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Tracking and detecting sargassum pathways across the Tropical Atlantic

Authors: Y.A., Fidai [1*]; J., Dash [1]; R., Marsh [2]; H.A., Oxenford [3]; L., Biermann [4]; N., Martin [4]; E.L., Tompkins [1]

*Corresponding author email: y.a.fidai@soton.ac.uk

1 School of Geography and Environmental Science, University of Southampton, Highfield Campus, University Road, Highfield, Southampton, SO17 1BJ

2 National Oceanography Centre, Waterfront Campus, European Way, SO14 3ZH

3 Centre for Resource Management and Environmental Studies (CERMES), The University of the West Indies, Cave Hill Campus, St Michael, Barbados, BB11000

4 Plymouth Marine Laboratory, Prospect Place, Plymouth, UK

Abstract

Pelagic sargassum (S. *fluitans* and S. *natans*) algal blooms and beach landings have become a regular occurrence in the Tropical Atlantic Basin since 2011; they have a variety of impacts on the marine ecosystem and blue economy. To reduce the impacts and enable effective management, forecasting and monitoring of the blooms are essential. Challenges associated with use of satellite imagery for sargassum detection in the Tropical Atlantic are spatial resolution and cloud cover, which is particularly dense in this region due to the inter-tropical convergence zone, tropical storms and hurricanes. Successful models of forecasting and prediction of pelagic sargassum are hindered by unreliable satellite data, uncertainty around windage and as well as growth and mortality. In the longer term, we aim to improve the forecast models of pelagic sargassum mat movements in open oceans by introducing evidence of the speed of travel, changing mat morphology, and size and health status of sargassum mats. To achieve this, we deployed eight trackers on floating sargassum mats in the Western Tropical Atlantic. In addition, we explore the coincidence of surface currents, wind stress and sea surface temperature as a parameter for growth on the tracker pathways. When used in conjunction with both remote sensing methods and climate data (wind, current and sea temperature), we find that GPS tracker data can facilitate more reliable monitoring of sargassum transport pathways, helps to overcome satellite-based challenges as well as model based uncertainties, and may improve the accuracy and general utility of sargassum early warning systems.

1 Introduction

Pelagic sargassum (*S. fluitans* and *S. natans,* henceforth sargassum) blooms have become a regular occurrence in the Tropical Atlantic region, resulting in sargassum deposits across the region's shorelines. In 2018 it was estimated that there was over 20 million metric tons of sargassum biomass covering an area of almost 3000 km^2, subsequently coined the 'Great Atlantic Sargassum Belt' (Wang et al., 2019). There is uncertainty in both the initial trigger of blooms in 2011 and the subsequent drivers of bloom proliferation in subsequent years (Marsh et al. 2023). Regarding the latter, hypotheses invoke roles for ocean-surface circulation patterns, wind associated with the inter-tropical convergence zone, and nutrient enrichment (Johns et al., 2020; Lapointe et al. 2021; Skliris et al. 2022). Sargassum inundation events have the potential to disrupt social, economic and ecosystem functioning, and to negatively impact human health (Chavez et al., 2020; Fidai et al. 2020; Ramlogan et al., 2017; Sissini et al., 2017; Solarin et al., 2014; van Tussenbroek et al., 2017), and have been described as an emerging environmental hazard to coastal communities across the Wider Caribbean region and countries of West Africa (UNEP-CEP, 2021).These impacts have led to growing demand for methods to detect, track and forecast the sargassum.

Remote sensing has been widely used to detect and monitor sargassum in the open-ocean at different scales (Wang and Hu, 2016; Arellano-Verdejo et al., 2019; Wang and Hu, 2020; Laval et al., 2023; Marsh et al., 2023). Most satellite based monitoring of floating sargassum is done at the basin-scale using optical data collected by Moderate Resolution Imaging Spectroradiometer (MODIS), Sentinel-3 Ocean and Land Colour Instrument (OLCI), Visible Infrared Imaging Radiometer Suite (VIIRS) and Medium Resolution Imaging Spectrometer (MERIS) at spatial resolutions of 250 - 1 km. Optical satellite data collected at higher spatial resolution satellite of 0.5 m – 30 m tend to be used to fill in 'gaps' on local to near-shore scales (Marsh et al., 2023). Forecasting models that integrate satellite-derived sargassum data products have also been developed, see examples including Maréchal et al. (2017), Johnson et al (2020) and Marsh et al. (2021). Across scales, however, cloud prevents optical sensors from viewing the ocean surface. This is particularly acute in the East Atlantic region and in the inter-tropical convergence zone, making satellite data acquisition and, by extension, model detection and forecasting less reliable across the Tropical Atlantic Basin (Marsh et al., 2022).

A number of studies have trialled the use of drifters and trackers to contribute to understanding sargassum transport pathways. To develop transport models, Van Sebille et al. (2021) used sophisticated Stokes drifters, Surface Velocity Program drifters, and GPS trackers to simulate surface currents; Johnson et al. (2020) used drifters from the Global Drifter Program to identify ocean currents; Franks et al. (2016) utilised drifting buoys as part of the World Ocean Circulation Experiment for surface drift data; Putman et al. (2020) combined ocean circulation models and wind velocities with the use of oceanographic drifters and GPS trackers on sargassum mats to improve transport prediction models. However, these models are limited in their capacity to track individual mats. Van Sebille et al. (2021) highlighted a need for further improvements to hydrodynamic models to better forecast sargassum. Whilst models used for forecasting are useful, they are largely reliant on current and wind data to predict where sargassum ‘pixels’ detected from satellite imagery will travel. Additionally, a major uncertainty in model predictions of sargassum drift is the extent of ‘windage’, the fractional influence of winds on sargassum mats (Marsh et al., 2022). Further, there are limited data on the speed that individual mats travel, and on whether changes in size and morphology of mats are primarily due to growth and mortality/sinking of sargassum thalli, or simply the coalescence or fragmentation of sargassum mats along their transport pathway. Ody et al. (2019) use ship deck and satellite observations to typify the shape of mats, however, they also acknowledge the challenge of high cloud cover to observe the mats with remote sensing. Identifying speed of travel and changing mat morphology requires very high spatial and temporal resolution remote sensing and/or time at sea following and observing individual mats. Both of these approaches would be difficult and costly, constraining attempts to address this data gap.

Improvements in satellite technology and design, combined with more satellites, have resulted in cheaper tracking options that are more widely accessible to the science community and are therefore now being used for many different applications. For example, data from GPS trackers and satellites have been combined and used for a variety of purposes in marine environments including to track wildlife and marine fauna such as turtles (Hays and Hawkes, 2018). These data have also been used to track the transport pathways of individual pieces of litter in both ocean and riverine systems (Duncan et al., 2022). In New Zealand, GPS trackers in plastic bottles were used to determine the influence of wind and tides on dispersal of detached algae (Hawes et al., 2017). In a hazard management context, radio frequency identification and GPS trackers were used to track tree log transport movements during flood events (Ravazzolo et al., 2015). They have also been used for monitoring surface currents, and technological developments in tracking have facilitated bespoke design and development of drifters and buoys at lower cost than pre-made options (see examples: Herbers et al., 2012; Mansor et al., 2016).

1.2 Aims

We aim to develop a framework that would provide quantitative evidence on speed of travel, changing mat morphology, and health of sargassum mats which in turn would improve the forecast models of pelagic sargassum mat movements in open oceans. These empirical dataset fills the gaps created by cloud cover, and the temporal and spatial coverage of satellite imagery. To achieve this, the following sub-aims were undertaken: i) to design a tracker that can track pelagic sargassum in open ocean for weeks-months (including selection of tracker, design and testing of suitable GPS housing); ii) to detect sargassum transport pathways, and describe their coincidence with current speed, wind stress, and sea surface temperature, and determine the speed of travel of individual mats; and iii) to document the morphological and size and health condition changes of the sargassum mats during the lifespan of the trackers.

2 Methods

2.1 Tracker selection, housing design and deployment

The GPS tracker and housing were selected and developed to be as cheap as possible and made from readily available, non-specialist items such that the method is widely accessible and simple to set-up for replication by anyone from researchers to local government personnel, fishers and community members. Additionally, for supporting improved forecasting and monitoring in the future, the number of deployed trackers will need to be expanded. Keeping costs as low as possible should ensure that future upscaling of this method is not prohibitively expensive. The GPS tracker had to also satisfy the minimum requirements of being able to track offshore in a marine environment, with coverage of the study area, and send multiple location updates per day to maximise potential pairing with satellite imagery. Other considerations in the design specification included operating temperature range and duration of power supply. The trackers that were researched and considered are discussed in more depth in the supplementary material.

Once the tracker was selected, the housing was designed. Trials were undertaken in pre-made cases but were found to have limitations (see supplementary material), as such we designed a bespoke housing from widely accessible materials. The housing was tested in a controlled environment and then in the near-shore at Southbourne Beach in the UK, before being deployed in sargassum mats in the Caribbean Sea. This was to ensure that the tracker and housing floated with minimal structure above the surface of the water and had a similar buoyancy to seawater (around 1022 kg/m^3), that it floated upright and did not overturn in high waves, and that it could tangle with the sargassum to successfully travel with the mat.

Once assembled, a label with contact details and project information was attached and the trackers and housing were deployed off the coast of Jamaica and Barbados, by researchers or fishers, on mats of sargassum that were classified as type 3 (windrows with small patches, a few metres in diameter), 4 (windrows dominated by large patches a few meters to a few tens of metres in diameter) or 5 (large quasi-circular patches that can reach hundreds of meters in diameter) (as typified by Ody et al., 2019) between August and October 2021.

2.2 Analysing the tracker pathways

The tracker pathways were downloaded from the Globalstar web service in '.csv' format. The tracker datasets were reformatted in Microsoft Excel to remove text formatting, empty/null cells, and non-location recordings of status updates such as power on and low battery alerts sent by the device. The data were then processed in 'ArcGIS Pro 3.0.0' software where the duration, distance and speed of travel were calculated using geoprocessing data management tools.

2.3 Tracking with satellite imagery

Optical data collected by the Sentinel-2 Multi-Spectral Instrument (MSI) have been previously used to detect sargassum (Wang and Hu, 2020; Leon-Perez et al., 2023). This dataset offers freely available high resolution data at 10 m resolution (Qi and Hu, 2021), where sargassum mats smaller than 10 m^2 can be identified, allowing detection of mat types 3, 4 and 5. In this study, we first used 'Sentinel Hub EO Browser' (EO Browser, https://apps.sentinel-hub.com/eo-browser/, Sinergise Ltd.) to explore the Sentinel-2 Level-2A data archive imagery and identify cloud-free images which overlapped spatially and temporally with the tracker positions. In a radius around the coordinates sargassum mats that could be associated with the tracker were searched for, with the radius size proportional to the amount of time that had elapsed between the time of image acquisition and the time associated with the tracker position. Average speeds of travel were calculated in section 3.2 to determine the radius. Sentinel-2 level-2A images were downloaded directly from the 'Sentinel Hub EO Browser' and further analysis was completed in 'ArcGIS Pro 3.0.0' software.

False colour imaging was used to highlight sargassum floating on the ocean surface, pixels with vegetation within the search radius were digitised as polygons. To determine the health status or 'greenness' of the floating vegetation the Normalised Difference Vegetation Index (NDVI) was applied using Sentinel Hub EO Browser. NDVI was selected as it has been used successfully to discriminate sargassum and other floating vegetation in satellite imagery (see examples Hu, 2009; Dierssen et al., 2015; Hu et al., 2015); it also offers an indication of the health of the sargassum mat as values closer to 1 are indicative of 'greenness'. The polygons and NDVI were then used to explore the morphology, size and health status of the mats.

It was not possible to use Sentinel-2 imagery for all trackers as some had substantial cloud interference, obscuring the view of the sargassum mats and tracker path. In the observation period, between August and December 2021, there were nine tropical storms (Fred, Kate, Julian, Mindy, Odette, Peter, Rose, Victor, Wanda) and six hurricanes (Grace, Henri, Ida, Larry, Nicholas, Sam) in the Western and Central Tropical Atlantic regions (National Hurricane Centre, 2023). These meteorological events made tracking with Sentinel-2 optical data challenging. As such we applied a method for sargassum detection using Sentinel-1 Synthetic Aperture Radar (SAR) developed by Biermann et al. (unpublished). SAR has a wide range of applications, including measuring vegetation biomass; it utilises microwave wavelengths and as such has all-weather day and night capability, meaning it provides ground observations regardless of clouds, storms and hurricanes and time of day (Malenovský et al., 2012; Torres et al., 2012).

Operational implementation of this automated method involved two main steps: preparing the data using a processing chain for Sentinel-1 SAR data, and detecting Sargassum (Biermann et al., unpublished). The SAR processing chain is composed of several steps. These include the downloading of Ground Range Detected High-resolution (GRDH) Interferometric Wide (IW) swath mode data from the NASA Alaska Satellite Facility (ASF) Distributed Active Archive Centres (DAAC); application of orbit file for accurate positioning; removal of thermal noise and GDR border noise; masking of land with 2-pixel extension of the shoreline; calibration for calculation of backscatter coefficient measurements for VV and VH; and calculation of the SARgassum Index (see supplementary material) to improve positive contrast between sargassum and water. Sargassum patches of at least 400 m^2 in size were detected using a two-stage approach described in Kurekin et al. (2018). In the first stage, a constant false alarm (CFAR) detector was applied to calculate target-to-clutter ratios (TCR) and discriminate pixels containing sargassum. Detected pixels with TCR values below 1.6 were masked as water, and TCR values above 3.0 were masked as vessels. In the second stage of automation, bright pixels with TCR values between 1.6 and 3.0 that met 8-pixel connectivity were grouped as sargassum patches, and a contouring algorithm was applied (Biermann et al., unpublished). Due to large numbers of false detections arising from strong atmospheric disturbances, an additional manual step was done to mask storms. Resulting output shape files were then explored and analysed in Arc Pro 3.0.0 software.

3 Results

3.1 GPS tracker and housing

The GlobalStar SPOT TRACE was selected as the most appropriate GPS tracking device as it gave hourly location updates in near-real time via the GlobalStar satellite network, had a browser-based interface or alternative mobile phone application, was relatively low cost, had a long battery life, and its compact size allowed it to be accommodated in a small waterproofed housing easily. It had also been previously used in ocean environments in surface drift experiments (Novelli et al., 2017) and been found to have >2.5m accuracy for 95% of recordings (Meyerjurgens et al., 2019).

Through trialling different materials and combinations to make the GPS housing, it was established that the density required to float was approximately 1000 kg m^{-3}, slightly lower than Tropical seawater. Table 1 shows the various combinations of weight (plasticine) as a proportion of the container that were trialled in the basin and their outcomes. To create the heavy stable base, it was found that plasticine, homemade dough or sand gave identical results as they are similarly dense materials when packed as a base weight. However, it was found that using rocks caused the housing to float at an angle or horizontally due to air gaps between them. The housed tracker needed to have a low centre of gravity (dense material in the base) to ensure upright attitude.

Table 1 Combinations of material proportions trialled for GPS housing. The percentage is a representative proportion of 1 L plastic bottle, excluding the space occupied at the top by the tracker.

Trial number	Weight	Silica Beads	Foam	Outcome (plasticine/sand/dough weight material)
1	0%	70%	30%	Floated horizontally on the surface
2	20%	40%	40%	Floated diagonally
3	30%	40%	30%	Floated diagonally
4	40%	40%	20%	Floated nearly upright with a portion of the bottle above the water surface
5	50%	40%	10%	Floated upright with the lid just above the surface
6	60%	30%	10%	Floated upright with the lid at the surface
7	70%	20%	10%	Sunk

Combinations 5 and 6 (table 1) were tested in the near-shore at Southbourne beach, UK. They both withstood the 2-hour test, however the height above water for combination 6 (figure 1) was thought to be more appropriate as the profile appeared to more closely match the seaweed floating on the surface.

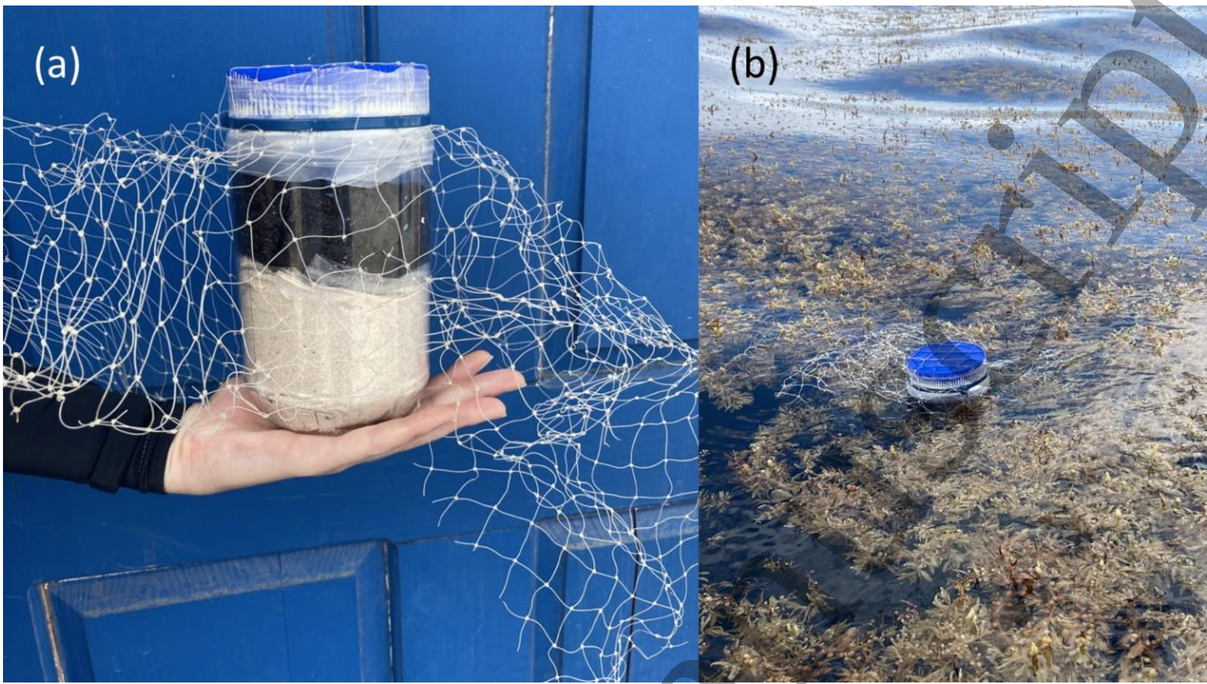

Figure 1 The successful GPS housing design, (a) prepared for deployment and (b) deployed into sargassum mat. From bottom to top: a dense weight (sand) at the base in plastic bag, a layer of packing foam above this, then the GPS tracker flush against the screw-top lid of the bottle, with gillnetting secured by a zip tie.

After exploration, the housing GPS 'recipe' included: 1L plastic jar/bottle, sand or plasticine to act as a dense weight at the bottom, packing foam, optional silica beads to absorb moisture that may enter (can be replaced with extra foam), and the SPOT tracker sitting at the top against the lid which was sealed with silicone and parafilm and had gillnetting (or similar material such as chicken wire) (approx. size 60 x 60 cm) wrapped around to tangle with the sargassum (figure 1). Through the tests and exploring of different materials, we expect that users of this method could substitute most materials for alternatives that are found locally.

3.2 What was the journey taken by the trackers?

Five trackers (numbered 1, 3, 6, 7, and 8) were deployed off the coast of Barbados and two off the coast of Jamaica (4, 5) (figure 2, table 2). These locations were selected as they experience regular sargassum influxes and were accessible by researchers and fishers for deployment. All trackers, regardless of their starting point moved across the Caribbean Sea in a similar overall direction, where the final location recordings for them were in a north-westerly direction from where they began (figure 2). Tracker 7 is the exception where it appeared to have been picked up by a boat based in St. Lucia as we watched it make regular trips out to sea and back to shore, where it remained stationary for long periods of time. Tracker 8 landed on the east coast of St. Lucia within 7 days of being deployed. Both the trackers deployed off the east coast of Jamaica travelled north around the island through complex local eddies and currents. Tracker 5 was initially deployed 02/10 but it returned to shore with sargassum on the same day and was redeployed. The last recorded location of tracker 5 was on the Caribbean coastline of Mexico's Yucatan Peninsula, and tracker 4 travelled into the Gulf of Mexico.

Tracker 4, followed by tracker 1, recorded the most location updates, but did not last the longest number of days (table 2). Tracker 7 recorded location updates for the longest number of days, however, as it was picked up by a boat the data were not useful for tracking sargassum (and as such is henceforth discounted from average calculations). Tracker 5 lasted one day less than tracker 1, but recorded significantly fewer location positions, a number of potential reasons are hypothesised for this, including: battery, poor connection with the satellite due to wave action, and water entering the housing. We hypothesise the same potential explanations for the shorter lifespans of trackers 3 and 6.

Figure 2 Tracker pathways depicted as lines, dates and speed of trackers in table 2.

Table 2 Tracker pathway analysis, including duration, distance, and speed. Average speed was calculated using position geometry, recorded speed is the mean speed as recorded by the tracker converted from mph to cm/s. Tracker 7 is discounted from the summary statistics at the bottom of the table as it was not tracking sargassum for most of its lifespan (results are rounded to 2dp, and mean is used to calculate the average speed).

Tracker	Dates	Time (Days)	Time (Hours)	Number Of Positions Recorded	Distance (Km)	Average Speed (cm/s)	Average Recorded Speed (cm/s)
1	09/08/21 – 05/11/21	88	1397.90	932	1622.30	32.22	25.28
2	No data due to battery failure						
3	09/09/21 - 24/09/21	15	360.26	311	430.93	33.33	24.17
4	01/10/21 - 15/12/21	65	1810.76	1043	2434.16	37.22	27.22
5	02/10/21 - 28/12/21	87	2100.59	84	2092.54	27.78	19.72
6	25/09/21 - 16/10/21	21	509.42	239	653.79	35.56	35.56
7	31/08/21 - 25/12/21	116	2781.37	314	1022.62	01.28	35.00
8	28/09/21 - 05/10/21	7	168.60	95	180.60	29.72	21.94
Average		47.17	1057.92	450.67	1235.72	32.78	25.56
Minimum		7	168.60	84	180.60	27.78	19.72
Maximum		88	2100.59	1043	2434.16	37.22	35.56

Trackers 4, 5 and 1 travelled the furthest distances across the Caribbean Sea (table 2). The average speed calculated from the distance and number of hours between the first location recording at deployment and last recording, shows that the tracker speed ranges from 27.78 to 37.22 cm/s, averaging 32.64 cm/s (discounting tracker 7). The tracker itself records the speed of movement at the same time the position is recorded; the average tracker-recorded speed was 25.56 cm/s, which is 6.94 cm/s lower than the average speed calculated from the data. In the Atlantic region, the predominant ocean surface current speed is 5-15 cm/s, but near more energetic eddies and major currents, the predominant speed is 20-40 cm/s (University of Miami, 2013). This supports that the observed movements are influenced by surface current speeds, for example, tracker 4 is the fastest moving tracker and it can be observed that it is transported through eddies around the Jamaican coast.

Figure 3 shows the tracker positions overlaid with monthly-mean surface currents from a high-resolution ocean model hindcast (Megann et al., 2022). The currents are highly variable in both space and time, with the strongest flows (exceeding 100 cm/s in places) found near the western boundary, where the North Brazil Current transitions to the Guiana Current and the Caribbean Current, progressing from southeast to northwest. Figure 3 highlights that the GPS trackers largely stay in the slower flows (0.2 – 10 cm/s), with the exception of tracker 4, following the swift Caribbean Current (over 50 cm/s) that exits the Yucatan Strait in December.

In Figure 4, the effect of wind on the trackers is considered, with monthly means of the wind stress used to force the hindcast. The trade winds that dominate the study region are predominantly blowing westward throughout the deployment period, with peak strength in the Caribbean, weakening from August to October before strengthening to December. Westward blowing winds aid tracker drift in this general direction. Tracker 4 travels through the Yucatan Strait in the opposite direction to wind, suggesting that strong currents play a significant role in GPS tracker movement. Tracker 1 likewise drifts across the prevailing winds through the Mona Passage, where the current also dominates tracker drift. In conclusion, the transport direction of the trackers is not consistently congruent with wind stress direction, suggesting that current is more significant than wind for transporting sargassum.

To further explore size and health of sargassum mats, the hindcast sea surface temperature is considered in Figure 5. The trackers deployed in August, September and October were deployed in relatively warm waters, between 28 and 29.5 °C, and the trackers generally stay in areas between these temperatures, with the exception of trackers 4 and 5. In December, tracker 4 experiences lower temperatures, down to 26 °C, and tracker 5 down to 27 °C. Marsh et al. (2023) suggest that sargassum grows optimally at 26 °C and that mortality increases above 28 °C, suggesting that the waters in which the trackers drift through August, September and October are too warm for maximum sargassum growth. However, it has been shown that different sargassum morphotypes have different growth rates in different temperatures (Corbin and Oxenford, 2023; Magana-Gallegos et al., 2023). These studies suggest that S. *fluitans* III has a maximum growth at 28°C, whilst S. *natans* VIII and S. *natans* I appear to prefer lower temperatures (22-25°C), and all three experience decreased growth at 31°C (Magana-Gallegos et al., 2023). This suggest that in the months of August to October S. *fluitans* III in particular could be thriving, which is further supported by the work of Corbin and Oxenford (2023) who show that S. *fluitans* III grew significantly faster than the other morphotypes over a temperature range of 27 - 30 °C.

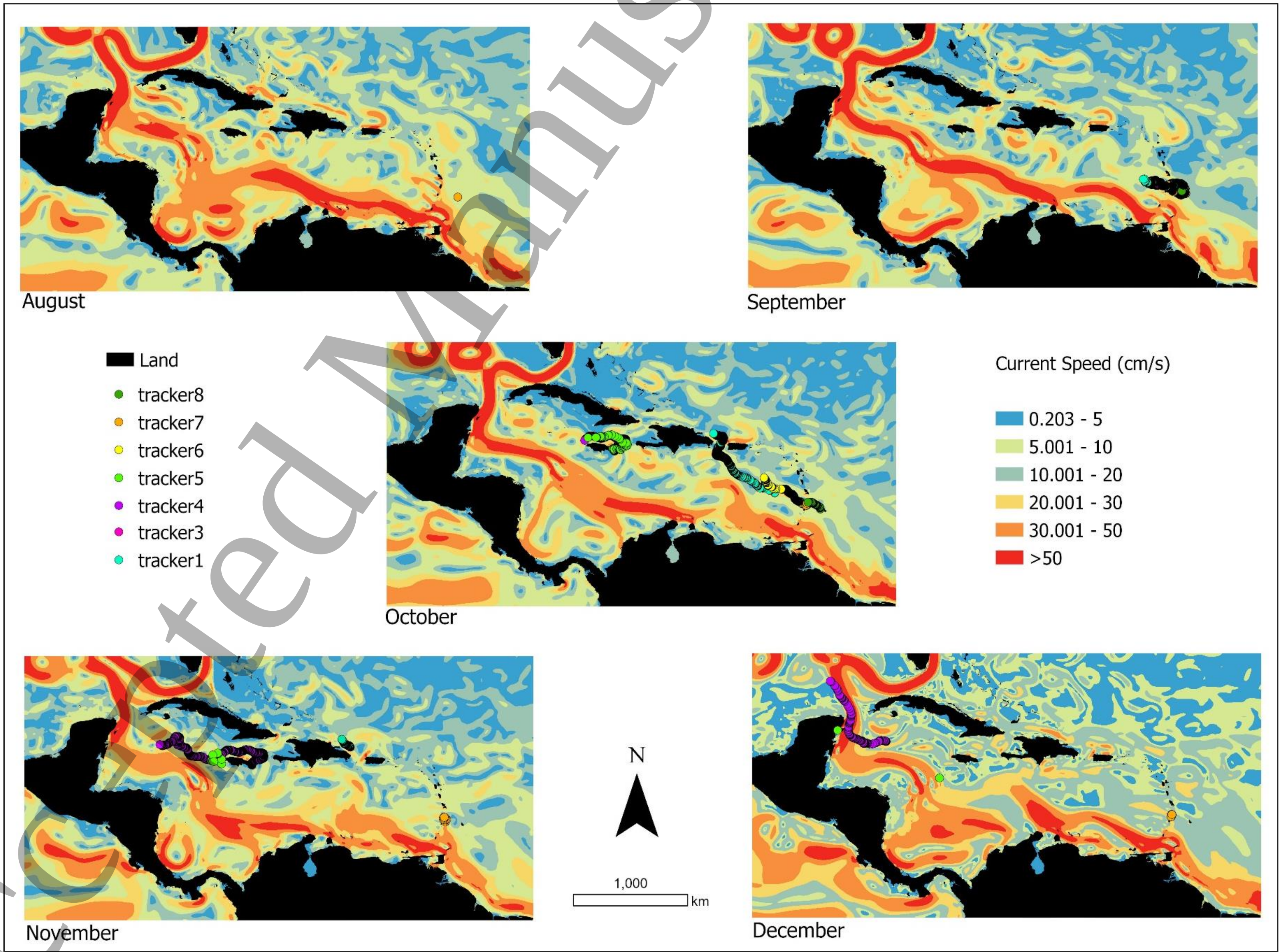

Figure 3 Hindcast surface currents for the duration of tracker data acquisition, obtained with ORCA12 version of NEMO ocean model (Megann et al., 2022).

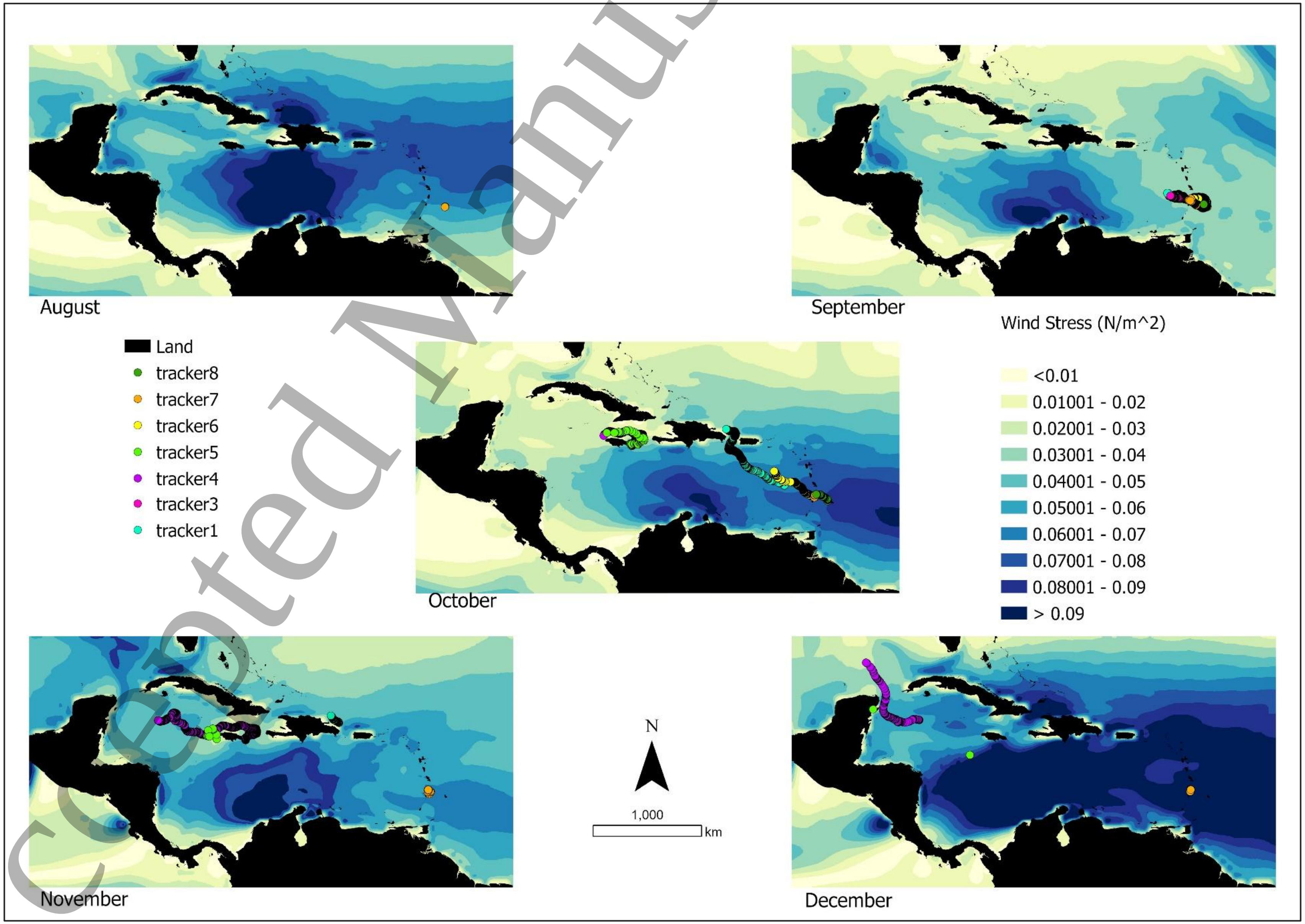

Figure 4 Monthly wind stress (in Newtons per square metre) for 2021 overlayed with tracker positions (wind stress data obtained from with ORCA12 version of NEMO ocean model (Megann et al., 2022)). In the Caribbean Sea, in August, November and December the wind direction is southwest from the Lesser Antilles towards Venezuela and Columbia, and in a south-westerly direction into Central America (Panama/Costa Rica). In September and October the wind ravels in a Westward direction from the Lesser Antilles, and then Southwest into Central America. Between Mexico and Cuba, in August, September, and October the wind travels in a Westerly direction (from Cuba/Jamaica to Mexico), and in November and December in a South/Southwest direction (from Cuba to Mexico).

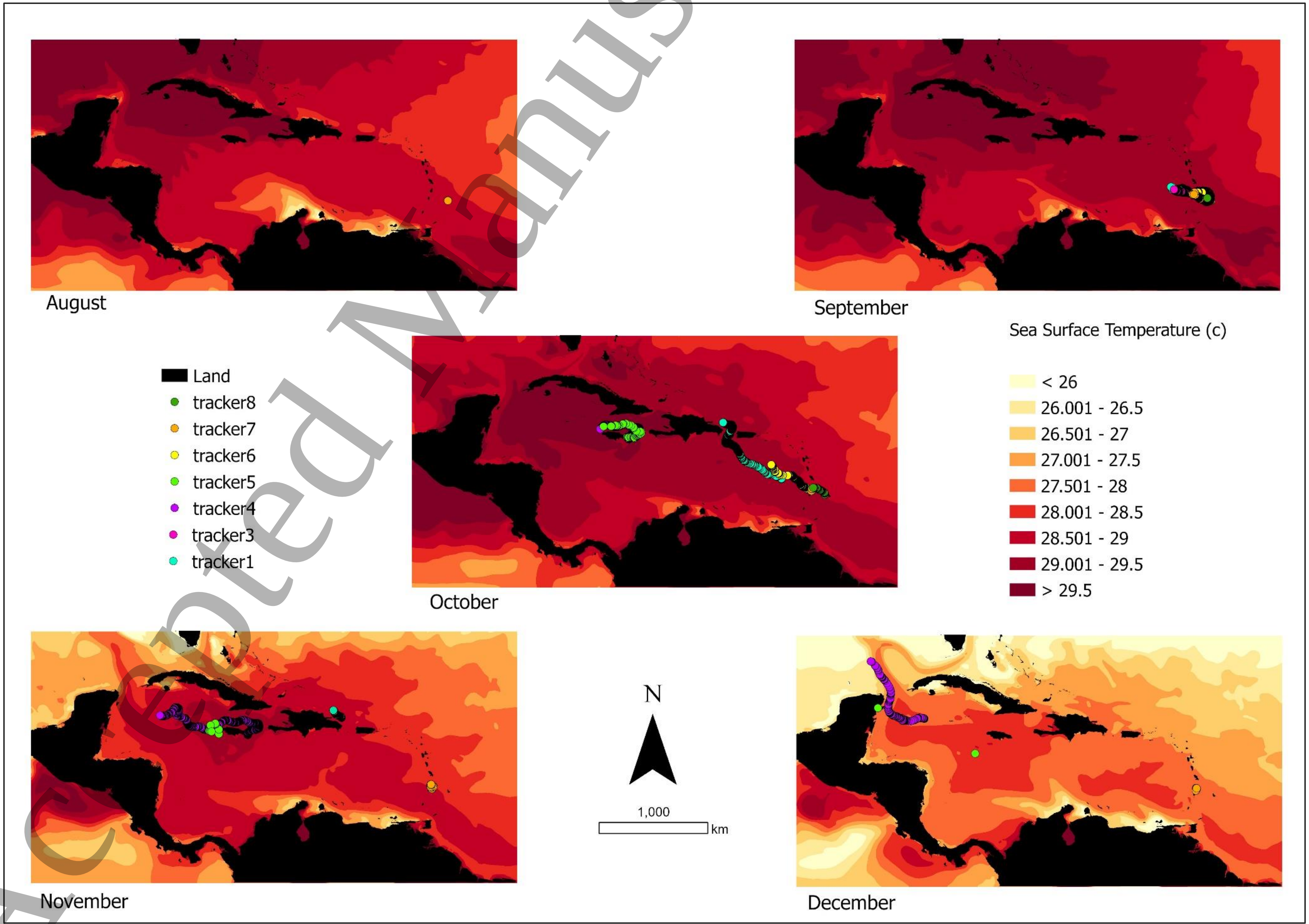

Figure 5 Monthly Sea surface temperature overlayed with GPS tracker positions for data acquisition months. Sea surface temperature data obtained from with ORCA12 version of NEMO ocean model (Megann et al., 2022).

3.3 What can we understand about the change in size and health of tracked sargassum mats?

The following section draws on Trackers 1 and 4 as they had the highest position frequency and longer tracked pathways.

Using the average speed calculated above to determine the search area, five images in sentinel-2 imagery were found that overlapped with the transport pathway of tracker 1. Three of these images contained sargassum (Figure 6).

In the first image (10/09/21) the sargassum raft appears more faintly with a vegetation signal across a few pixels, two aggregations within the search radius can be observed signalling that its morphology was type 4. The NDVI ranged between 0.50 and 0.70. From the imagery, a minimum area of 1200 m^2 was estimated for the mats combined, with a total perimeter of over 120 m. Nearby pixels in the image with moderate NDVI values (0.2-0.5) could be observed, indicating mixed pixels, where sargassum rafts were likely present but less than 10 m supporting that type 4 windrows were present and suggesting that the sargassum presence is higher than detected.

In the second image (06/10/21) with the main aggregation morphed in a tear-drop shape and smaller patches formed to the east, indicating multiple type 5 mats had formed, with one very large one. The area estimated for the largest patch was 16,280 m^2 with a perimeter of nearly 780 m. The total area estimated for the sargassum within the search radius of the tracker was over 27,600 m^2 (equivalent of nearly 4 football pitches) and the total perimeter was nearly 2900 m. The orientation of the aggregation indicates that it travels with the largest patch at the forward end and the smaller patches at the tail. The sargassum is likely to have grown between the images, Corbin and Oxenford (2023) indicate that sargassum doubles in biomass between 13 and 31 days depending on the species morphotype and temperature. Given that there are 26 days between the images, it is likely that the biomass grew as well as was aggregated with other mats by wind and currents to form this larger mat. Furthermore, the NDVI ranged between 0.6 and 0.9, indicating a stronger 'green' signal than the first image. This indicates that the sargassum mat was showing new growth. The increase in greenness (higher NDVI value) could also be due to mortality and sinking of 'browner' sargassum (lower NDVI values) between images.

The third image (19/10/21), shows fragmentation of the large aggregation where the total area estimated is close to 9000 m^2 and total perimeter of the aggregations is close to 1600 m. The NDVI ranged between 0.3 and 0.9, the wider range indicated that there was a weaker 'green' signal in some areas of the mat than previous images, which was indicative of the sargassum aging (becoming more brown). Two images at the end of October and start of November did not contain any visible sargassum, within the search radius or beyond. As the aggregation appears to grow and peak in size and then fragment and become smaller overtime, it was hypothesised that the sargassum continued to fragment and was formed as type 1 or 2 mats, which cannot be detected easily by Sentinel-2 due to its resolution. Additionally, given the declining NDVI it was further hypothesised that the sargassum may have continued to age, loosing gas bladders. and ultimately sunk. It can be observed in figure 5 that throughout its journey in September and October this tracker stays in water that is 29 – 29.5 °C, and in November 28.5 - 29 °C. Following Marsh et al. (2023) this would suggest that sargassum is experiencing a growth factor close to 90% of peak in September and October, and close to peak in November. Where the aggregation grows in early September, we must consider that there are other variables supporting its growth, such as nutrients, or that a specific morphotype is growing faster (as shown by Magana-Gallegos et al., 2023). Alternatively, wind causing sargassum to coalesce could also be a factor of apparent mat growth especially where temperature may not be optimal for growth, the wind stress at the maximum area of the tracked sargassum is moderately high at 0.06-0.07 N/m^2 (figure 4).

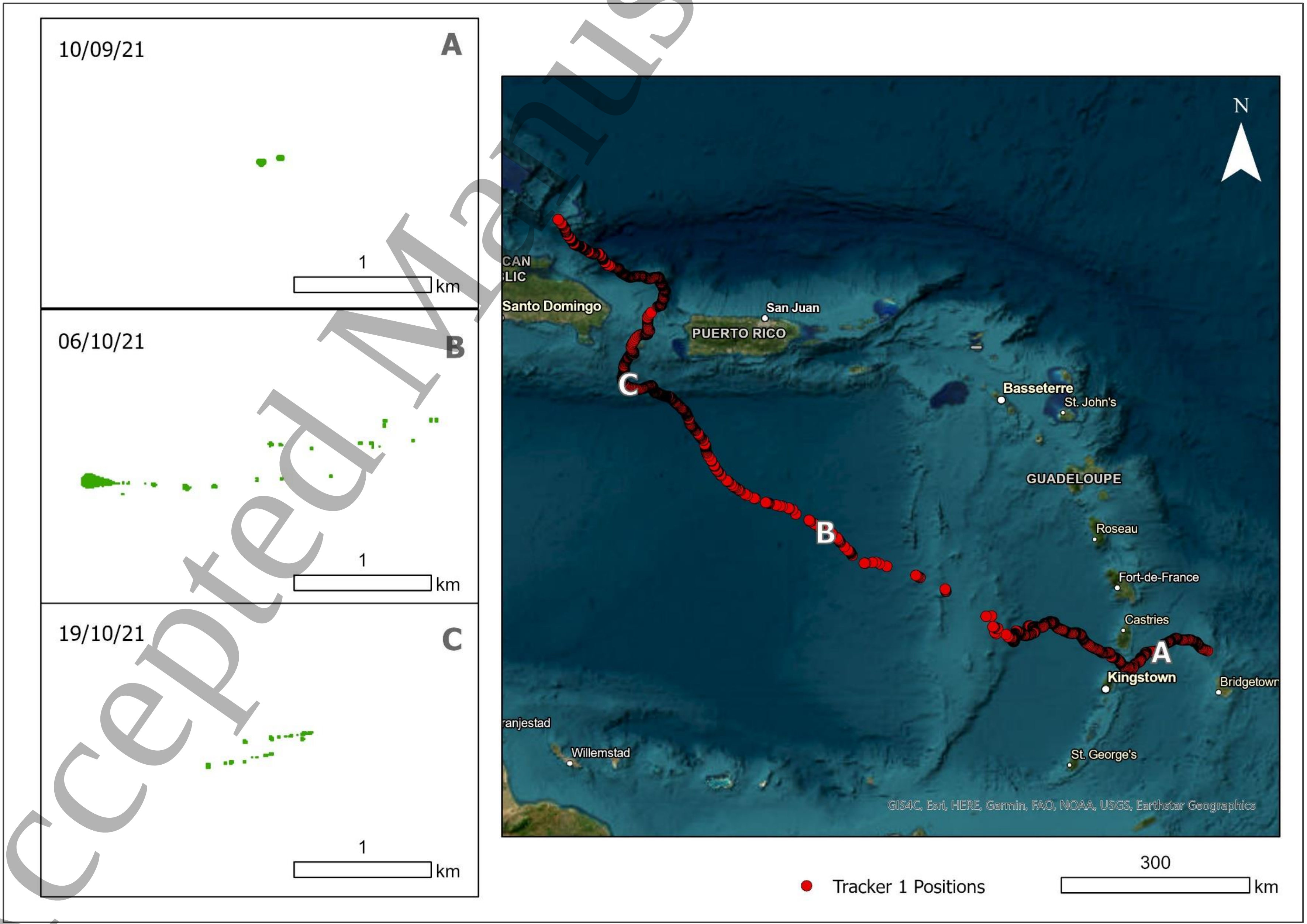

Figure 6 The morphological changes of the sargassum mat tracked identified using sentinel-2 imagery. The left panels (A-C) show the pixels identified as floating vegetation and the change in morphology across the journey can be observed, the position and pathway of the tracker and detected mats are indicated on the right.

As the positions for tracker 4 were heavily obscured by dense cloud and storm cover it was not possible to identify the sargassum mats associated with the tracker using Sentinel-2 imagery. Therefore, to detect sargassum along the tracker pathway, an alternative method using sentinel-1 SAR data was applied. A total of eleven scenes which overlapped spatially and temporally with the tracker pathway were identified and processed for sargassum detection. After this, the average speed calculated above was used to determine the search area to identify the sargassum mat associated with the tracker. Four polygon aggregations were identified from four scenes (presented in figure 7).

In the first scene (02/10/21), a single large polygon was identified with an area of 17,162 m^2. In the second scene (07/10/21), two medium polygons with a total area of 21,517 m^2 were identified within the search radius. The third scene (15/10/21) had the smallest polygon with an area of 609 m^2, and the fourth scene (12/12/21) a single polygon with an area of 1,830 m^2. The progression shows that the sargassum aggregation grew by over 3000 m^2, before significantly shrinking, indicating a similar pattern to tracker 1. However, there is a significant temporal gap in the tracking using SAR between the third and fourth detections of over one month. Whilst four scenes were available in this time gap, none of them contained detections within the search radius of the tracker, the nearest sargassum detection was over 45 km from the tracker pathway. Given that sargassum was detected towards the end of the tracker path (D), it is theorised that during this time gap the sargassum mat formation was too small to be detected using this method. However, separation of the tracker and sargassum mats is also a possibility.

The size and orientation of the polygons indicate that they are type 5 aggregations detected. The rectangular morphology and orientation suggests they are similarly positioned to image B of tracker 1 (figure 6) as the long-side of the rectangles are usually perpendicular to the direction of travel. Image B (figure 7) is an exception to this where the south polygon is orientated with the short-side (111 m) parallel rather than the long-side (120 m), this detection is nearly square which indicates it is not a false flag such as a ship. A possible explanation for this shape and orientation is that there are adjacent type 5 aggregations beside each other which have been grouped together by the automated detection method. Due to the resolution of the detections, it is not possible to determine if there are smaller windrows or aggregations adjacent to the large mats detected. Using SAR for detecting mats is limited by challenges in calculating NDVI and therefore understanding the health status of sargassum is not possible from this detection method.

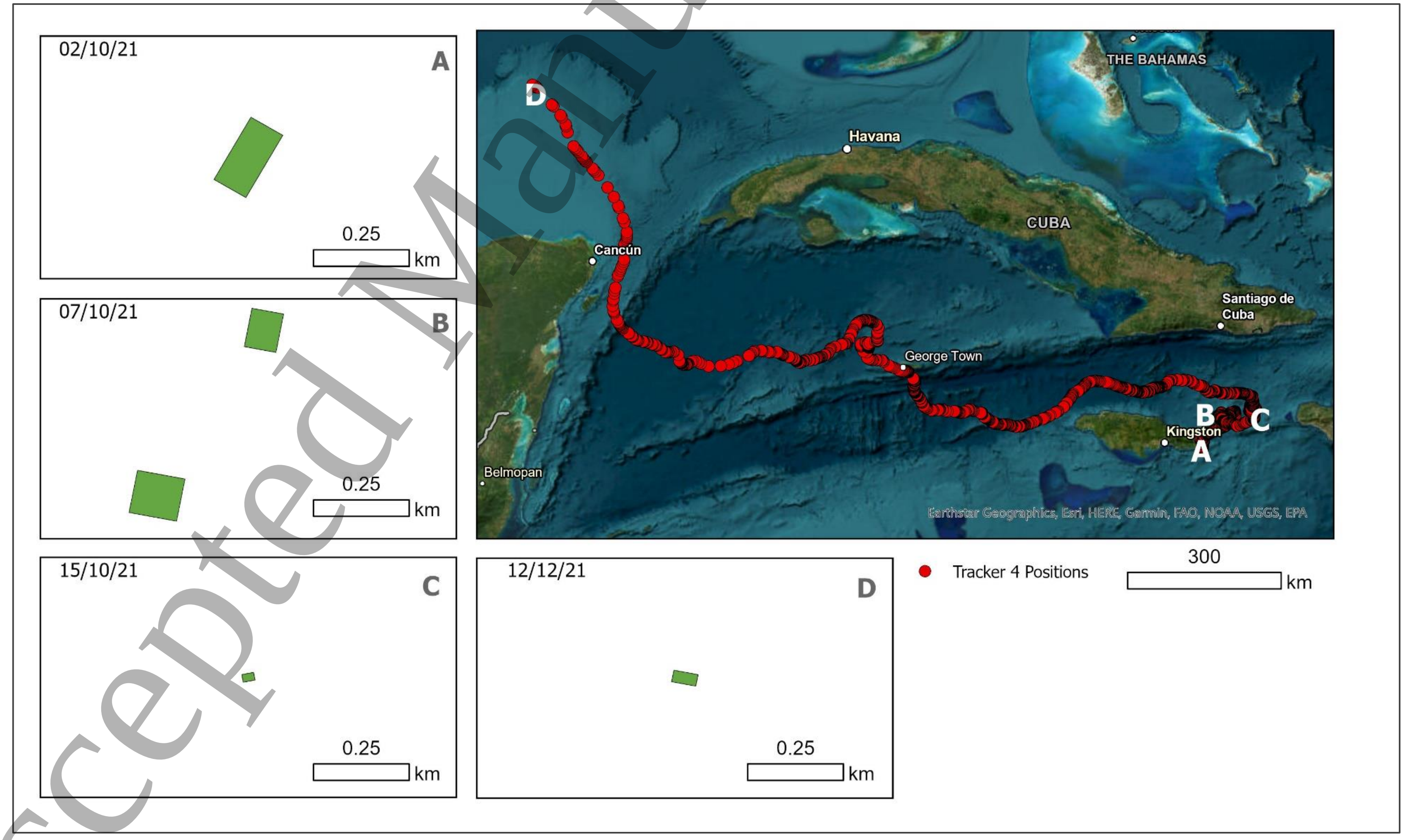

Figure 7 The morphological changes of the sargassum mat tracked identified using sentinel-1 data. The panels (A-D) show the pixels identified as floating sargassum mats and the change in morphology across the journey can be observed, the position and pathway of the tracker and detected mats are indicated in the top right box.

4 Discussion

By using GPS trackers, continuous data can be collected to observe the full pathway of an individual mat, using this method enables the temporal and spatial data gaps between remote sensing to be filled. The GPS trackers show that sargassum mats generally move in a north-westerly direction (from both Barbados and Jamaica) across the Caribbean Sea and towards Mexico and the Gulf of Mexico. Even where multiple trackers were deployed at similar starting points, it was observed that different paths were taken, for example tracker 8 landed on the coast of St. Lucia, whereas tracker 1 travelled up through the Mona Passage; similarly, off Jamaica, tracker 5 arrived at the Yucatan Peninsula, whereas tracker 4 travelled through the Yucatan strait into the Gulf of Mexico.

The trackers predominantly reveal sargassum pathways through the interior of the Caribbean. Away from broad western boundary flows, Caribbean currents are fine-structured, comprising jets only a few km wide. These jets may be highly chaotic, shedding eddies with diameter 10s of km that typically drift west across the Caribbean in the slower background flow (e.g., Centurioni and Niiler, 2003). Of the seven trackers, only tracker 4 was entrained into the western boundary current, just east of the Yucatan peninsula. From a fix in the mid Yucatan Straits (86.23°W, 21.64°N at 1354 on 12 December) to a final fix in the Gulf of Mexico (87.89°W, 24.26°N at 2216 on 15 December), tracker 4 moved progressively to the northwest at an impressive average speed of 116 cm s^{-1}. However, most sargassum reaching the Caribbean is seen outside of the boundary current system. To understand this distribution and the influence of strong boundary flows, we need to appreciate the upstream provenance of Caribbean-bound sargassum in spring and early summer. Previous studies (e.g., Marsh et al. 2021) show that sargassum originally in the North Brazil Current is gradually drifting to the north, out of the boundary current and towards the central/northern Caribbean.

Further examination of pathways and drift has been undertaken with virtual particles and simulated (ocean model) currents – see Supplementary Material. Forward trajectories from Barbados and Jamaica (Fig. S2) confirm that trackers drift pathways are within a wide range of possibilities. Backward tracking of large ensembles of virtual particles from east of Jamaica (Fig. S3) likewise confirms that the western boundary current conveys sargassum towards the Caribbean, subject some northward drift which is a likely consequence of prevailing easterly trade winds that drive surface Ekman drift oriented at 45° to the right of wind direction. Our observed tracker trajectories are of course highly subject to starting location and time, but from a broader perspective these trajectories confirm that sargassum tends to accumulate in the central and northern Caribbean, only rejoining the western boundary current via drift westward of Jamaica.

These observations further complement evidence from remote sensing, that sargassum migrates north then west across the Caribbean, moving north through passages Windward, Mona and Anegada, and then west to the Gulf of Mexico (Frazier et al., 2013). However, it has also been suggested that sargassum likely takes different routes in different months due to variable winds and currents (Oxenford et al., 2021). Whilst these data suggest that currents are more significant than wind in transporting sargassum mats, by deploying GPS trackers more widely across the Tropical Atlantic and in different months, the uncertainty of windage and currents can be reduced as transport pathways can be established by continuously monitoring mat positions with in-situ data from trackers.

From the remote sensing data paired with GPS tracker positions the size of the mat can be quantified, it was observed that an individual mat can rapidly grow and shrink. Using this combined method of tracking individual mats has also provided information on the orientation of the mats to the direction of travel. The NDVI indicated that in the growth phase the sargassum bloom was 'greener' and when it was smaller it was 'browner' which demonstrates the capacity to detect growth and mortality phases of an individual mat using these combined datasets. Through using these observations alongside sea surface temperature and existing knowledge on the effect of temperature on sargassum growth (by Marsh et al., 2023; Corbin and Oxenford, 2023; Magana-Gallegos et al., 2023) we could observe the growth and mortality of an individual mat.

There are a variety of forecast methods including automated satellite imagery detection, statistical methods and models undertaken at different scales, as well as a variety of input data including surface currents, winds and waves (Marsh et al. 2022; Marsh et al., 2023). By combining these models with in-situ ground truth data of tracked sargassum mats more accurate and more reliable sargassum forecasts can be established. This is possible because: (1) the GPS trackers continue to collect high resolution position data regardless of cloud cover, which is a barrier to date in effective detection of sargassum mats (as noted by multiple sargassum detection studies including: Wang and Hu, 2016; Maréchal et al., 2017; Ody et al., 2019; Marsh et al. 2022). (2) the combination of datasets enables tracking the change in area of an individual sargassum mat which means that not only can arrivals be forecast but the amount could also be quantified. This is vital from a management perspective as different quantities arriving on shore demand different responses. (3) Tracking sargassum that is also remotely sensed, in an environment for which we know the currents, winds and sea surface temperature provides the opportunity for better defining the windage of sargassum mat transport, and the growth and mortality rates. Putman et al. (2020) state that windage coefficient estimates differs depending on wind and currents and the local ocean region and more work is needed to represent wind in forecasting models. This work is a step towards this goal, as using in situ-trackers can provide the opportunity for constraining windage parameters in forecast models.

This work presents a case study for a methodology that can be scaled and expanded in the future. To enable transport pathways to be established across the region and effectively support forecasting for the region, GPS trackers should be released on sargassum mats across different months of the year and from multiple starting points, including the Eastern Tropical Atlantic, South Caribbean, Gulf of Mexico and Central America. To support this aim, the data has been made openly accessible on Zenodo (see Fidai et al., 2023). To reduce the potential for the trackers to detach from sargassum, a shallower design which may be more fluid and flexible to closer match the profile of floating sargassum is suggested. Additionally, to extend the battery life a battery pack can be included (but the change in density must be accounted for). A remaining challenge is detecting small (type 1 and 2) mats of sargassum using satellite imagery, for which there is a need for open-access high resolution imagery in open-ocean areas.

Conclusions:

This work has demonstrated the potential for tracking sargassum mats using GPS trackers to determine the transport pathways, and when combined with satellite imagery, the capacity to determine changes in morphology, size and health status. The GPS trackers provide high temporal and spatial resolution in-situ ground truth data to support remote sensing methods. The GPS trackers not only enable the temporal and spatial gaps of satellite imagery (and those caused by cloud cover) to be filled for continuous tracking of individual mats, but they also facilitate exploration of the growth and mortality of the mats, especially when combined with wind, current and sea surface temperature parameters. This has significant value for improving forecasting and sargassum population dynamics (growth and mortality of sargassum mats), as whilst they provide information about the physical and biological drivers of sargassum, using GPS trackers and remote sensing reduces uncertainty in key processes such as windage.

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Author contributions:

YF: conceptualisation, investigation, methodology, data collection, formal analysis, visualisation, writing – original draft

JD: supervision, methodology

RM: MONISARG PI, methodology, writing – review and editing

HO: methodology, data collection, writing – review and editing

LB: SAR data services and management, writing – review and editing

NM: SAR data processing

ET: SARTRAC PI, supervision, methodology, writing – review and editing

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