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Carbon stocks of coastal macroalgal beds in the SW Atlantic

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Abstract

Macroalgae beds are extensive and productive marine benthic vegetated habitats globally, occurring in nearly 28% of coastal habitats worldwide. These marine forests may be important coastal carbon sinks but there are very limited *in-situ* assessments of their carbon stocks. In this study, we assessed the blue carbon stocks (aboveground and belowground) of typical coastal macroalgae beds in the SW Atlantic coast by comparing shallow (< 2 m) subtidal environments with and without the presence of macroalgae. We estimated a total ecosystem carbon stock (TECS) of 1.64 ± 0.24 Mg C ha^{-1} on macroalgae beds, which was on average 30% higher than areas without macroalgae (1.14 ± 0.16 Mg C ha^{-1}). The differences between areas were attributed to the aboveground carbon stock in macroalgal biomass (0.49 ± 0.23 Mg C ha^{-1}), which corresponded to nearly 30% of the total stocks. *Sargassum* sp. (Phaeophyceae) was the most representative macroalgae on the studied areas (59%), and contributed to a higher proportion of the aboveground carbon stocks. Using satellite imagery, we estimated an area of 527 ha of macroalgae beds along a stretch of 410 km in the Eastern Marine Ecoregion of Brazil, representing a TECS of 869 ± 128 Mg C. Nearly 45% of these macroalgae beds are currently within coastal marine protected areas in the region, and although they hold a limited value for climate mitigation, they remain largely unrecognized in the conservation planning in the SW Atlantic.

Highlights

- We present the first mapping and regional assessment of carbon stocks in macroalgal beds in the SW Atlantic.
- We mapped 527 ha of macroalgae beds with carbon stocks of 869 ± 128 Mg C, with 30% as aboveground biomass.
- Macroalgal beds hold on average 30% higher C stocks compared with bare sand subtidal habitats.
- Coastal macroalgae beds are of limited value for climate mitigation.

Keywords Blue carbon, Marine protected areas, Brazil, Coastal ecosystem, Marine sediment, Macroalgae biomass

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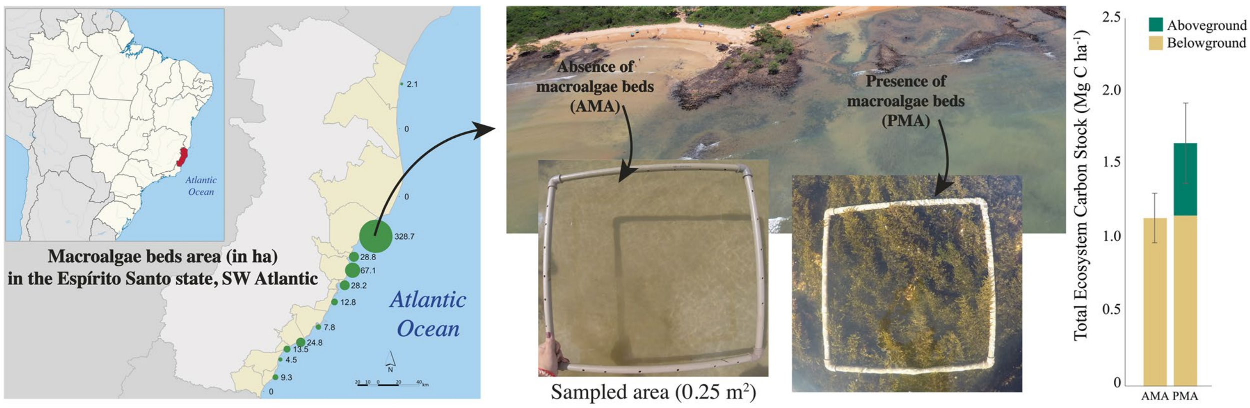
Graphical Abstract



1 Introduction

Macroalgae beds (seaweeds) are subtidal coastal ecosystems associated to multiple ecosystem services, with unique associated biodiversity and potentially holding carbon along global coastal areas (Mazzuco et al. 2019; Cai et al. 2024a). These marine forests may represent an additional coastal carbon sink within their standing biomass and in belowground sediments (Pederson et al. 2020; Paine et al. 2021). In addition, macroalgae can release dissolved nutrients and labile organic compounds on coastal areas (61 to 268 tg C y^{-1}), potentially increasing their importance in coastal alkalinity and contributing to long-term deposits of carbon in coastal and deep-sea sediments (Filbe-Dexter and Wernberg 2020; Paine et al. 2021). Although some studies suggest that macroalgae may be an important component of marine blue carbon (Gallagher et al. 2022; Ould and Caldwell 2022; Young et al. 2022; Cai et al. 2024a), there are very few attempts to measure their carbon stocks in coastal areas worldwide.

Blue carbon studies are mostly focused on coastal mangrove forests, saltmarshes and seagrasses, partially due to their high total ecosystem carbon stocks (TECS) and long-term preservation (Kauffman et al. 2020). Although macroalgae may cover large coastal areas globally, it is estimated that most of their productivity is lost to herbivory resulting in limited sequestration in sediments (Gallagher et al. 2022). Macroalgae beds therefore are assumed to hold limited carbon stocks but may act as an important carbon source to deep-sea regions, contributing an estimated amount of 1.5 Pg C per year globally, and sequestering as much carbon as other coastal ecosystems (e.g., seagrass meadows, salt marshes, and mangroves) (Krause-Jensen et al. 2016; Howard et al. 2017). For instance, the global carbon stock of *Sargassum* sp., whether it is floating or adhered to the sediment, is 13.5 Pg C (Gouvea et al. 2020). Although macroalgae beds are recognized as a potential source and sink of coastal carbon, their role as carbon sink is poorly explored (Moreda et al. 2024).

There is a large gap in understanding direct and indirect benefits of macroalgae beds in coastal areas, especially in the SW Atlantic. Macroalgae beds in the SW Atlantic are of potential relevance to marine biodiversity in coastal reefs and rhodolith ecosystems (Mazzuco et al. 2022; Tuya et al. 2023). There is only one study which reported an aboveground biomass of macroalgae (*Sargassum* sp.) in the SW Atlantic off Brazil (Gouvea et al. 2020). Although the work by Gouvea et al (2020) reveals an important role of macroalgae as blue carbon stocks in the South Atlantic, there is yet no information of the importance of seaweed in increasing sediment (belowground) carbon stocks on coastal areas. This information is key for the potential inclusion of macroalgal beds in global mitigation actions alongside with mangroves, saltmarshes and seagrasses (Kauffman et al. 2020; Bernardino et al. 2024; Cai et al. 2024b). This study aimed to fill some of these gaps by quantifying the TECS associated to macroalgae beds and paired areas without seagrasses in the Eastern Marine Ecoregion of Brazil. We hypothesized that macroalgae beds would increase local TECS through incorporation of biomass (aboveground) and intensification of burial (belowground) when compared to bare (no macroalgae) sediment areas. This work brings new data on the carbon stocks of coastal macroalgal beds in the tropical SW Atlantic, an area with large potential for the occurrence of macroalgae (Gouvea et al. 2020).

2 Material and methods

2.1 Study area and sampling

This study was conducted in seven coastal sites within the Eastern Brazilian Marine Ecoregion of Brazil in sites distributed within a Marine Protected Area (Fig. 1; Table S1). This region is characterized by lateritic coastal reefs with unique benthic diversity, under a microtidal regime and fluvial influence (Mazzuco et al. 2019, 2020). Additionally, it may have the largest potential for macroalgae biomass and richness in the Tropical Atlantic (Gouvea et al. 2020; ICMBio 2024). The region is typically influenced by E-NE winds of the South Atlantic high-pressure system, E-SE swells and strong tidal currents, with rainy summers and dry winters (Bernardino et al. 2015; Quintana et al. 2015).

Sampling occurred in August 2022, during spring low tide when macroalgae samples (adhered to unconsolidated sediment) could be collected manually ($n=3$ per beach) using 0.25 m^2 quadrats (Fig. 1). Drift or washed-up macroalgae were not collected for this study as we could not determine their origin. Additionally, we collected three replicated sediment samples (upper 5 cm, approximately 160 g per sample) using a semi-cylindrical auger (6 cm diameter) within and outside macroalgae beds to quantify belowground carbon stocks. Macroalgae samples were kept cold in ice until freezing upon return to the laboratory. As the paired control areas had no macroalgae cover, the TECS of the bare areas are solely represented by the amount of organic carbon belowground. Sediment samples were also collected for granulometric analysis. This sampling was previously authorized by the Biodiversity Authorization and Information System from the Brazilian Institute for the Environment and Renewable Natural Resources (SISBIO-IBAMA, 57,819–7).

2.2 Macroalgae and sediment analysis

In the laboratory, macroalgae samples were thawed at room temperature, washed in current water to remove attached organisms and identified at genus level using a binocular stereomicroscope and dichotomic taxonomic identification keys (Nassar 2012). Each macroalgae sample was wet weighted after removing the excess water and dry weighted after 48 hs at 60 °C. We calculated the aboveground carbon stock (AGC) based on the macroalgal dried biomass per sample using conversion rates of dry biomass to organic carbon from three macroalgae classes from the same marine ecoregion (Phaeophyta = 0.35; Chlorophyta = 0.12 and Rhodophyta = 0.11; Table S2; Serafim et al. 2014; Gouvea et al. 2020).

Sediment samples were dried (45 °C until constant weight), and then crushed, and homogenized for soil organic carbon (SOC) quantification. For sediment

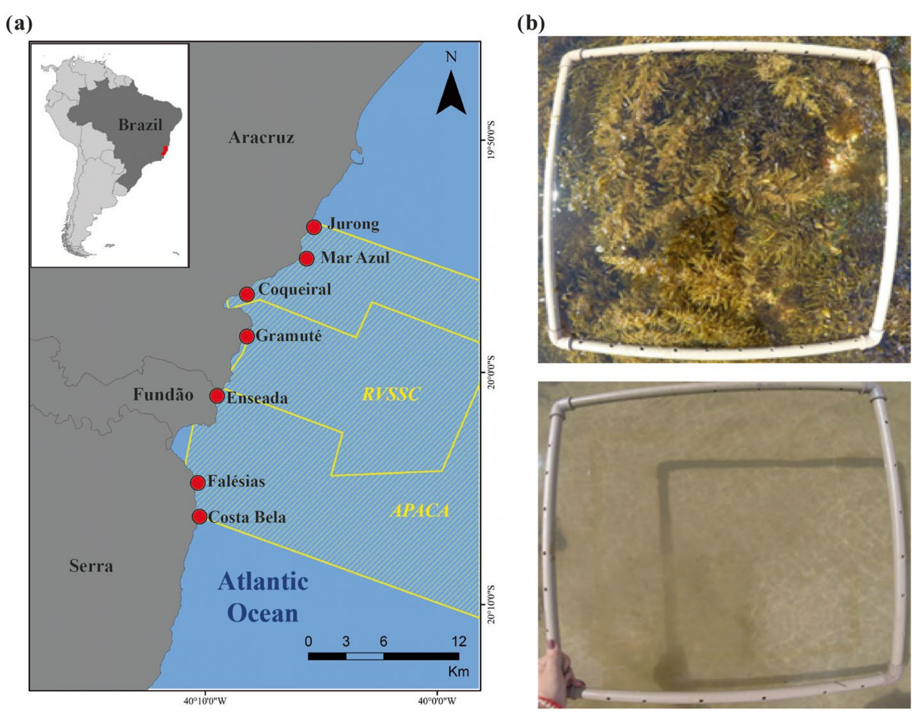


Fig. 1 (**a**) Location of the seven sampled beaches in the SW Atlantic, within the marine protected area Refúgio da Vida Silvestre de Santa Cruz (RVSSC) and Área de Proteção Ambiental Costa da Algas (APACA; polygon areas). (**b**) Sampled sites, with (PMA) and without (AMA) macroalgae bed coverage

organic carbon (SOC) quantification, sediment subsamples were acidified to remove carbonate (HCl 1 M, 37% P.A./ACS, Neom Comercial, Brazil). SOC was determined using a Total Organic Carbon Analyzer (TOC-V, LECO CN-2000, EUA) (Analytical precision, C = 0.1%) at the Escola Superior de Agricultura "Luiz de Queiroz" (ESALQ), Universidade de São Paulo (USP, Gomes et al. 2021). Sediment bulk density was determined from the dry mass of sediments divided by the sample volume (g cm^{-3}). The belowground carbon stocks (BGC) quantification on sediment was based on sediment bulk density (Table S3) and the OC content of sediments (Kauffman and Donato 2012; Kauffman et al. 2018). The Total Ecosystem Carbon Stocks (TECS) of macroalgae beds corresponded to the sum of the AGC and BGC pools. For granulometric analyses, sediment samples (50 g) were dried in stove (50 °C for 72 h), sieved using a sieve shaker, and then classified as gravel ($\Phi < =-1$), medium/coarse sand ($-1 < \Phi < =2$), fine sand ($2.5 < \Phi < 4$), and silt ($\Phi = > 4$; Fig. S1; Stelzer et al. 2021).

2.3 Coastal macroalgae bed area

We conducted a classification of coastal water substrate along the coast of Espírito Santo state, Brazil using satellite imagery and a supervised learning algorithm. The imagery was processed on the Google Earth Engine (GEE) platform, leveraging its extensive datasets and computational power. GEE has shown to be a powerful tool to map coastal ecosystems (Li et al. 2022; Bessinger et al. 2022). We used the Harmonized Sentinel-2 MSI: Multi-Spectral Instrument, Level 2A dataset (Fig. 2). This dataset was selected for its high spatial resolution (10 m), multispectral imaging capability, and revisit frequency, making it ideal for generating a high-quality composite of the region. We selected images captured from January to September of 2024, removed those with over 75% cloud coverage and masked out the remaining cloudy pixels with the Sentinel-2: Cloud Probability auxiliary dataset. The composite was then created with the median pixel values. From this composite, we derived a 1000-m wide stripe along the coast using a coastline dataset (Sayre et al. 2019) and the OSM Water Layer (Yamazaki et al. 2019). This Region of Interest (ROI) was wide enough to contain the typical macroalgae depths (< 10 m).

We used a Random Forest algorithm to classify the ROI pixels into five distinct categories: "macroalgae", "laterite", "granite", "unconsolidated" and "other" (Fig. 2). While the primary goal of this classification was to map only the macroalgae class, an exploratory analysis indicated that it was useful to classify in five categories of similar features—as opposed to a binary classification— – to increase the overall accuracy of the model. The training set consisted of 10 *in-situ* verified polygon geometries of the "laterite" class and 10 of the "macroalgae" class along with 62 polygons of the five classes selected from visual identification on the composition. The polygons were sampled to extract a total of 23.325 labeled pixels. To train the model, we used the bands 'B1' to 'B12', comprehending all the visible spectrum, NIR and SWIR frequencies.

The model was trained using a train-test split of 80/20 and Grid Search using the F1-Score of the "macroalgae" class to evaluate it and adjust the hyperparameters. The F1-Score was selected because it provides a better evaluation when dealing with imbalanced classes in training data. As a post-processing step, we used Simple Non-Iterative Clustering (SNIC), an unsupervised clustering method to replace sparse, potentially misclassified points, with the majority value of its neighbors. This was

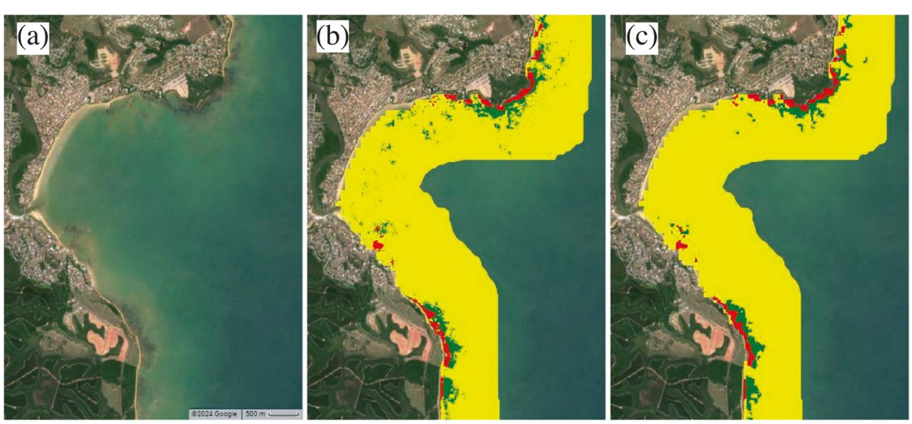


Fig. 2 Steps of the mapping process. (**a**) Sentinel 2 image composition, (**b**) classification of the region of interest pixels with Random Forest model, (**c**) final map with post-processing clustering technique. Yellow = unconsolidated sediment, red = laterite (rocky reefs), green = macroalgae, and cyan = other

necessary to better represent the natural tendency of these classes to be formed in continuous chunks.

2.4 Statistical analysis

The normality of environmental data was tested by the Shapiro–Wilk test (Shapiro and Wilk 1965). Macroalgal and sedimentary carbon stocks were compared among sampled sites and areas with and without macroalgae beds using a Permutational Analysis of Variance (PERMANOVA; Anderson et al. 2008) based on a Euclidean distance matrix. Significative differences were considered when $p < 0.05$. All statistical analyses were performed using the software PRIMER 7 + PERMANOVA (Clarke and Gorley 2006).

3 Results and discussion

Macroalgae beds showed significant differences on composition and biomass among sampled sites (PERMANOVA, df = 6; Pseudo-F = 2.998; $p = 0.014$; Fig. 3; Table S4). Phaeophyceae (*Sargassum* sp.) dominated the aboveground biomass at all sites, except in one area where *Dichotomaria* sp. (Rhodophyta) dominated. The mean macroalgae biomass was 1.73 ± 0.90 Mg DW ha^{-1}, with up to 2.4 to 2.5 Mg DW ha^{-1} in high-density macroalgae beds and 0.67 to 0.94 DW ha^{-1} in low-density beds within the Marine Protected Area (Fig. 1). The aboveground carbon stocks of macroalgae beds were 0.49 ± 0.23 Mg C ha^{-1} (Table 1). The macroalgae bed biomass found in this study was within range of the estimated macroalgae biomass in Brazil (1.93 Mg DW ha^{-1}; Gouvea et al. 2020). Using the biomass to organic carbon conversion from our study, the aboveground carbon stocks of our macroalgae beds were also within range of their estimates for the Brazilian coast (0.5 ± 0.39 Mg C ha^{-1}; Gouvea et al. 2020).

Table 1 Carbon pools of macroalgae beds in the Eastern Brazil Marine Ecoregion. ABG-aboveground pools; BGD-belowground pools, TECS-Total Ecosystem Carbon Stocks. Stock values in Mg C ha^{-1}

	N plots	ABG	BGD	TECS
Macroalgae beds	21	0.49 ± 0.23	1.14 ± 0.12	1.64 ± 0.24
Bare sediments	21	0	1.14 ± 0.16	1.14 ± 0.16

Our study suggests that another important component of macroalgae carbon stocks lies buried in sediments below these beds. We found that the organic carbon content in macroalgae beds averaged 8.1 ± 0.7% OC, but we did not find any difference between areas with and without macroalgae beds (8.6 ± 1.32% OC). These values are relatively high when compared to seagrass sediments in the Red Sea (0.61 ± 0.23%; Cai et al. 2024b). The carbon density in sediments was also similar among areas with and without macroalgae (0.11 ± 0.02 g cm^{-3}), suggesting a limited transfer of algal organic carbon to underlying sediments. Furthermore, the spatial variability between the PMA and AMA regions (approximately 100 m) suggests a transport of this carbon content to adjacent areas. Our data suggests that contrary to typical blue carbon wetlands, macroalgae beds have a limited role to increase the burial of organic carbon in coastal sediments likely due to their high susceptibility to degradation (Trevathan-Tackett et al. 2015; Krause-Jensen et al. 2016). Given the similar sedimentary carbon density, the belowground carbon stocks of macroalgae beds and nearby unvegetated sediments were 1.14 ± 0.12 Mg C ha^{-1} (PERMANOVA, df = 6; Pseudo-F = 0.553; $p = 0.738$; Fig. 4; Table S5).

The total ecosystem carbon stocks of macroalgae beds averaged 1.64 ± 0.24 Mg C ha^{-1}, with a range of 1.93 to 1.34 Mg C ha^{-1} with no difference among sites (PERMANOVA, df = 6; Pseudo-F = 1.147; $p = 0.33$; Fig. 4;

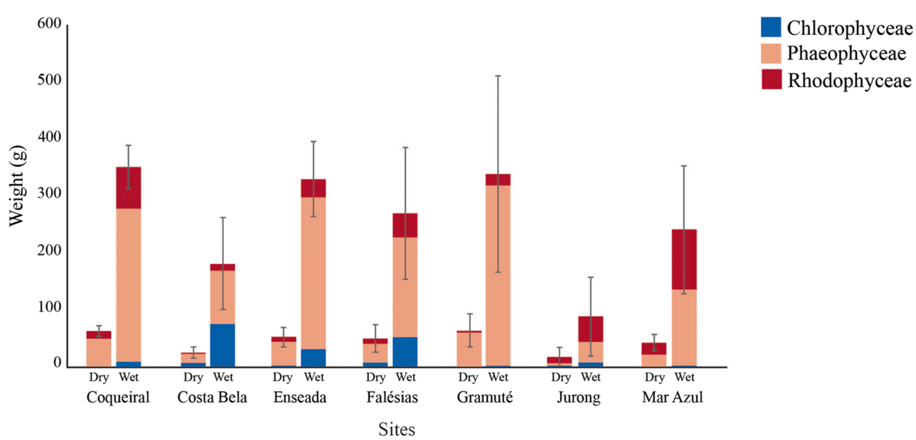


Fig. 3 Total macroalgae biomass (dry and wet weight) in each sampled site (0.25 m^2). Data are presented as mean ± standard deviation

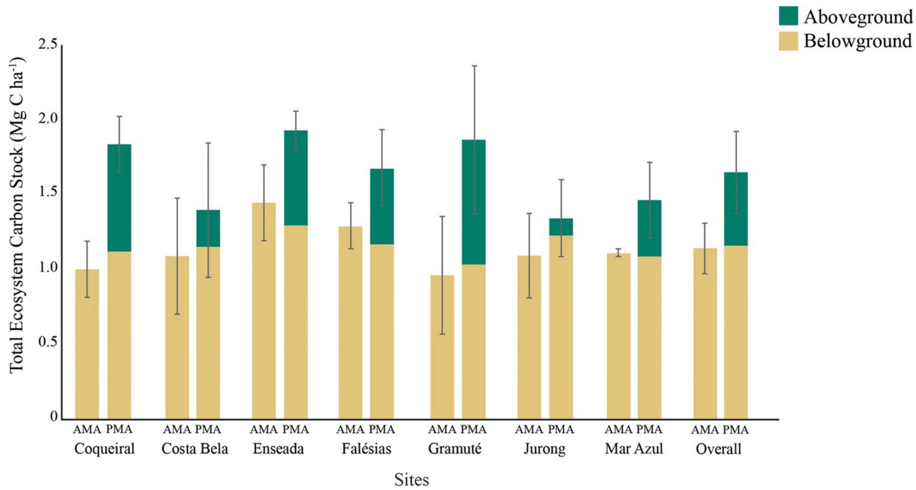


Fig. 4 Total ecosystem carbon stocks (above and belowground) in areas with (PMA) and without macroalgae (AMA) at each sampled site

Table S6). The belowground carbon stock represents nearly 2/3 of TECS, and as a result, our data indicates a limited importance of aboveground macroalgal carbon to overall carbon stocks in coastal sediments (0.49 ± 0.23 Mg C ha^{-1}). In comparison, the aboveground stocks of macroalgae are only 22% of the AGC in seagrasses (1.9–2.52 Mg C ha^{-1}; Fourqurean et al. 2014; Serrano et al. 2019). However, macroalgae AGC are similar to seagrass stocks in Brazil (0.32 ± 0.23 Mg C ha^{-1}; Hatje et al. 2023), but significantly lower than stocks found in other coastal blue carbon ecosystems. For example, mean aboveground carbon stocks of mangroves in Brazil range from 80 to 137 Mg C ha^{-1} (Gomes et al. 2021; Bernardino et al. 2024), and 7.8 Mg C ha^{-1} in saltmarshes (Hatje et al. 2023). This variation in carbon concentrations is often observed when assessing the total carbon stocks in these ecosystems. For example, global mangrove forests have TECS ranging from 217 to 1141 Mg C ha^{-1} (Kauffman et al. 2020), and seagrass TECS ranging from 0.61 to 7.29 Mg C ha^{-1} (Fourqurean et al. 2014). These differences may rise from productivity and coastal geomorphological gradients globally, and it is likely that macroalgae standing stocks will be subject to similar spatial variability worldwide.

Based on the results of our imagery model, all the pixels of the ROI were classified into one of the five classes (macroalgae, laterite, granite, unconsolidated sediment, and others). The model scored a training accuracy of 0.9994, test accuracy of 0.9833 and F1-Score for "macroalgae" class of 0.9753, indicating that the model has good generalization capability for new data (Fig S2). The total macroalgae area in the studied region was 527.5 ha (Fig. 5), which represented a total macroalgae carbon stock of 869.8 ± 128.3 Mg C. Much of these macroalgal beds are within the *Marine Protected Areas* Costa das Algas, and are important areas for coastal marine biodiversity in the region (Mazzuco et al. 2019, 2020; Mazzuco and Bernardino 2022). Our study suggests that there is limited value of macroalgal beds with current blue carbon mitigation mechanisms. This is mainly due to their limited carbon stocks when compared to wetlands, but also to their limited additionality in increasing autochthonous belowground stocks in coastal environments. In addition, the persistence criteria for macroalgae blue carbon in coastal ecosystems is likely limited due to biological and physical effects of herbivory and storm removal (Krause-Jensen et al. 2016; Gallagher et al. 2022). Carbon sequestration through macroalgal biomass transfer to the deep ocean may be a potential sink although experiments show that macroalgae is also rapidly consumed by benthic organisms once deposited in the seafloor (Bernardino et al. 2010; Krause-Jensen et al. 2016). Determining the persistence times of macroalgae and the additionality effect of these beds in coastal ecosystems are thus necessary before these ecosystems can be considered for blue carbon mitigation strategies.

4 Conclusion

This study provides the first estimate of total ecosystem carbon stocks of macroalgae beds in the SW Atlantic. Our data revealed the importance of *Sargassum* sp. (Phaeophyceae) to aboveground carbon stocks, which accounted for nearly 1/3 of total ecosystem stocks. Our work revealed a large area of previously unknown

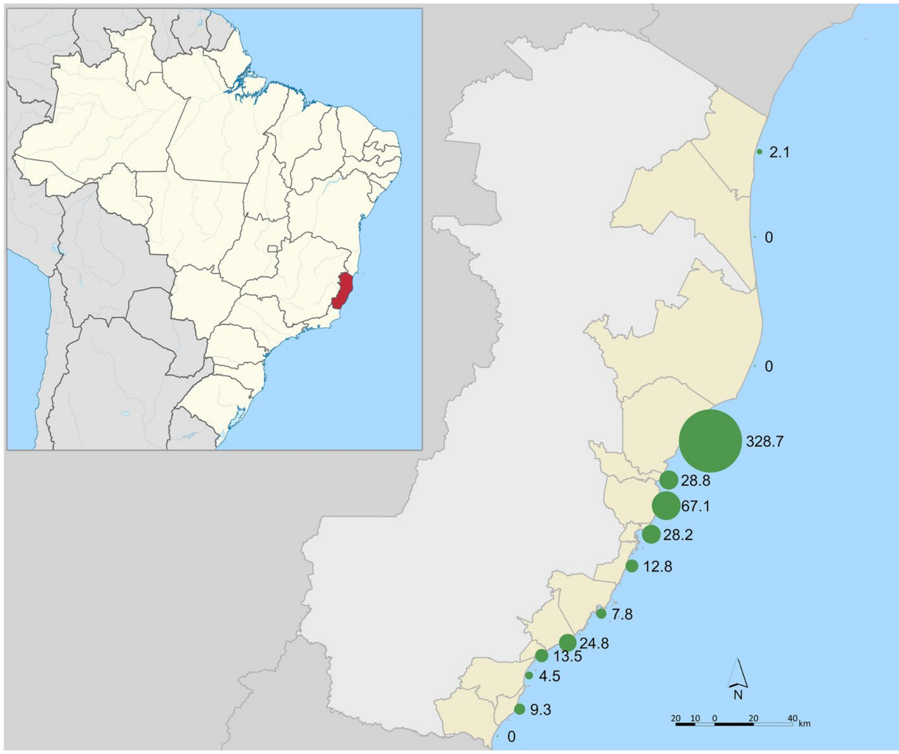


Fig. 5 Macroalgae beds area (in ha) for each coastal municipality in the Espírito Santo state, SW Atlantic

macroalgae beds in the Eastern Brazil Marine Ecoregion (527 ha of macroalgae beds), with a total carbon stock of 869.8 ± 128.3 Mg C. Despite their limited value in mitigating global greenhouse gas emissions compared to other blue carbon ecosystems (e.g., seagrasses meadows, and mangroves), they have a significant value to coastal marine biodiversity and should be included in conservation strategies. Our study indicates that quantifying the additionality effects and persistence times of macroalgae blue carbon should be a priority before these ecosystems can be considered in global climate mitigation strategies.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1007/s44246-025-00208-6.

Supplementary Material 1

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Authors' contributions
André Vassoler and Angelo Fraga Bernardino contributed to the study conception, funding and design. Material preparation, data collection and analysis were performed by Angelo Fraga Bernardino, Gabriel Carvalho Coppo, Tiago Osório Ferreira, and Ricardo Nogueira Servino. The first draft of the manuscript was written by André Vassoler and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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Data availability
The datasets used or analyzed during the current study are available from the corresponding author on reasonable requests.

Declarations

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

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