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Evolution of the riverine nutrient export to the Tropical Atlantic over the last 15 years: is there a link with *Sargassum* proliferation?

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The Tropical Atlantic is facing a massive proliferation of *Sargassum* since 2011, with severe environmental and socioeconomic impacts. As a contribution to this proliferation, an increase in nutrient inputs from the tropical rivers, in response to climate and land use changes or increasing urbanization, has been often suggested and widely reported in the scientific and public literature. Here we discuss whether changes in river nutrient inputs could contribute to *Sargassum* proliferation in the recent years or drive its seasonal cycle. Using long-term *in situ* and satellite measurements of discharge, dissolved and particulate nutrients of the three world largest rivers (Amazon, Orinoco, Congo), we do not find clear evidences that nutrient fluxes may have massively increased over the last 15 years. Moreover, focusing on year 2017, we estimate that along the year only 10% of the *Sargassum* biomass occurred in regions under river plume influence. While deforestation

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and pollution are a reality of great concern, our results corroborate recent findings that hydrological changes are not the first order drivers of *Sargassum* proliferation. Besides, satellite observations suggest that the major Atlantic river plumes suffered a decrease of phytoplankton biomass in the last two decades. Reconciling these observations requires a better understanding of the nutrient sources that sustain *Sargassum* and phytoplankton growth in the region.

Context

Before 2010, holopelagic *Sargassum* spp. were preferentially found in the Sargasso Sea and in the Gulf of Mexico. They now develop in large quantities on the southern part of the North Atlantic between 0 and 10°N forming a '*Sargassum* belt' stranding in millions of tons on the coasts of the Lesser Antilles, Central America, Brazil and West Africa. (e.g., Smetacek and Zingone 2013, Wang and Hu 2016, Langin 2018, Wang et al. 2019).

Satellite imagery pointed to the presence of large amounts of *Sargassum* in areas under seasonal influence of the Amazon plume (Gower et al. 2013, Sissini et al. 2017, Oviatt et al. 2019, Wang et al. 2019) raising the hypothesis that river nutrient fluxes might play a role in this proliferation (Langin 2019, Wang et al. 2019, Oviatt et al. 2019). A possible influence of the Congo has also been invoked in several studies (Djakouré et al. 2017, Oviatt et al. 2019). A recent study by Johns et al. (2020), however, did not find strong evidence to support this hypothesis as there appears to be a spatiotemporal mismatch between *Sargassum* occurrence and these riverine sources of nutrients. Given the importance of this question and the present discrepancies in the scientific literature we find it important to examine to which extent the riverine source of nutrients may contribute to the proliferation of pelagic *Sargassum*. Indeed, several elements give support to a possible influence of the riverine sources of nutrients. First, rivers export nitrogen and phosphorus, which are key limiting nutrients required for *Sargassum* growth (Lapointe 1986, 1995). Specifically, the Amazon also contains important concentrations of dissolved organic substrates that could be an important source of nutrient for *Sargassum* growth as reviewed in Oviatt et al. (2019). Second, the Tropical Atlantic receives the fresh and nutrient rich waters of the three largest rivers on the planet - in terms of flow (Amazon, 209 000 $m^3 s^{-1}$, Congo, 42 000 $m^3 s^{-1}$ and Orinoco, 35 000 $m^3 s^{-1}$), which alone represent 21% of the total global riverine flow (Milliman and Farnsworth, 2011). Their low-saline and productive plumes extend thousands of kilometers far offshore (Muller-Karger et al. 1988, Signorini et al. 1999). Third, the watersheds undergo strong climatic and anthropogenic pressures that are thought to have

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the potential to modify oceanic biogeochemical systems. For instance, Seitzinger et al. (2010) estimated that the total river input of nitrogen to the coastal seas has approximately doubled since the 70s, with South America representing ~20% of the global increase. The Amazon basin already shows some signs of a transition to a disturbance-dominated regime in response to agricultural expansion and climate variability (Davidson et al. 2012). The region experiences a strong anthropogenic pressure associated with a rapid urbanization (Richards and VanWey, 2015), intense hydropower dam construction (Latrubesse et al. 2017), and increase of mining and oil extraction contamination (e.g. Moquet et al., 2014). The overall consequences of these changes in terms of nutrient budget remain uncertain since they can act as a source or a sink of nutrients.

In this context, the long-term evolution of the continental nutrient export to the Tropical Atlantic is investigated on the basis of *in situ* observations of the major dissolved and particulate nutrients exported by the three main rivers of the basin (Amazon, Orinoco and Congo). Satellite estimates of chlorophyll provide an independent set of observations to monitor the long-term changes of biological activity in the large river plumes. Finally, the large-scale seasonal distribution of *Sargassum* for year 2017 is confronted to numerical experiments of river plume dispersal. We focused on this year because basin scale *Sargassum* fractional coverage observations from MODIS were available (Berline et al. 2020), with concurrent observations carried out during two cruises in the Tropical Atlantic (Ody et al. 2019). Year 2017 was the third most important year of the decade in terms of quantity of Sargassum (as inferred from time series in Wang et al. 2019), with a seasonal pattern that closely mirrors the averaged seasonal pattern from Wang et al. (2019).

River nutrient fluxes

The productivity of the *Sargassum* is enhanced by N (nitrogen) and P (phosphorus) availability (Lapointe, 1995). At global scale, the rivers carry N to oceanic coastal zone in dissolved and particulate forms in almost equal proportion (Joo et al., 2013) while P is mainly exported as particulate form (90-95% of the total P flux to the ocean; Ruttenberg, 2004). About 25-45% of the particulate P (Ruttenberg, 2004) and a significant proportion of particulate N are reactive in the sea water and bioavailable for marine organisms including the seaweed. The dissolved and particulate N and P fluxes measured or estimated at the seaward-most stations for the Amazon, Orinoco, and Congo basins are shown in Figure 1 for the last two decades. These data were collected by the SO-HYBAM observatory and are presented together with riverine flux calculation methods in the supplementary material.

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For the three rivers, the largest input of N is provided by the dissolved organic matter. Dissolved organic nitrate delivered by the Amazon is thought to become bioavailable in the offshore fraction of the plume through bacterial and photochemical transformations (Medeiros et al. 2015). For the Amazon, this flux appears to regularly increase from 2004, apart from maxima in years 2007 and 2008. Observations for the Orinoco suggest a doubling of this flux over the last 15 years (Figure 1). The particulate fluxes of N, estimated from remote sensing, is also expected to contribute to nutrient supply through desorption of the shelf (Demaster and Aller 2000). It is stable for the three rivers. The dissolved inorganic N flux, computed from NO_3^- in situ measurements, show larger values during the last decade for the three rivers (Figure 1a-c). Before 2013, values above the detection limit (0.01 mg/l) were of similar magnitude than independent Amazon (Richey et al. 2009, Ward et al. 2015, Doherty et al. 2017), Orinoco (Lewis and Saunders, 1989) and Congo (Descy et al., 2016) water analyses. They did not show a marked evolution over this period. From the years 2013-2014, the average concentration of NO_3^- has increased for the three rivers. On the one hand, the scatter of the measured concentrations is so high that it is difficult to determine how significant the NO_3- increase really is. On the other hand, the more frequent recording of high NO_3^- fluxes is of concern and suggests a potential evolution of the dissolved NO_3^- export that needs to be investigated. However, it should be noted that the marked changes in terms of NO_3^- for the different rivers occurred 2-3 years after the first massive proliferation of 2011.

In the Amazon river, the largest amount of P is delivered in particulate form (Figure 1g). The importance of the particulate P is in line with observations by Berner and Rao (1994) who conclude that the solubilization of P from bacterial decomposition of river-transported organic matter and desorption from ferric oxide/hydroxide may result in an effective flux of reactive P about three times greater than that carried only in dissolved form. This particulate flux shows a slight decrease over the last two decades, while the inorganic and organic dissolved fluxes remained stable. The P fluxes for the Orinoco and Congo are one order of magnitude smaller than those of the Amazon.

So, observations show different long-term trends of inorganic, organic and particulate fluxes of N and P. No direct and clear relationship with *Sargassum* growth can be drawn, neither in terms of long-term evolution, nor in terms of interannual variability (e.g. no major peak of nutrient fluxes was observed during the record *Sargassum* years 2015 and 2018, and there is no clear

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relation with the basin scale Sargassum biomass time series from Wang et al. 2019). Large uncertainties remain in the nutrient fluxes estimation and the fate of these nutrients in the open ocean, but these results already question whether the order of magnitude of the observed trends and variability are large enough to contribute to the inter-annual variability of the oceanic biological response.

Link with changes in plume productivity and *Sargassum* distribution

The diversity of the nutrient trends and the lack of knowledge on the lability of the dissolved and particulate riverine material render uncertain the assessment of the long-term evolution of the riverine fertilization of the ocean. As an independent marker of possible changes in the nutrient export by the large tropical Atlantic rivers, the long-term evolution of surface chlorophyll estimated from satellite ocean color is now analyzed. Chlorophyll is the main pigment in phytoplankton and here we use chlorophyll as a proxy of phytoplankton biomass. As it has been evidenced for the Mississippi in the northern Gulf of Mexico (Lohrenz et al. 1997, Rabalais et al. 2002, Wysocki et al. 2016), we expect that fluctuations in riverine nutrients alter the dynamics of phytoplankton growth and thus phytoplankton biomass in the large tropical river plumes. The difference between the "*Sargassum* period" (2011-2018) and the years before (2003-2010) reveals an overall decrease of the chlorophyll concentration in the tropical Atlantic (Figure 2b). This decline is sharper in the Amazon, Orinoco, and Congo plume regions. Since Chlorophyll retrieval from space is subject to large discrepancies between the different available products, we compared five monthly chlorophyll products from three different groups (GlobColour, NOAA, and CCI). For the three rivers considered, four out of the five different products show a consistent decrease of Chlorophyll concentration in the plume areas (Figure S5).

The basin scale decrease of chlorophyll evidenced in Figure 2b is in line with the study by Gregg and Rousseau (2019) that suggested that global net ocean primary production has experienced a small but significant decline in the 18-year satellite records from 1998 to 2015, in response to shallowing surface mixed layer depth, decreasing nitrate supply and changes in the phytoplankton communities. Chlorophyll concentrations in river plumes exhibit a larger decrease. The underlying cause of these changes in the chlorophyll content of the plumes is difficult to ascertain from observations only. It is worth mentioning that 1) colored detrital material contributes to total light attenuation in the blue region of the spectrum where chlorophyll-a also absorbs strongly (Fournier et al. 2015) which could lead to large errors in

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ocean color retrievals, 2) the response of the productive plumes may not only depend on the riverine nutrient flux but on other variables such as temperature, stratification, turbidity, or dust deposition. But this decrease, whether it is caused by a decrease of plume productivity or weaker discharge of dissolved colored material (which is not observed in SO-HYBAM observations of organic and particulate nutrient fluxes, Figure 1) is difficult to reconcile with the hypothesis of an overall increase in fertilization by tropical rivers in recent years. A better understanding of the river plume biogeochemistry is required, together with analysis of possible competing growth dynamics between phytoplankton and *Sargassum*.

The seasonal distribution of *Sargassum* for year 2017 is shown in Figure 3 together with the chlorophyll concentrations. The *Sargassum* bloom during the first 6 months of the year occurs preferentially in the Intertropical Convergence Zone (ITCZ; located between the equator and 10°N), where chlorophyll is relatively high compared to the surrounding subtropical oligotrophic area. To our knowledge, the causes of the high chlorophyll level have not been identified, but could be the result of diatoms-diazotroph assemblages (Subramanian et al. 2008, Schlosser et al. 2014), atmospheric deposition of dust (Yu et al. 2015), or biomass burning emissions (Barkley et al. 2019). Yet, the presence of relatively high chlorophyll concentration indicates nutrient availability that may participate to sustain *Sargassum* growth.

Interestingly, we remark that during September-October, when the North Brazil Current retroflects and transports the Amazon riverine freshwater to the east, the abundance of *Sargassum* in the plume area between 60°W and 40°W, is drastically reduced relative to the two previous months. The North Brazil Current is mainly fed by waters originating from the equatorial area and the southern Tropical Atlantic (Johns et al. 1998) where no massive proliferation of Sargassum was observed in the previous months. Our interpretation is that the weak abundance of Sargassum in the plume at this time is mainly controlled by advection of low *Sargassum* water in the region. The low salinity of the plume could also limit the proliferation of Sargassum there. Indeed, culture experiments of *Sargassum natans* and *Sargassum fluitans* described in Hanisak and Samuel (1987) revealed some dependence of their growth rate to salinity. A reduction in salinity from 36 to 30 caused a reduction in the growth rates by almost half, and no growth was observed for salinity below 18. This effect may likely limit the fertilizing effect of the nutrient rich river plumes.

The river plume dispersion numerical experiment (Figure 3) also reveals that the central Atlantic is not under the influence of the Amazon plume during the first half of the year. The

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largest coincidence between the plume and *Sargassum* distribution occurs in June-July-August (Figure 4), when the Amazon plume extends toward the Lesser Antilles. This is in line with the analysis by Gouveia et al. (2019) that showed that the Amazon plume fingerprints on oceanic primary productivity spatio-temporal variability are restricted to the western Tropical Atlantic. The first 6 months of the year appear to be crucial for the occurrence of *Sargassum* along the south American and Caribbean coasts a few months later (Wang and Hu 2017, Putman et al. 2018, Wang et al. 2019, Berline et al. 2020). Even if Amazon river fertilization could contribute to the seasonal growth in the portion of western tropical Atlantic under seasonal influence of the Amazon plume (an area between 60°W and 40°W and between 0° and 20°N), this analysis further suggests that it does not drive the large-scale seasonal bloom. At the annual scale, we found that only 9% of the *Sargassum* biomass occurred in the river plume area in 2017, with occurrence below 5% from September to May and peak at 23% in July when the plume is well extended toward the Lesser Antilles. It is even more unlikely that the Congo and Orinoco rivers could contribute to the large-scale bloom due to the limited imprint of the plumes on the chlorophyll distribution and remoteness of the river plumes from the main *Sargassum* bloom areas.

As a conclusion, while increasing inputs of nitrogen and phosphorus in the watershed from human activity, predominantly from land-based activities, are thought to have the potential to significantly increase the nutrient fluxes toward the ocean and have been proposed as contributors of the *Sargassum* proliferation, this analysis suggests that riverine fertilization is unlikely a key controlling factor of both seasonal and interannual variability of the *Sargassum* biomass. In agreement with recent findings by Johns et al, (2020), it fails to explain the *Sargassum* distribution shift that occurred after 2010. Instead, Johns et al. (2020) proposed that an extreme negative phase of the North Atlantic Oscillation triggered the 2011 event and that vertical mixing dynamics below the ITCZ sustains *Sargassum* growth in the Central Tropical Atlantic. This is in line with the enhanced chlorophyll concentrations observed below the ITCZ (Figure 4). However, the forcing processes sustaining the productivity there remain to be clarified. This study also reminds us that advection is instrumental in controlling the seasonal distribution of *Sargassum*, as already revealed by several studies (Brooks et al. 2018, Wang et al. 2019, Berline et al. 2020). Although much progress has been made recently on how *Sargassum* advection responds to currents and winds (Berline et al. 2020, Putman et al. 2020,

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Miron et al. 2020), this issue has yet to be fully evaluated and understood. That key aspects of growth and movement are missing from for our ability to understand and forecast spatiotemporal variability in the distribution of pelagic *Sargassum*.

Methods

Methods and associated references are available in the supplementary material.

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Authors contributions

All authors contributed to the interpretation of the results and writing of the manuscript. J.J. and J.S.M. designed the study. J.J. implemented the numerical simulations, and conducted the comparison with observations. G.M.M and F.M. participated to the long-term hydrological measurements. J.S.M, W.S. and J.M.M. performed the hydrological analysis. L.B. and W.P. produced the basin scale *Sargassum* observations. M.H.R. contributed to the ocean color analysis.

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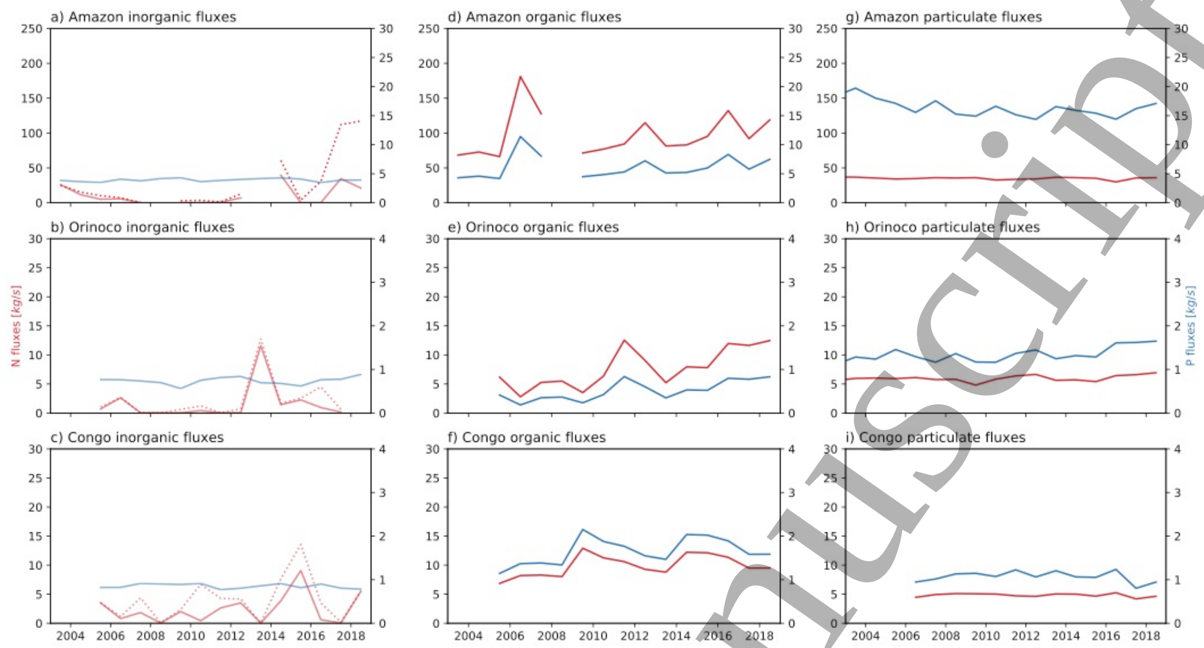

Figure 1. Interannual variations of dissolved inorganic N (red) and P (blue) fluxes (left column), dissolved organic N and P fluxes (central column) and particulate N and P fluxes (right column). Data are from 2003 to 2018 and include the three largest rivers of the Tropical Atlantic: a,d,g) the Amazon at Óbidos station, b,e,h) the Orinoco at Ciudad Bolivar station and c,f,i) the Congo at Brazzaville station. Fluxes were computed from different data sources (in-situ, satellite, literature) and details are given in supplementary material. In a-c, the annual mean N flux has been computed considering all the available Hybam monthly measured NO3- concentrations (dashed line) but also removing the 10% extreme values for each year (continuous line).

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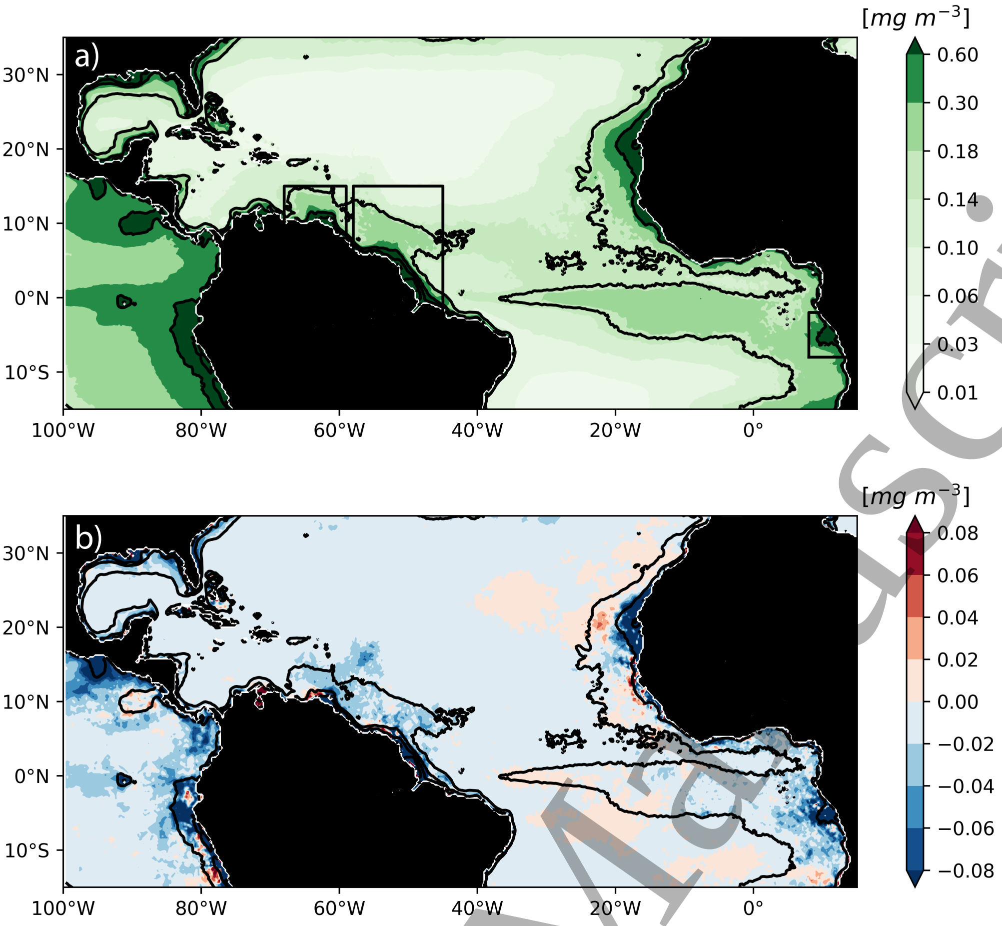

Figure 2. a) Mean chlorophyll concentrations (in mg m^{-3}) from GlobColour monthly MODIS GSM product at ¼° horizontal resolution for the period 2003-2018. b) Difference of chlorophyll concentration between the period 2011-2018 and the period 2003-2010. Black contours indicate the 0.3 and 0.6 mg m^{-3} chlorophyll concentration iso-contours. The boxes indicate the extent of the regions used to computed the chlorophyll time series in Figure S5.

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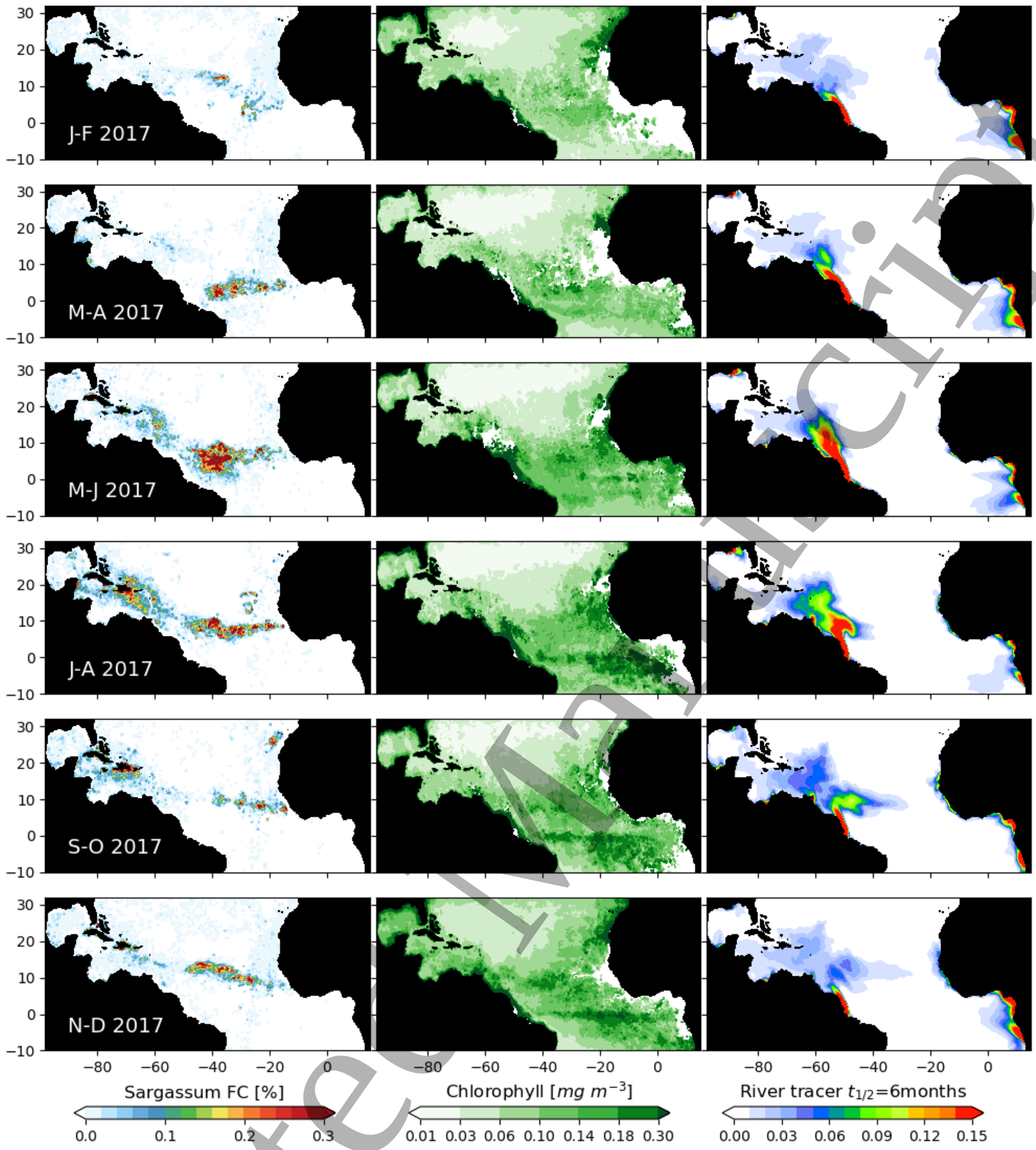

Figure 3. (a) Fractional Coverage (%) of *Sargassum*, (b) chlorophyll from monthly GlobColour GSM merged product (mg m^{-3}), (c) river tracer surface distribution (no unit, initialized at 1 at the river mouth) with half-life time scale of 6 month from a ¼ degree NEMO regional simulation. Data are all for year 2017 and have been averaged over two-month periods.

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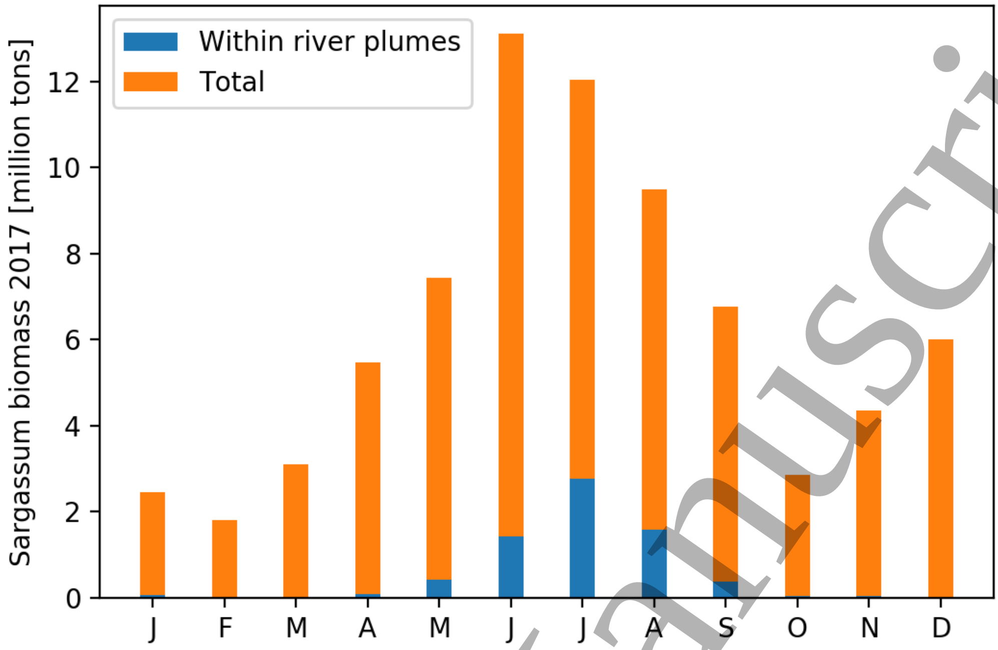

Figure 4. Monthly mean *Sargassum* biomass for year 2017 estimated from MODIS in the Caribbean and Central Atlantic (5°S-25°N, 89°W-15°E). The blue bar marks the fraction of the biomass which is colocalized with the model river plume (defined as areas with surface concentration of riverine waters > 0.05, i.e. more than 5% of kg of water with riverine origin per kg of ocean water; the spatial distribution of the river tracer is shown in Fig. 3c).

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