Science of the Total Environment 781 (2021) 146801

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

# On the Atlantic pelagic *Sargassum*'s role in carbon fixation and sequestration

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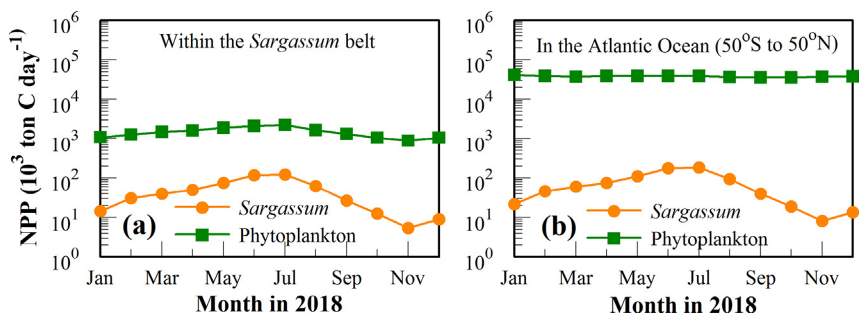
## HIGHLIGHTS

- Pelagic *Sargassum* is important in carbon fixation and sequestration at a local scale.
- At basin or global scale, it may not be as important as phytoplankton.
- More research is required on *Sargassum* primary production and sequestration rates.

## GRAPHICAL ABSTRACT

Pelagic *Sargassum* in the Atlantic Ocean is important in carbon cycling and carbon sequestration at a local scale. However, at a basin or global scale, it may not be as important as phytoplankton carbon simply due to the scale difference: *Sargassum* in the Atlantic Ocean, when aggregated together, covers at most 18,000 km$^2$ of the surface ocean, while the Atlantic Ocean is >100 million km$^2$ in its surface area.




## ARTICLE INFO

*Article history:*
Received 27 December 2020
Received in revised form 23 March 2021
Accepted 24 March 2021
Available online 27 March 2021

Editor: Lotfi Aleya

*Keywords:*
*Sargassum*
Atlantic Ocean
Biomass
Phytoplankton
Carbon stock
Primary production
Carbon fixation
Carbon sequestration
Climate change
Remote sensing

## ABSTRACT

The extensive blooms of the pelagic *Sargassum* in the Atlantic raised the question of whether this brown seaweed may play an important role in climate change mitigation through carbon fixation and carbon sequestration, as argued in several recent papers. Using simple calculations and published values on *Sargassum* coverage, biomass density, carbon/biomass ratio, primary productivity, and carbon sequestration efficiency, we show that the total carbon stock in pelagic *Sargassum* of the entire Atlantic, even during the peak month, is unlikely to exceed $3.61 \times 10^{-3}$ Pg C, and carbon fixation cannot exceed 6.0 million tons C month$^{-1}$. While the carbon fixation estimate represents an upper bound, it is still <0.2% of carbon fixation by phytoplankton in the Atlantic Ocean. The carbon stock estimate is 2000 times lower than predicted using a machine learning model in another recent paper. In contrast, carbon sequestration by *Sargassum* appears significant locally within the Atlantic *Sargassum* belt. The analysis further suggests that, while the Atlantic pelagic *Sargassum* may play an important role in affecting local carbon budget and carbon sequestration, its contribution to either carbon stock or carbon sequestration at a global scale may be insignificant. This, however, does not diminish the importance of Atlantic pelagic *Sargassum* in many other aspects.



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https://doi.org/10.1016/j.scitotenv.2021.146801
0048-9697/

## 1. Introduction

The recurrent blooms of the pelagic *Sargassum* (one type of brown macroalgae) in the tropical Atlantic and the Caribbean Sea since 2011 (Gower et al., 2013; Schell et al., 2015; Wang et al., 2019) stimulated multi-disciplinary research on their causes (e.g., Oviatt et al., 2019; Johns et al., 2020) and consequences on the oceanic and coastal environments as well as on local tourism, human health, and economy (Hu et al., 2016; Maurer et al., 2015; Siuda et al., 2016; van Tussenbroek et al., 2017; Rodríguez-Martínez et al., 2019). Among these, because *Sargassum* contains a significant amount of carbon (~30% of *Sargassum* dry weight, Wang et al., 2018, others), its potential roles in carbon stock, carbon fixation, and carbon sequestration have been investigated (Laffoley et al., 2014; Krause-Jensen et al., 2018; Ortega et al., 2019; Gouvea et al., 2020; Paraguay-Delgado et al., 2020). Researchers and managers are also actively discussing whether/how to use *Sargassum* as a potential tool to mitigate some effects from climate change, for example, through active discussions in an "Evolving and Sustaining Ocean Best Practices IV" workshop in September 2020 (https://drive.google.com/file/d/1V0TBuYe6_FOdc0pFo6ilHj936GhMs9CJ/view) and another workshop on the "Atlantic *Sargassum* Belt" sponsored by the European Algae Biomass Association in November 2020 (EABA, https://algaeworkshops.org/atlantic-sargassum-belt/). Because recurrent *Sargassum* blooms may become the new norm in the future (Wang et al., 2019) and because the estimates outlined in Laffoley et al. (2014) do not include *Sargassum* in the tropical Atlantic, it is desirable to clarify the role of pelagic *Sargassum* in carbon science, which is the objective of this communication.

## 2. Carbon stock

Earlier estimates of *Sargassum* carbon by Laffoley et al. (2014) are based on satellite-derived *Sargassum* wet biomass (2 million tons, Gower and King, 2011) in the North Atlantic, the Caribbean Sea, and the Gulf of Mexico, combined with factors to convert wet biomass to dry biomass and to convert dry biomass to carbon (Table 1). However, the biomass estimates may be subject to large uncertainties due to simple remote sensing algorithms used to quantity *Sargassum* biomass, and such estimates do not include *Sargassum* in the tropical Atlantic in the recently discovered *Sargassum* belt (Wang et al., 2019). Therefore, based on recent advances in *Sargassum* observations and to estimate *Sargassum* carbon explicitly, we take a step-wise approach below.

Specifically, total carbon (*TC*, Pg) contained in *Sargassum* at a given time can be estimated as (Table 1):

$$TC = A \times \alpha \times \beta, \quad (1)$$

where *A* is the total *Sargassum* area (km$^2$), α is the *Sargassum* wet biomass density (kg m$^{-2}$), β is the *Sargassum* carbon concentration (gC kg$^{-1}$ wet biomass).

Although simple in algebra, because the three parameters in the right-hand side of Eq. (1) have been reported in the literature in different ways, caution is required when plugging these numbers in the equation. Specifically,

1) There is a critical difference between "pure" *Sargassum* area and the *Sargassum* "niche" area or sampling area. The former refers to the *Sargassum* area when all the scattered *Sargassum* clumps, mats, and rafts are aggregated together to completely cover the ocean surface (Wang et al., 2019). In contrast, the latter refers to the water area where *Sargassum* can grow (i.e., the "niche" area as reported in Gouvea et al., 2020) or is sampled with net tows (e.g., Parr, 1939; Schell et al., 2015). In Wang et al. (2019), the "pure" *Sargassum* area was reported to be 6000 km$^2$ in the *Sargassum* belt of ~5.5 million km$^2$ during the peak month (Fig. 1a, i.e., the "niche" area). The ratio between the two areas is about 0.1%.
2) Correspondingly, α has also been reported in different ways in the literature. In Wang et al. (2018), it is reported as biomass density of "pure" *Sargassum*, with an average of 3.34 ± 1.34 kg m$^{-2}$ (range: 1.26–6.74 kg m$^{-2}$). In contrast, for the sampled area, α is reported to be 0.50–1.50 g m$^{-2}$ (Parr, 1939), 0.17–0.25 g m$^{-2}$ (Schell et al., 2015), or 0.024–0.84 g m$^{-2}$ (Baker et al., 2018). In the review by Butler et al. (1983), the weighted means from all reported net tows from previous publications were below 0.2 g m$^{-2}$.
3) β has often been reported as gC per dry biomass (Laffoley et al., 2014; Wang et al., 2018). Therefore, it needs to be converted to gC per wet biomass when plugged in Eq. (1). The wet:dry biomass ratio has been reported to be ~5:1 (Butler et al., 1983; Wang et al., 2018) and has been assumed to be ~10:1 (Gouvea et al., 2021).

When the three parameters are used in Eq. (1) to calculate *TC*, they need to be used consistently. Likewise, when they are compared from different reports, the interpretation also requires caution to avoid a flawed comparison (i.e., "apples to oranges"). Therefore, for clarity and simplicity, in this paper "*Sargassum* area" is defined as the area when all *Sargassum* are aggregated to cover the ocean surface completely, while "*Sargassum* niche area" is defined as the water area where *Sargassum* can grow or can be found.

With these definitions, *TC* can be estimated from the reported values of *A*, α, and β. Below we compare mainly two estimates, whose parameterization and *TC* estimates are all listed in Table 1.

The first estimate is provided by Gouvea et al. (2020), who predicted that the Atlantic Ocean could have "a suitable niche area of 227.89 × 10$^4$ km$^2$ and a potential standing stock 82.58 Gg km$^{-2}$ of

**Table 1**
Estimates of various parameters of the Atlantic pelagic *Sargassum*, cited from Gouvea et al. (2020, 2021) and calculated in this study based on Wang et al. (2018 & 2019) and other relevant literature.

| [a]*A*: *Sarg.* area or "niche" area (km$^2$) | α: *Sarg.* wet biomass density (kg m$^{-2}$) | β: *Sarg.* carbon per wet biomass (g kg$^{-1}$) | *TC* (Pg): ($TC = A\alpha\beta$) | References |
|---|---|---|---|---|
| 227.89 × 10$^4$ | [b]82.58 | [c]40 | 7.52 | Gouvea et al. (2020) |
| [d]3 × 6000 during peak month | 3.34 (1.26–6.74) | [e]60 | 3.61 × 10$^{-3}$ | This study, based on Wang et al. (2018 & 2019) and others |
| 2 × 10$^9$ kg wet biomass | | 40 | [f]8 × 10$^{-5}$ | Laffoley et al. (2014) |

[a] Here, the *Sargassum* area is defined as an area when all *Sargassum* is aggregated to fully cover the water (second row), while the "niche" area is defined as an area suitable for *Sargassum* growth (first row). See Eq. (1) for more details.
[b] This number was reported in Gouvea et al. (2020) as wet biomass density. In Gouvea et al. (2021) a dry biomass density of 8.25 kg m$^{-2}$ was reported, which is equivalent to the original 82.58 kg m$^{-2}$ wet biomass density (assuming a 10% dry:wet ratio).
[c] 40% (or 400 g kg$^{-1}$) was reported in Table S4 of Gouvea et al. (2020); in Gouvea et al. (2021) this was clarified to be 4% (or 40 g kg$^{-1}$) of *Sargassum* wet biomass.
[d] The factor of 3 to multiply the reported maximum of 6000 km$^2$ by Wang et al. (2019) is to account for possible underestimates by MODIS over the *Sargassum* belt and for *Sargassum* in Atlantic waters outside the *Sargassum* belt (see text for more details).
[e] This number is calculated from the carbon per dry biomass ratio (~30%) and a wet:dry biomass ratio of 5, both reported in Wang et al. (2018).
[f] This is based on earlier satellite-based biomass estimates (2 × 10$^9$ kg wet biomass, Gower and King, 2011) and the biomass/carbon conversion factors. If the biomass estimates from earlier ship-based net tows (4–11 × 10$^9$ kg wet biomass, Parr, 1939; Stoner, 1983; Butler and Stoner, 1984), with updates from Gower and King (2011) are used, the *Sargassum* carbon will be 1.6–4.4 × 10$^{-4}$ Pg.

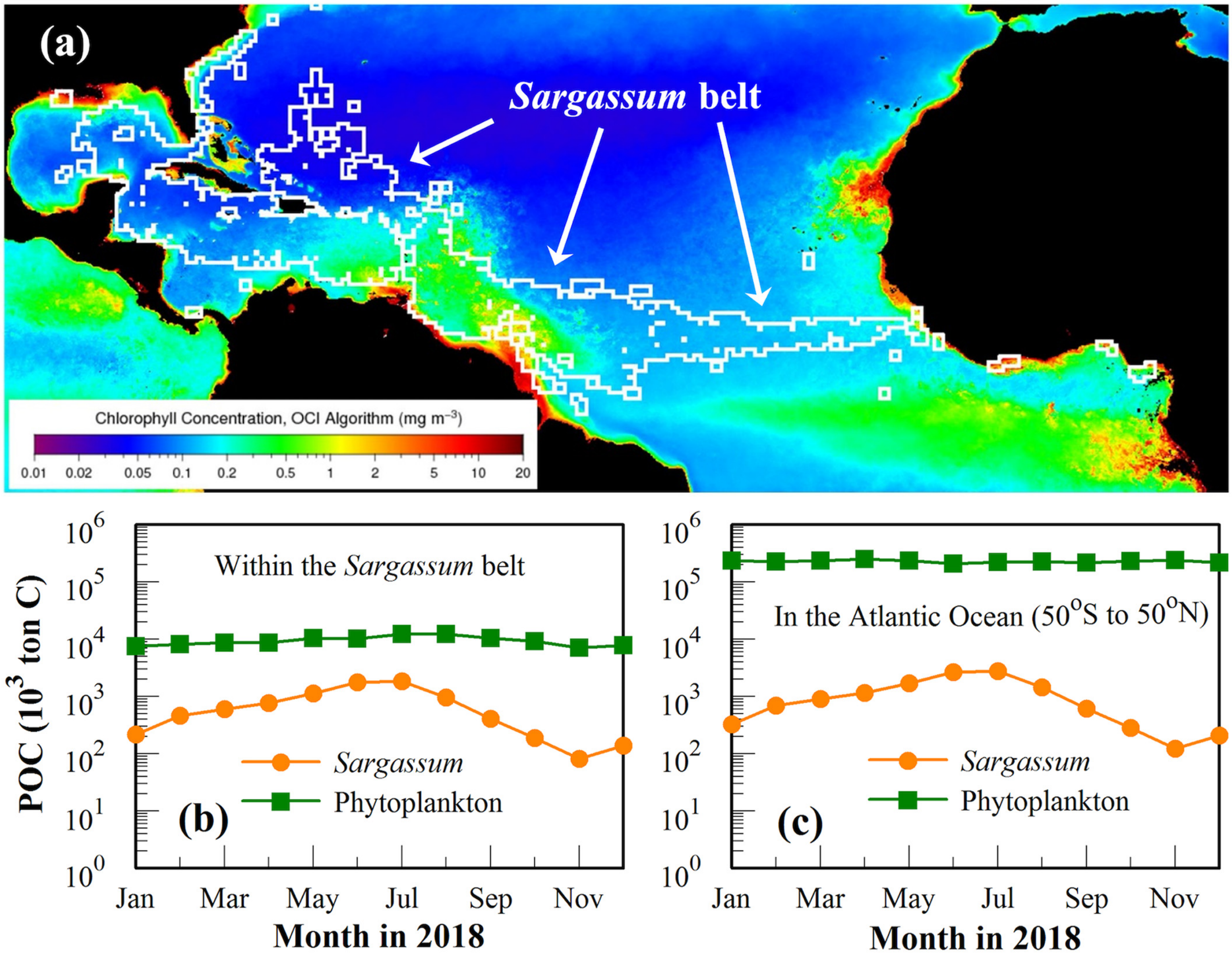


**Fig. 1.** (a) The approximate boundary of the Atlantic *Sargassum* belt (white color) overlaid on a climatological monthly mean chlorophyll concentration map, both for July 2018. (b) Comparison of *Sargassum* carbon and phytoplankton carbon within the *Sargassum* Belt. Their mean ratio is ~7.6%, with the peak of 26.3% in June 2018. Here, phytoplankton carbon was estimated by assuming a 50-m mixed layer depth, and phytoplankton POC data were obtained from NASA. (c) Same as in (b), but the comparison is made over the Atlantic Ocean (50°S – 50°N, 98°W – 15°E) excluding high-latitude waters. The mean ratio is ~0.5%, with the peak of 1.3% in June 2018. The y-axes are presented in log scale to visualize the scale difference better.

floating *Sargassum*." These, combined with the carbon per biomass of 40 gC kg$^{-1}$ *Sargassum*, led to the estimated "7.52 Pg C" in floating *Sargassum* in the Atlantic Ocean (Fig. 1b of Gouvea et al., 2020). A corrigendum by the same authors (Gouvea et al., 2021) clarified that both 82.58 Gg km$^{-2}$ and 40 gC kg$^{-1}$ referred to wet *Sargassum* biomass. This predicted 7.52 Pg *Sargassum* carbon is actually much higher than phytoplankton carbon in the Atlantic Ocean (< 1 Pg C, Fig. 1). However, after literature and mathematical review, this predicted *Sargassum* carbon does not appear realistic.

Indeed, the second estimate in Table 1, provided in this study based on Wang et al. (2018 & 2019) and other literature, suggests that the number of 7.52 Pg *Sargassum* carbon may be overestimated by a factor of ~2000 ($3.61 \times 10^{-3}$ versus 7.52 Pg C) even for the peak months of *Sargassum* blooms (Table 1). For non-peak months, the factor is much higher. Even though the estimate in this study is for the current upper bound of the *Sargassum* carbon standing stock while the Gouvea et al. (2020) estimate is for the future potential *Sargassum* carbon, a difference of >2000 times still appears out of the envelop. Below we elaborate on what caused the dramatic difference in these two estimates.

First, Wang et al. (2019) estimated *Sargassum* area of ~6000 km$^2$ from the Atlantic *Sargassum* belt (i.e., excluding the *Sargasso Sea* and other waters) during the peak month of June 2018, where the area of the belt (i.e., *Sargassum* niche area) is ~5.5 million km$^2$ (Fig. 1a) (compare: the *Sargasso* Sea has an area of ~4.2 million km$^2$, Laffoley et al., 2014). This suggests a mean *Sargassum* areal density of ~0.1% within the belt as a result of scattered *Sargassum* clumps, mats, and/or rafts. Such satellite-based observations have been confirmed by field surveys (Ody et al., 2019). One may argue that due to the large pixel size of the Moderate Resolution Imaging Spectroradiometer (MODIS, ~1 km$^2$), small *Sargassum* mats may not be captured in MODIS imagery, leading to an *underestimate*. While in theory, this is true; in practice, a comparison between MODIS and higher-resolution (10-m) data from Sentinel-2 MSI shows comparable results between the two observations (Wang and Hu, 2020a), possibly due to the high sensitivity (signal-to-noise ratio) of MODIS (Hu et al., 2012). A recent work using 12,025 Planet Dove images (3-m resolution) for the entire Gulf of Mexico suggests that MODIS may underestimate the *Sargassum* area by 50% (Wang and Hu, submitted). Another underestimation factor is possibly due to variable winds, as *Sargassum* mats may be submersed under high winds (Woodcock, 1993), yet such an underestimation is mostly <50% (Woodcock, 1993). After considering all these factors, the *Sargassum* area in the Atlantic belt even during the peak month is unlikely to exceed $2 \times 6000$ km$^2$. Even after considering the Atlantic waters outside the *Sargassum* belt (e.g., the *Sargasso Sea*, South Atlantic, including the Brazilian coast), the total *Sargassum* area in these waters is unlikely to exceed 6000 km$^2$. This is because *Sargassum* mats in these waters are typically small and require net tows to quantify (i.e., $< 0.25$ g m$^{-2}$ with most around or $<0.1$ g m$^{-2}$ from all literature, see Parr, 1939; Butler et al., 1983; Stoner and Greening, 1984; Schell et al., 2015; Baker et al., 2018), and 0.1 g m$^{-2}$ is equivalent to ~0.03% areal density (assuming $\alpha = 3.34$ kg m$^{-2}$, see below) for the towed area, 3 times lower than areal density in the *Sargassum* belt during the peak month (~0.1%). Indeed, earlier ship-based estimates of *Sargassum* wet biomass of $4–11 \times 10^9$ kg (Parr, 1939; Stoner, 1983; Butler and Stoner, 1984) is equivalent to only 1200–3300 km$^2$ *Sargassum* area. The <0.1% density is also consistent with the review of Huffard et al. (2014), who reported $0.0 \pm 0.5$% and $0.0 \pm 0.0$% for the *Sargassum* growth zone. Overall, for the entire Atlantic, even during the peak month after accounting all potential factors leading to an underestimate, the *Sargassum* area is expected not to exceed $3 \times 6000$ km$^2$ (Table 1). This is still 126 times lower than the *Sargassum* niche area of $227.89 \times 10^4$ km$^2$ as predicted in Gouvea et al. (2020). Note that such a *Sargassum* niche area is equivalent to a wide band in the Atlantic ($4^o \times 50^o$), or half of the *Sargassum* belt size (Fig. 1a). While such a *Sargassum* niche area (including its spatial distribution, see Fig. 2b of Gouvea et al., 2020) is certainly reasonable by definition, applying the factor of $\alpha = 82.58$ kg m$^{-2}$ uniformly to the area is not, even after considering the "potential growth" in the future. Indeed, if this were the case, it suggests that the entire niche area would be *completely* covered by thick *Sargassum* mats, a true ecological disaster in many aspects.

Second, for *Sargassum* wet biomass density ($\alpha$), 43 quadrat measurements in the Gulf of Mexico and the Strait of Florida showed 1.26–6.74 kg m$^{-2}$ ($3.34 \pm 1.34$ kg m$^{-2}$ *Sargassum* wet biomass) (Wang et al., 2018), 27 times lower than the Gouvea et al. (2020) estimates of 82.58 kg m$^{-2}$. In the supplemental Table S4 of Gouvea et al. (2020), although it is claimed that the listed numbers correspond to "floating *Sargassum* biomass," they actually refer to different measures and represent an inconsistent comparison. For example, Sissini et al. (2017) explicitly stated that "the biomass accumulation of the stranded *Sargassum* was estimated during four events, peaking in 98 kg m$^{-2}$ wet weight on a beach on the Amazonian coast." Yet this number was still used in Table S4 of Gouvea et al. (2020) to represent "floating *Sargassum*." Likewise, most numbers in Table S4 (e.g., those from Stoner and Greening, 1984) refer to those estimated from net tows and they represent *Sargassum* biomass density in the towed water area, which has a completely different meaning from "pure" *Sargassum*. The density of 82.58 kg m$^{-2}$ (*Sargassum* wet biomass) used in Gouvea et al. (2020, 2021) appears completely out of the envelop when applied uniformly to the entire *Sargassum* niche area where in reality *Sargassum* mostly covers <0.1% (or $<0.1$ g m$^{-2}$) of surface area, as suggested by field measurements (Parr, 1939; Butler et al., 1983; Stoner and Greening, 1984; Schell et al., 2015; Baker et al., 2018). The density of 82.58 kg m$^{-2}$ used for the *Sargassum* niche area is 820,000 times higher than the field measured $<0.1$ g m$^{-2}$.

Third, for *Sargassum* carbon per wet biomass ($\beta$), from 288 *Sargassum* samples collected from both Gulf of Mexico and the Strait of Florida, the mean dry/wet biomass ratio was determined to be about 20% (Wang et al., 2018). This, multiplied by the carbon per dry biomass factor of $27.16 \pm 2.23$% (Wang et al., 2018), would result in ~6% carbon per wet biomass, or $\beta \approx 60$ g C kg$^{-1}$ wet *Sargassum*. The 20% dry/wet biomass ratio has also been reported from earlier studies (Butler et al., 1983), and the 27.16% *Sargassum* carbon per dry biomass is also very close to those reported in Lapointe et al. (1992). The 6% *Sargassum* carbon per wet biomass is close to ~40% used in Table S4 of Gouvea et al. (2020) when the latter refers to *Sargassum* carbon per dry biomass, assuming a wet:dry ratio of 10 (Gouvea et al., 2021).

From these calculations, for the entire Atlantic Ocean, there appears no way to have anywhere close to the projected 7.52 Pg *Sargassum* carbon even during the peak month. Even after considering the upper bound of *Sargassum* amount in which MODIS-based estimates are multiplied by a factor of 3 to account for the wind effect and for the small "missing" clumps as well as *Sargassum* in Atlantic waters (including the Brazilian coast) other than the belt, *Sargassum* carbon is estimated to be at most $4 \times 10^{-3}$ Pg during the peak month, which is negligible in the context of climate at a basin or global scale (Fig. 1). This estimate is 45 times higher than provided in Laffoley et al. (2014) (Table 1) mainly because 1) the latter estimate is based on earlier satellite-based biomass estimates, which may be subject to large algorithm-induced uncertainties, 2) the latter estimate does not include *Sargassum* in the Tropical Atlantic Ocean, and 3) the estimate in this study is purposely biased high in order to provide an upper bound. A realistic estimate is that total carbon in the Atlantic pelagic *Sargassum* should be lower than $3.61 \times 10^{-3}$ Pg (this study) but higher than $8 \times 10^{-5}$ Pg (Laffoley et al., 2014) during the peak months of June – July.

However, this does not mean *Sargassum* is not important in affecting the total carbon budget and carbon cycling at a *local* scale, for example within the *Sargassum* belt. Using simple approximations, Wang et al. (2018) estimated that "total *Sargassum* carbon can account for ~18% of the phytoplankton carbon over the entire study region during the peak months," where the "entire study region" refers to the Caribbean Sea and central West Atlantic Ocean (0 – 23$^o$N, 88 – 29$^o$W). This percentage sharply decreases to a negligible number when the Atlantic waters outside the *Sargassum* belt are included, due simply to a matter of scale difference: while the Atlantic Ocean covers a surface area of ~100 million km$^2$, the *Sargassum* belt is only 5.5 million km$^2$ (Fig. 1a) and the *Sargassum* niche area is only 2.3 million km$^2$ (Gouvea et al., 2020). Such a scale-induced difference is clearly revealed in Fig. 1b & 1c. As a rough estimate, within the *Sargassum* belt, *Sargassum* carbon is at most 7.6% of phytoplankton carbon at an annual scale, and the maximum ratio during the peak *Sargassum* months is 26.3%. When the scale is enlarged to most of the Atlantic Ocean (50°S – 50°N, 98°W – 15°E) without the polar regions, the annual mean ratio of *Sargassum* carbon to phytoplankton carbon decreases sharply to 0.5%. At a monthly scale, the ratio ranges between 0.1% in the winter months and 1.3% in the summer months. If the polar regions are included, the ratio is even lower. At a global scale, phytoplankton carbon is 3–4 times higher than in the Atlantic Ocean. Therefore, whether *Sargassum* carbon is important in carbon stocks depends on the spatial scale: local, regional, basin-wide, or global.

## 3. Carbon fixation and sequestration

Understanding carbon sequestration by pelagic *Sargassum* requires the knowledge of both *Sargassum* carbon fixation (i.e., net primary production or NPP) and *Sargassum* carbon burial rate on the ocean floor. Although there is a lack of measurement on the latter, the limited measurements on the former can lead to some simple calculations based on the above carbon stock estimates, especially when presented in the perspective of carbon fixation and sequestration by phytoplankton as both pelagic *Sargassum* and phytoplankton are abundant in the Atlantic Ocean.

A literature search suggests that measurements of pelagic *Sargassum* NPP are very scarce. Lapointe (1995) reported *Sargassum* NPP of up to 12 gC day$^{-1}$ kg$^{-1}$ dry biomass while most other measurements were lower (e.g., ~ 9 gC day$^{-1}$ kg$^{-1}$ dry biomass (Lapointe and Hanisak, 1985), 4.7 gC day$^{-1}$ kg$^{-1}$ dry biomass (Laffoley et al., 2014), all after assumptions of 10 h a day and 1 kg dry biomass m$^{-2}$). Therefore, the upper bound for *Sargassum* NPP is 12 gC m$^{-2}$ day$^{-1}$. Even if some of the fixed carbon may be released in the form of dissolved organic carbon (DOC), measurements by Powers et al. (2019) indicate that this release is at most a few percent of the fixed carbon (i.e., 23 to 41 μg C g$^{-1}$wet biomass hr$^{-1}$). For phytoplankton, net productivity for the open ocean is lower but mostly $>0.3$ gC m$^{-2}$ day$^{-1}$. However, after taking into account the scale difference ($6000 \times 3$ km$^2$ *Sargassum* area during the peak month in the Atlantic Ocean versus >100 million km$^2$ Atlantic Ocean surface area), total phytoplankton NPP is at least 400 times higher than total *Sargassum* productivity for any given month.

A rough estimate in Fig. 2 shows the upper bound of *Sargassum* NPP as compared with phytoplankton NPP. To provide a perspective on scales, the comparison is made for two regions: a static region encompassing the *Sargassum* belt during the peak month of July 2018 (5.5 million km$^2$, Fig. 1a), and the entire Atlantic Ocean excluding the polar regions. For the former region, the *Sargassum* area is assumed to be 2 times of those observed from MODIS (i.e., reported in Wang et al., 2019, see rationales above behind the factor of 2). For the latter region, the *Sargassum* area is assumed to be 3 times of those observed from MODIS (see rationales above behind the factor of 3). For both regions, the *Sargassum* NPP rate is assumed to be the maximum reported value of 12 gC m$^{-2}$ day$^{-1}$ throughout the year. Even for this upper bound estimate, *Sargassum* NPP is much lower than phytoplankton NPP within the *Sargassum* belt. For the Atlantic Ocean, *Sargassum* NPP is negligible (<0.2%) when compared with phytoplankton NPP.

Considering the huge difference between the total *Sargassum* area and the Atlantic Ocean's surface area, this result is not surprising. Indeed, the *Sargasssum* NPP estimates here are purposely biased high in order to provide an upper bound, while in reality they may be much lower. Paraguay-Delgado et al. (2020) used an X-ray energy dispersion method to estimate carbon fixation by *Sargassum*. They estimated that the total $CO_2$ fixed by the pelagic *Sargassum* in the *Sargassum* belt ranged from 0.5 to 6.5 million tons per year between 2011 and 2019 (excluding 2013), corresponding to 0.13–1.63 million tons of fixed carbon every year. Our estimates of 6 million tons of fixed carbon during the peak month is much higher because we used the maximum carbon production rate reported in the literature (12 gC m$^{-2}$ day$^{-1}$) and we also multiplied the MODIS-based *Sargassum* amount by a factor of 3 to account for *all* pelagic *Sargassum* in the Atlantic (including those not captured by MODIS and those outside the *Sargassum* belt). Even though, when considering the entire Atlantic Ocean, this amount is negligible.

However, NPP represents only carbon fixation instead of carbon sequestration, as most of the fixed carbon may be recycled. The question is how much of this fixed carbon can eventually reach the seafloor to be permanently buried or become sedimentary rock. Unfortunately, direct estimates of macroalgae carbon burial rate are not available (Krause-Jensen et al., 2018), and *Sargassum* data on this aspect are too scarce to make reliable conclusions. Using samples collected from the *Sargassum* belt, Baker et al. (2018) showed higher *Sargassum* biomass density on the ocean floor than in the surface ocean; yet given the limited sampling sites and unknown time for the surface *Sargassum* to reach the ocean floor, it is difficult to estimate a rate. On the other hand, the thermogravimetric analysis of Paraguay-Delgado et al. (2020) suggests that approximately 5% of the *Sargassum* fixed carbon is converted into calcite. Because calcite is one of the best ways to retain the fixed carbon from carbon cycling and in the long run it may be set as a sedimentary rock, carbon sequestration by *Sargassum* might be approximated by *Sargassum* NPP × 5%. As a comparison, the carbon burial rate from phytoplankton NPP is only ~0.3% (i.e., of the 48 Pg C fixed per year, only 0.15 Pg C is buried in the seafloor, Muller-Karger et al., 2005). Therefore, even though *Sargassum* NPP is negligible compared to phytoplankton NPP in the Atlantic Ocean, depending on the region considered, carbon sequestration by *Sargassum* may still be significant as compared to carbon sequestration by phytoplankton.

This argument is illustrated using Fig. 2 and Table 2 as an example. During 2018, phytoplankton NPP is 0.5 Pg C in the *Sargassum* belt and 14 Pg C in the Atlantic, compared with *Sargassum* NPP of 0.017 Pg C and 0.026 Pg C, respectively (Fig. 2). After applying the 0.3% phytoplankton carbon burial rate and 5% *Sargassum* burial rate, total carbon sequestration by phytoplankton is 1.5 × 10$^{-3}$ Pg C in the *Sargassum* belt and 42 × 10$^{-3}$ Pg C in the Atlantic Ocean, while total carbon sequestration by *Sargassum* is 0.85 × 10$^{-3}$ Pg C and 1.3 × 10$^{-3}$ Pg C, respectively. Therefore, within the *Sargassum* belt, carbon sequestration by *Sargassum* is 57% of that by phytoplankton, representing a significant portion of total carbon sequestration by marine plants. Even for the Atlantic Ocean (excluding high-latitude waters), carbon sequestration by *Sargassum* is 3% of that by phytoplankton. Although small, it is not negligible. Only when this comparison is put in the global context, carbon sequestration by *Sargassum* may be negligible.

For clarity, the above results are summarized in Table 2. To put them in the context of earlier estimates, those provided by Laffoley et al. (2014) are also listed in the last row of Table 2, where *Sargassum* carbon sequestration is listed as the *Sargassum*-produced non-reactive recalcitrant rDOC, as this part of DOC will not be recycled and therefore may be considered as being removed from the atmosphere. The large difference in *Sargassum* carbon sequestration between these two estimates (1.3 × 10$^{-3}$ versus 1.6 × 10$^{-5}$ Pg) mainly comes from the *Sargassum* NPP estimates (2.6 × 10$^{-2}$ versus 2.7 × 10$^{-4}$ Pg), because earlier estimates did not consider *Sargassum* in the tropical Atlantic and because our *Sargassum* NPP estimates were purposely biased high by using the maximum reported production rate and by applying a factor of 3 to the satellite-derived *Sargassum* biomass (see above). If a more realistic and time-dependent *Sargassum* carbon production rate (currently unknown) and a factor of 1.5 instead of 3 is applied to satellite-derived *Sargassum* biomass for the Atlantic, both our *Sargassum* NPP and carbon sequestration estimates may be 5–10 times lower. Such large

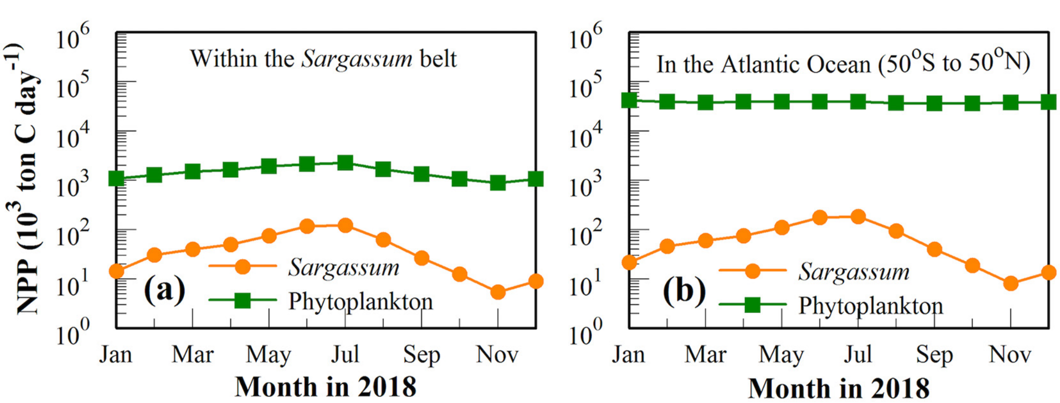


**Fig. 2.** Comparison of *Sargassum* NPP and phytoplankton NPP within the Atlantic *Sargassum* belt (a) and for the Atlantic Ocean (b). The belt is illustrated in Fig. 1a, while the Atlantic Ocean is defined as 50°S – 50°N, 98°W – 15°E (i.e., excluding high-latitude waters). Within the *Sargassum* belt, the mean ratio is ~3.2% with the peak ratio of 8.3% in summer and 1.0% in winter. Over the Atlantic Ocean, the mean ratio is only ~0.2%, with a peak ratio of 0.5% in summer and 0.03% in winter. For the entire year, phytoplankton NPP is 0.5 Pg in the *Sargassum* belt and 14 Pg in the Atlantic Ocean, compared with *Sargassum* NPP of 0.017 Pg and 0.026 Pg, respectively. The monthly phytoplankton NPP data were downloaded from http://sites.science.oregonstate.edu/ocean.productivity/index.php (Behrenfeld and Falkowski, 1997).

**Table 2**
Annual carbon fixation (i.e., NPP) and carbon sequestration by pelagic *Sargassum* and phytoplankton in the Atlantic Ocean during 2018. The comparison is made for two regions: the region within the *Sargassum* belt (Fig. 1a), and the Atlantic Ocean excluding high-latitude waters (50°S – 50°N, 98°W – 15°E). The graphical format of the NPP estimates is presented in Fig. 2, while sequestration rates are discussed in the text. The last row shows global *Sargassum* NPP and recalcitrant DOC (rDOC) based on the estimated rate of 6% (Laffoley et al., 2014). Note that both *Sargassum* NPP and *Sargassum* carbon sequestration can be 5–10 times lower than presented in the first row (see text for more details).

| | NPP in the *Sargassum* belt (Pg C) | NPP in the Atlantic (Pg C) | Sequestration rate | Sequestration in the belt (Pg C) | Sequestration in the Atlantic (Pg C) |
|---|---|---|---|---|---|
| *Sargassum* | 0.017 | 0.026 | [a]5% | $0.85 \times 10^{-3}$ | $1.3 \times 10^{-3}$ |
| Phytoplankton | 0.5 | 14 | [b]0.3% | $1.5 \times 10^{-3}$ | $42 \times 10^{-3}$ |
| Ratio | 3.4% | 0.19% | 16.7 | 57% | 3.1% |
| Laffoley et al. (2014) | | $2.7 \times 10^{-4}$ | [c]6% | | $1.6 \times 10^{-5}$ |

[a] 5% of the *Sargassum* fixed carbon is converted into calcite (Paraguay-Delgado et al., 2020), which may be set as sediment rock and removed from carbon cycling.
[b] 0.3% of the phytoplankton fixed carbon is buried in the seafloor (Muller-Karger et al., 2005).
[c] 6% refers to the rDOC rate of *Sargassum* fixed carbon (Laffoley et al., 2014).

uncertainties emphasize the need to measure *Sargassum* primary production under different environmental conditions.

The above carbon removal from *Sargassum* is from natural processes. Another process may be through physical removal by humans as part of the mitigation efforts to minimize the impacts of *Sargassum* inundation in coastal waters and on beaches. Although such data is mostly unavailable, data collected by researchers in Mexico showed that in Puerto Morelos (Quintana Roo, Mexico) alone, several hotels removed about 0.1 million tons of *Sargassum* wet biomass (equivalent to $0.4 \times 10^{-5}$ Pg) in 2018 (Salter et al., 2020). Although this is only 0.3% of the carbon sequestration from natural processes ($1.3 \times 10^{-3}$ Pg year$^{-1}$), it does not include *Sargassum* removal along many coastal waters and beaches in the Caribbean Sea, east coast of Florida, and west coast of Africa. If all removals are combined, the portion will be much higher.

From the above analysis, it is clear that although carbon fixation by *Sargassum* in the Atlantic Ocean is a negligible portion of carbon fixation by phytoplankton, carbon sequestration by *Sargassum* is not. This is especially true for carbon sequestration within the *Sargassum* belt. Such a contrast is attributed to the much higher carbon sequestration efficiency in *Sargassum* through sinking, sedimentation, and release of rDOC as well as to physical removals by human beings. Although this is still "negligible in terms of mitigating effects caused by climate change or human activities" when compared with the total $CO_2$ amount generated by the USA (Paraguay-Delgado et al., 2020), increased *Sargassum* amount in the Atlantic and/or increased removal efforts in future years may make it non-negligible. This is of particular importance as carbon sequestration by pelagic *Sargassum* may play an important role in blue carbon strategies when all macroalgae (including kelps and those growing on rocks) are considered (Krause-Jensen et al., 2018; Ortega et al., 2019). On the other hand, the large uncertainties in the estimates of *Sargassum* carbon fixation and sequestration, as shown here, call for more field measurements of *Sargassum* NPP and carbon burial rate under different conditions.

Finally, although not being as well-known as the Atlantic pelagic *Sargassum*, *Sargassum horneri* in the East China Sea of the western Pacific is another major macroalgae species that can float on the ocean surface (Kim et al., 2019) and reach the ocean floor (Kokubu et al., 2019). However, satellite-based estimates suggest that the *Sargassum horneri* area is typically <530 km$^2$ (Qi et al., 2017) or < 10% of the *Sargassum* area in the Atlantic *Sargassum* belt during the peak month. Therefore, its contribution to carbon fixation and carbon sequestration at both basin and global scales should be much lower than from the Atlantic pelagic *Sargassum*, although such a contribution at a local scale may be important.

## 4. Concluding remarks

While the objective of this short note is not to provide exact estimates on either the Atlantic *Sargassum* carbon standing stock, carbon fixation, or carbon sequestration due to several unknown factors, the simple calculations, based on field measurements and satellite estimates, show that although pelagic *Sargassum* carbon stock and carbon fixation may be important at a local scale (e.g., within the *Sargassum* belt), they are not at a basin scale or a global scale. The Atlantic *Sargassum*'s carbon sequestration is a significant portion of carbon sequestration by phytoplankton at a local scale, and a non-negligible portion at a basin scale, although it is still negligible in terms of mitigating effects of climate changes at a global scale. More measurements are required to understand how *Sargassum* carbon fixation responds to changes in environmental conditions and to better quantify *Sargassum* carbon sequestration rate. On the other hand, numerous other studies have shown its importance in affecting local fisheries, environment, tourism, human health, management, and economy, thus calling for more research to understand the underlining mechanisms behind the recent blooms and to quantify their various impacts.

## CRediT authorship contribution statement

**Chuanmin Hu:** Conceptualization, Supervision, Project administration, Methodology, Writing - original draft and revision, Funding acquisition. **Mengqiu Wang:** Data curation, Methodology, Writing- original draft and revision. **Brian Lapointe:** Supervision, Writing – review & editing, Funding acquisition. **Rachel Brewton:** Investigation, Writing – review & editing. **Frank Hernandez:** Investigation, Writing – review & editing, Funding acquisition.

## Declaration of competing interest

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.

## Acknowledgements

This work was funded by the U.S. NASA Ocean Biology and Biogeochemistry Program (NNX16AR74G, 80NSSC20M0264) and Ecological Forecast Program (NNX17AE57G), and NOAA RESTORE Science Program (NA17NOS4510099). We thank NASA for providing phytoplankton POC data and Oregon State University for providing phytoplankton NPP data. We thank the five anonymous reviewers for their insightful comments and suggestions.

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