastal and Shelf Science. 2013;125:27-35.

8. Ricart AM, Ricart AM, Dalmau A, Perez M, Romero J. Effects of landscape configuration on the exchange of materials in seagrass ecosystems.

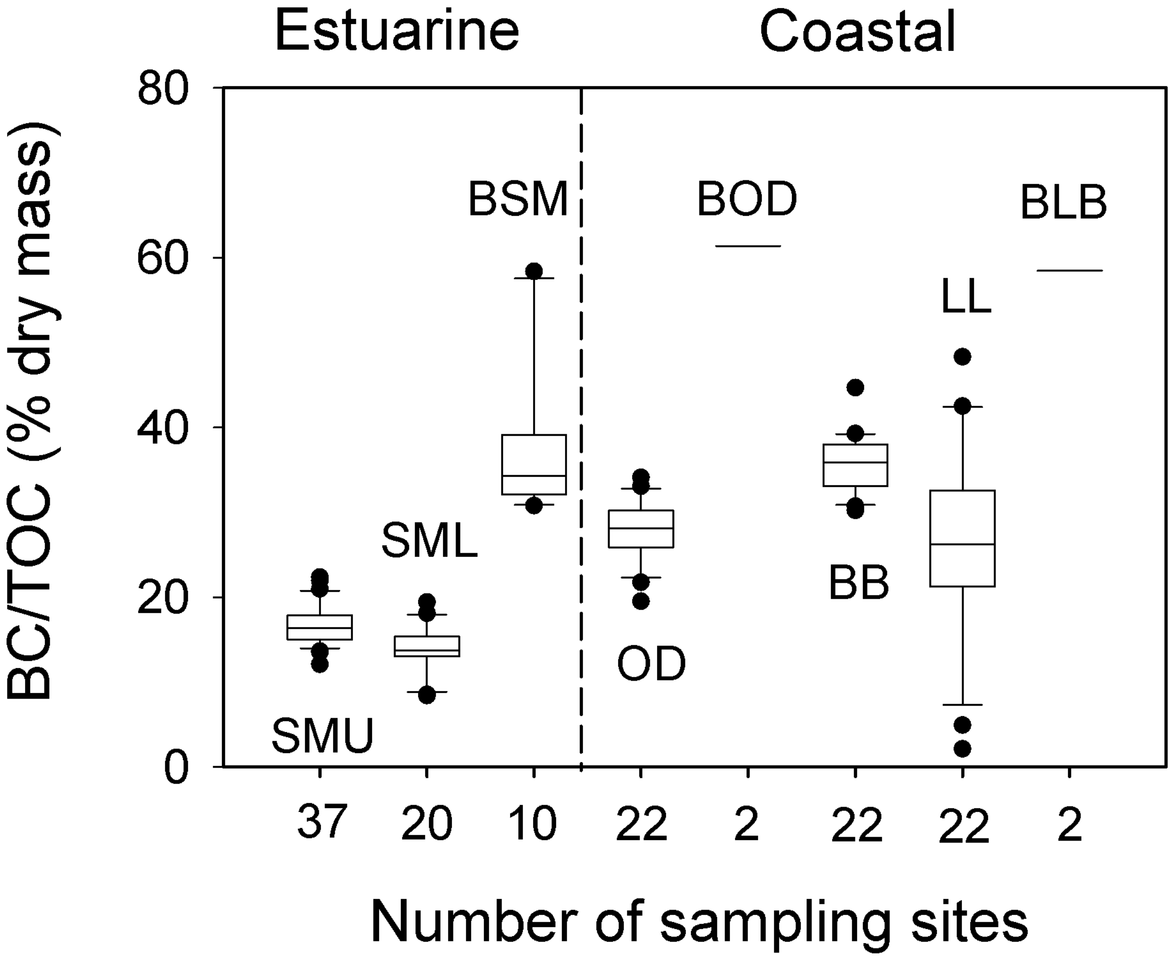
9. Portillo E. Relation between the type of wave exposure and seagrass losses (Cymodocea nodosa) in the south of Gran Canaria (Canary Islands — Spain). Oceanological and Hydrobiological Studies. 2014;43(1):29-40.

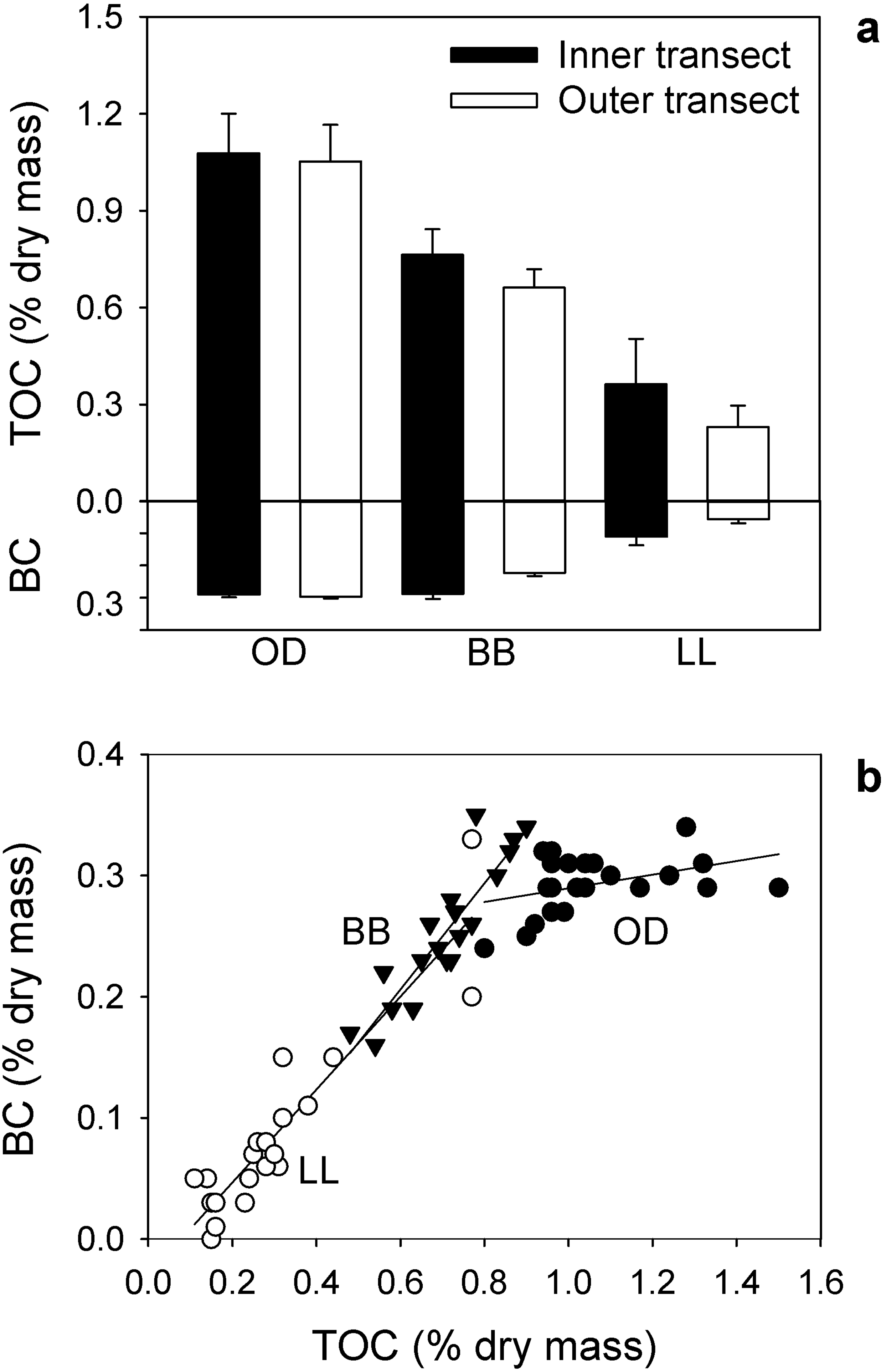
10. Kilminster K, McMahon K, Waycott M, Kendrick G, Scanes P, McKenzie L, et al. Unravelling complexity in seagrass systems for management: Australia as a microcosm 2015.

11. Christianen MJA, van Belzen J, Herman PMJ, van Katwijk MM, Lamers LPM, van Leent PJM, et al. Low-Canopy Seagrass Beds Still Provide Important Coastal Protection Services. PLoS ONE. 2013;8(5).

12. Fonseca MS, Cahalan JA. A preliminary evaluation of wave attenuation by four species of seagrass. Estuarine, Coastal and Shelf Science. 1992;35(6):565-76.

13. van Katwijk MM, Bos AR, Hermus DCR, Suykerbuyk W. Sediment modification by seagrass beds: Muddification and sandification induced by plant cover and environmental conditions. Estuarine, Coastal and Shelf Science. 2010;89(2):175-81.


Estuarine
Coastal
BC/TOC (% dry mass)
80
60
40
20
0
SMU
SML
BSM
OD
BOD
BB
LL
BLB
37
20
10
22
2
22
22
2
Number of sampling sites


a
Inner transect
Outer transect
TOC (% dry mass)
BC
1.5
1.2
0.9
0.6
0.3
0.0
0.3
OD
BB
LL
b
BC (% dry mass)
0.4
0.3
0.2
0.1
0.0
BB
OD
LL
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
TOC (% dry mass)