# Mapping the timing, distribution, and scale of *Sargassum* influx events in the coastal zone of Bonaire, Caribbean Netherlands

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# Contents

# Summary

Since 2015, the island of Bonaire (Caribbean Netherlands) has periodically received massive influxes of the holopelagic brown algae *Sargassum*. These influxes have negative impact on the coastal environment, tourism industry and public health, while the costs and efforts related to *Sargassum* clean-up activities pose severe socioeconomical impacts on the local society. To offset these negative impacts, there is a growing interest towards potential opportunities for *Sargassum* reuse and valorization on Bonaire. Unfortunately, insufficient knowledge about the approximate volumes of *Sargassum* arriving at specific locations over time, makes it difficult to determine suitable uses of *Sargassum* and the necessary scale of potential enterprises on Bonaire. To fill this knowledge gap, we have used Sentinel-2 (S2) satellite imagery, to reconstruct the timing, distribution and scale of *Sargassum* influx events in the coastal zone of Bonaire in the years 2017 to 2022, with the ultimate goal to determine the mean annual harvestable biomass of *Sargassum* within the coastal waters of Bonaire. Ground truth data for training and validation purposes was determined for 6 S2-images by manually annotating floating *Sargassum* patches. For the detection of floating *Sargassum* we have used a Random Forest (RF) model for which we used the 10 m resolution S2-bands (Blue, Green, Red and NIR) and Normalized Difference Vegetation Index (NDVI) as predictors. Results showed that floating *Sargassum* can be well detected with the RF-model (overall accuracy 99.9%). However, to have the best results, good cloud masking is essential. Since the cloud masking using AI-techniques was unsatisfactory, the masking was done manually. *Sargassum* influxes were primarily observed between February and July. The cumulative area coverage (ha) of *Sargassum* ranged from 20.3 ha in 2017 to 405.5 ha in 2018, and was on average 111.9 ha per year. Most of the floating *Sargassum* was detected near the eastern coast (i.e. 10-200 m from the shore) and in the western part of two coastal bays (i.e. Lagun and Lac Bay), which is mainly the result of prevailing easterly trade winds pushing *Sargassum* from open sea towards these locations. Moreover, on average 950.9 ton dry weight of *Sargassum* (range 50.8 − 1751.8) washed up annually between 2017 and 2022 in Lac Bay and Lagun. These are the only 2 sites where *Sargassum* can potentially be harvested due to relatively calm waters in these bays. This study provides the first assessment of the approximate volumes of *Sargassum* biomass arriving at specific locations over time, which will aid identification of suitable uses of *Sargassum* and the scale of potential enterprises on Bonaire, while it also allows assessments of economic feasibility and sustainability for proposed ventures. In addition, the obtained information will help identify priority areas for coastal management of these *Sargassum* influxes.

# 1 Introduction

Floating rafts of the holopelagic brown algae *Sargassum* spp. (*Sargassum* hereafter) provide an essential marine habitat for a wide range of organisms and serves as a hotspot for biodiversity and productivity in otherwise substrate poor, low-nutrient open-ocean waters (Laffoley *et al*., 2011). However, since 2011, there has been a drastic increase in *Sargassum* biomass in the Caribbean Sea and tropical Atlantic Ocean, and consequently, massive amounts of *Sargassum* have intermittently washed ashore the coastlines of the Caribbean, northern and central America, and West Africa (Gower *et al*., 2013; Wang *et al*., 2019). These recent mass *Sargassum* beaching events had devastating impacts on tourism, have disrupted fisheries, damaged critical nearshore ecosystems, and coastal livelihoods, and caused significant health problems for populations exposed to rotting *Sargassum* (Desrocher *et al*., 2020).

To stop further decline in tourism and to avoid a deterioration of coastal ecosystems and associated fisheries, local governments, together with the tourism industry have spent much money to remove *Sargassum* from their beaches and coastal waters. For example, the Mexican government invested ~USD 17 million dollars in the removal of 522,226 tons of *Sargassum* in 2018, and ~USD 2.6 million dollars for the removal of 85,000 tons in 2019 (Chávez *et al*., 2020). For Cancun, Mexico, they estimated that the cleaning of each meter of coastline could be as high as USD 1000 dollars (Louime *et al*., 2017). Clearly, the costs and efforts related to these clean-up activities posed severe socioeconomical impacts on the local society. As such, there is a rapidly growing interest across the Caribbean region in turning this hazard into a benefit by developing industries that can utilize stranded *Sargassum* as a raw material (Oxenford *et al*., 2021).

Despite this interest, progress has been slow and there are still relatively few examples of sustainable businesses making *Sargassum*-based end products. This has been mainly attributed to the following five categories of constraints that *Sargassum* stakeholders (i.e. entrepreneurs, businesses owners, researchers) face, namely (1) unpredictable supply of *Sargassum* due to uncertainty in *Sargassum* influx timing, quantity and location; (2) issues related with the chemical composition of *Sargassum*; (3) issues with harvest, transport and storage of *Sargassum*; (4) governance; (5) funding (Oxenford *et al*., 2021; Desrocher *et al*., 2022).

Since 2015, the island of Bonaire (Caribbean Netherlands) has also been hit hard by *Sargassum* influx events, especially on the East coast where *Sargassum* rafts washed up on beaches (Lagun, Lac Bay, Washikemba) and in coastal bays (Lagun and Lac Bay) (Dutch Caribbean Nature Alliance, 2019). In Lac Bay and Lagun, these *Sargassum* beaching events resulted in die-offs of fish, seagrasses and mangroves, while the gases emitted by rotting *Sargassum* reached concentrations known to cause health problems for people (Dutch Caribbean Nature Alliance, 2019). As such, these *Sargassum* beaching events are considered to cause significant problems to nature, tourism, and public health, while the costs and efforts related to *Sargassum* clean-up activities pose severe socioeconomical impacts on the local society. As a result, there is a growing interest towards potential opportunities for *Sargassum* reuse and valorization on Bonaire (López-Contreras *et al*., 2021). Unfortunately, the current lack of knowledge about approximate volumes of *Sargassum* arriving at specific locations over time, makes it difficult to determine suitable uses of *Sargassum* and the scale of potential enterprises on Bonaire, while it also hinders assessments of economic feasibility and sustainability for proposed ventures (López-Contreras *et al*., 2021). To fill these knowledge gaps, a new project was started in 2022, called "Circular uses of organic biomass streams in Bonaire" (short name "BONCIRC"), a collaboration between several Wageningen University & Research (WUR) departments, local entities and companies[1].

As part of the BONCIRC project, the aim of this study was to explore the use of freely available Sentinel-2 imagery with a global coverage every 5 days, to reconstruct the timing, distribution and scale of *Sargassum* influx events in the coastal zone of Bonaire in the years 2017 to 2022. Next, the obtained information was used to predict when, where and how much *Sargassum* seaweed can potentially be harvested in the coastal area of Bonaire. In addition, the obtained information was used to map the cumulative impact of subsequent *Sargassum* influxes along the coastline of Bonaire, which will help identify priority areas for coastal management of these influxes.

[1] https://www.wur.nl/en/project/circular-uses-of-organic-biomass-streams-in-bonaire.htm

# 2 Materials and methods

## 2.1 Study area

The island of Bonaire is situated at 12°N and 68°W, about 60 km off the coast of Venezuela in the Caribbean Sea. In recent years, many areas along the east coast of Bonaire have been hit with *Sargassum*, including Lagun and Lac Bay (Fig. 1). Lac Bay is a shallow sheltered coastal bay on the southeast side of Bonaire and is dominated by three unique biotopes, a mangrove forest on the northern side, an open water area of great importance for the seagrass meadows, and a coral dam that forms a natural barrier between the turbulent Caribbean Sea and the bay. Lagun is a small inlet on the east side of Bonaire and has some mangroves and small patches of seagrass growing along its edges. To detect *Sargassum* influxes at an 'early stage' when it's still at open sea relative far from the east coast of Bonaire, when it approaches the exposed coastline, and when it enters the sheltered coastal bays (i.e. Lagun and Lac Bay) where *Sargassum* could potentially be harvested, we divided the total study area into 4 sub-areas (Fig. 1), the open sea, defined as the area >200 m away from the east coast of Bonaire (167895.1 ha indicted in white), the coastline stretching 10 m - 200 m distance from the east coast (914.3 ha indicated in orange), Lagun (13.4 ha indicated in red) and Lac Bay (363.9 ha indicated in green). The grey area west of Bonaire is excluded from analysis as *Sargassum* has never been observed to approach Bonaire from this side due to the prevailing easterly trade winds.

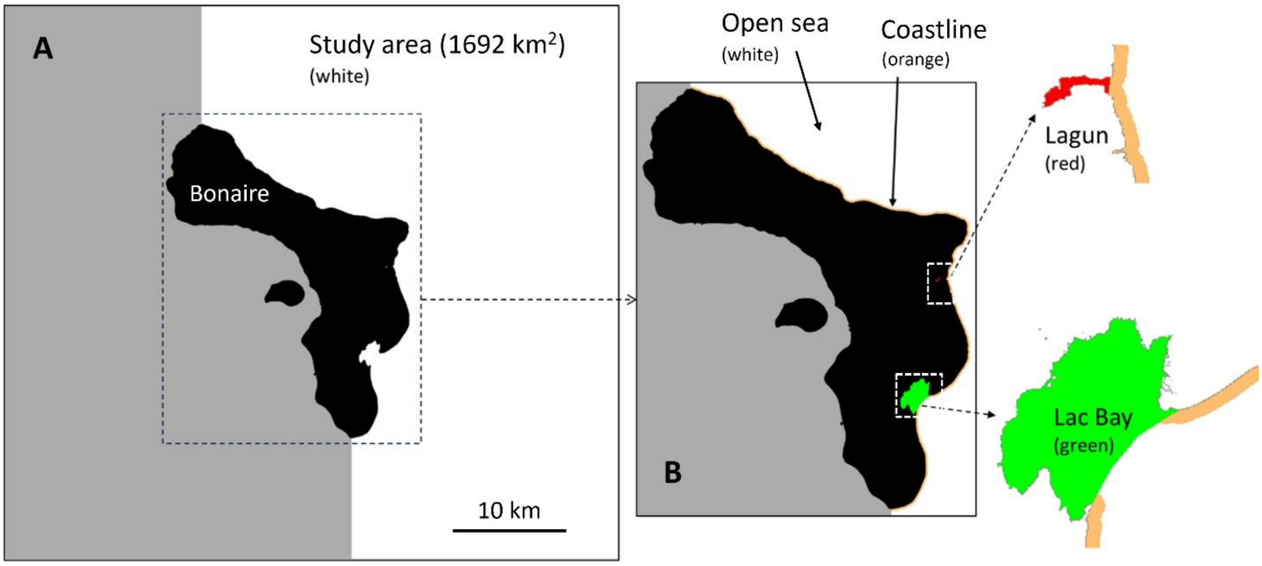


***Fig. 1.*** *The study area East of Bonaire and sub-areas within this area that were monitored for coverage of Sargassum. (A) Total study area (indicated in white). (B) The four different sub-areas within our study area, namely (1) open sea (area in white > 200m away from the shore), (2) the coastline (area in orange 10-200m away from the shore), (3) Lagun (area in red), (4) Lac Bay (area in green)*.

## 2.2 Satellite imagery

Satellite imagery was obtained from 2015 to 2022 from the multi-spectral instrument (MSI) sensor onboard Sentinel-2 (S2), which is carried out by the European Union's Copernicus Earth Observation programme and consists of a constellation of two identical satellites: S2A was launched in 2015 and a second satellite S2B was launched in 2017. The revisit frequency of the constellation with 2 satellites is five days. The MSI-sensor has several (13) multispectral bands in the visible (VIS), near-infrared (NIR) and shortwave infrared (SWIR) part of the EM-spectrum and has a spatial resolution of 10 m, 20 m and 60 m (band dependent). To detect *Sargassum* in the coastal waters of Bonaire, the visible 10 m bands (i.e., Blue Band 2, Green Band 3, Red Band

4) and near-infrared (NIR)-band (Band 8) were used to have the highest possible detail (i.e., 10 m x 10 m pixels).

For the years 2015 to 2022 we have collected and processed all available S2A and S2B images for Bonaire (whole area is covered by 1 tile, 19PEP), available via the Copernicus Open Access Hub (https://scihub.copernicus.eu/) and the EarthExplorer of the U.S. Geological Survey (USGS). As the first (minor) *Sargassum* influx on Bonaire was reported in June 2015 (Dutch Caribbean Nature Alliance, 2019), we have also looked for suitable S2-images of 2015 and 2016. However, as the S2B satellite was launched after 2016, the number of available images was very limited in those years (0 and 13, respectively). Moreover, as the second *Sargassum* influx on Bonaire was reported in 2017 (Dutch Caribbean Nature Alliance, 2019), we decided to focus on S2-images from 2017 and later. At the time of our search for S2-imagery in 2022 only Level-1C products were available for Bonaire. Due to differences in the exact format of the S2-data it was not possible to reprocess all images to Level-2A products (Bottom-Of-Atmosphere (BOA)). Therefore, it was decided to use Level-1C products, which are geometrically and radiometrically corrected images for top-of-atmosphere reflectance's (TOA). On average 70 images per year are available when S2A and S2B are both operational as a S2-constellation (with a revisit time of 5 days), except for 2017 when S2B data became available near the end of that year (Table 1). From these S2-images, we had to discard 11 images due to 100% cloud cover (Table 1).

***Table 1.*** *Number of available Sentinel-2 images per year and number of used images with <100% cloud cover.*

| Year | Satellite | Nr. of available images | Nr. of used images (< 100% cloud cover) |
|---|---|---|---|
| 2017 | Mostly S2A (some S2B) | 32 | 32 |
| 2018 | S2A & S2B | 70 | 67 |
| 2019 | S2A & S2B | 68 | 67 |
| 2020 | S2A & S2B | 70 | 69 |
| 2021 | S2A & S2B | 70 | 69 |
| 2022 | S2A & S2B | 72 | 67 |

## 2.3 *Sargassum* detection method

For the detection of floating (not beached) *Sargassum* we have used a Random Forest model. Random Forest (RF) or random decision forests, is a powerful but simple data mining and supervised machine learning technique. It allows quick and automatic identification of relevant information from large datasets. One of the advantages of this technique is that it relies on the collection of many predictions (trees) rather than trusting on one. RF can be used for both classification and regression studies. In the case of classification as in this study, the RF-classifier is a set of decision trees obtained by the random selection of a group of variables from the variable space and a bootstrap procedure that recurrently selects a fraction of the sample space to fit the model (Conesa and Hernández, 2014). It aggregates the votes from different decision trees to decide the final class of the test object. This means the "winner" class is the one who appears most times in the list of outputs from all the decision trees used (Fig. 2). We have used the Scikit-learn free software machine learning library for Python (https://scikit-learn.org/stable/).

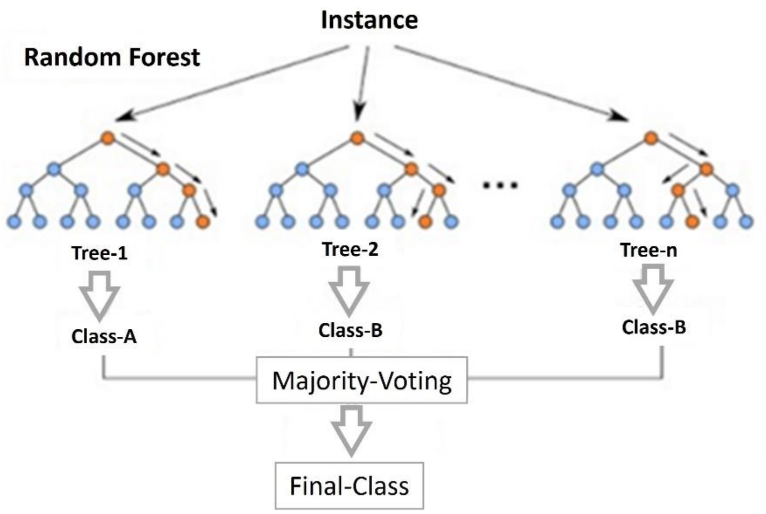


***Fig. 2***. *Random Forest for classification, where the Final-Class in our case is whether a pixel on a S2-images is classified as Sargassum or not (Image source: KDNuggets).*

As we aim to detect floating *Sargassum* in nearshore areas and small inlets (e.g. Lagun) and as in many cases the sizes of the patches of floating *Sargassum* are narrow and elongated (see Fig. 3), we have decided to use only the 10 m resolution S2-bands, namely the Blue, Green, Red and Near-Infrared (NIR)-band, to have the highest possible spatial detail. We also added the Normalized Difference Vegetation Index (NDVI), which is the normalized difference between the NIR- and the red-band, which is calculated as:

$$NDVI = \frac{NIR - RED}{NIR + RED} \quad (1)$$

where RED and NIR are the digital numbers (DN) corresponding to the spectral values in the red and near-infrared regions, respectively. The NDVI takes advantage of the red edge of the vegetation spectral reflectance and is an index that is widely used to monitor photosynthetic active vegetation on land, but is also suitable for detecting floating algae (Son *et al*., 2012). Other indices have been developed specifically for the detection of *Sargassum* brown algae, such as the Maximum Chlorophyll Index (MCI, requires bands 4, 5 and 6) and Modified Floating Algae Index (MFAI, requires bands 4, 8 and 9) specifically for S2 sensor MSI, however these indices rely on 20 m or 60 m S2-bands, thus not proving enough spatial detail for our aim (Ody *et al*., 2019; Descloitres *et al*., 2021).

***Fig. 3.*** *Aerial photo of floating Sargassum in the Caribbean Sea near St. Eustatius (photo taken by Sander Mücher on March 26, 2023).*

## 2.4 *Sargassum* detection model validation

Ground truth data for training and model validation purposes was determined for a set of S2-images by manually annotating floating (not beached) *Sargassum* patches (based on True/False Color and NDVI images). Images were selected for dates when there was a high influx of *Sargassum* on the east coast of Bonaire (selected dates: March 4 and 9, 2018; March 14, 2019; February 26, March 3, and May 2, 2022). Particularly the image of March 4, 2018, shows many patches of floating *Sargassum* (Fig. 4) along the coastline of Bonaire, but also further from the coast at open sea. However, it must be noted that this image is exceptional, as most images with floating *Sargassum* at open sea or near the coast show much smaller amounts. The resulting binary masks contain 10 m x 10 m pixels with value 1 (identified as *Sargassum*) and value 0 (the rest, mostly water pixels but also cloud and haze pixels). Since we are only interested in floating *Sargassum a*t sea and along the coast, the entire island of Bonaire (i.e., pixels on land) plus a 10 m seaward buffer are masked out to avoid mangroves and other vegetation along the shores being classified as *Sargassum*. The land mask plus the 10 m buffer is based on a coastline map, which is visually digitized from high-resolution Pléiades images (Mücher *et al*., 2017) and rasterized in a 10 m x 10 m mask. It must be emphasized that the training data, which is based on the visual annotation of *Sargassum* pixels in the S2-images with a 10 m resolution, is not the exact truth, since we did not visually check for *Sargassum* at sea. As such, our training data may slightly vary from the real extent of *Sargassum* rafts.

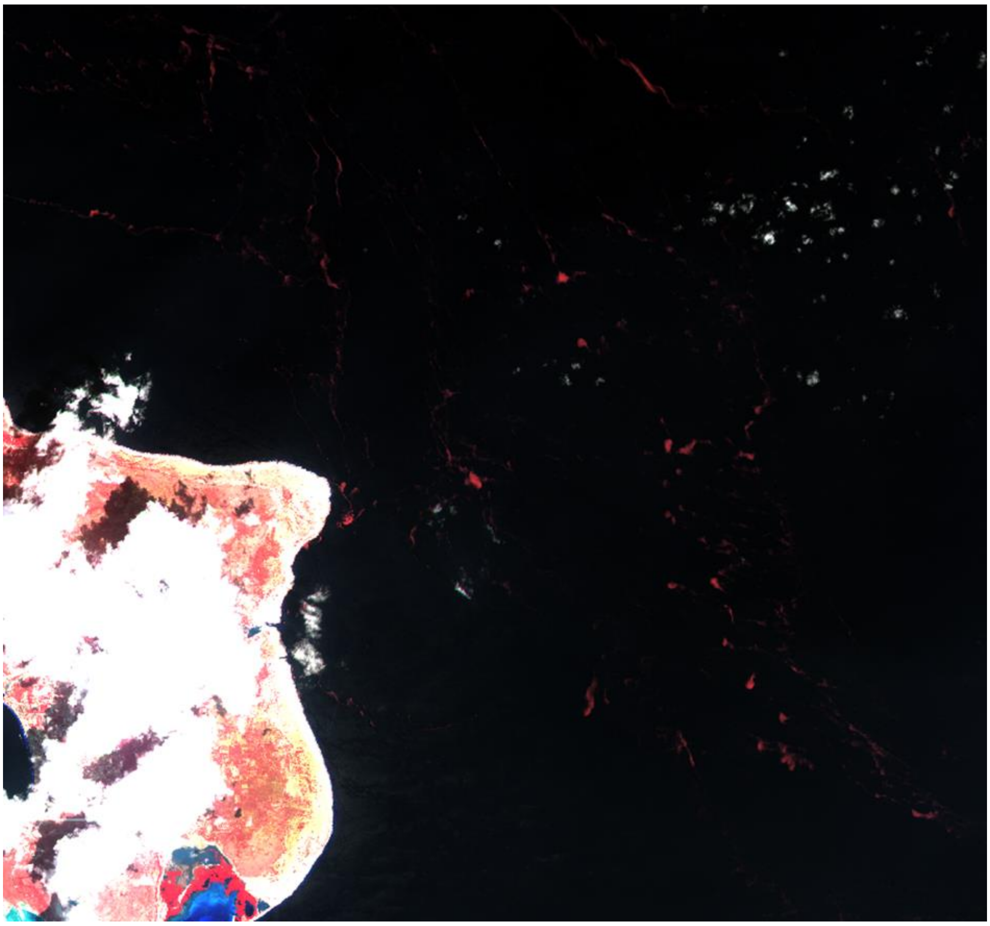

***Fig. 4.*** *False color image of March 4, 2018, showing floating Sargassum rafts (red areas) north and east of Bonaire. The bright white areas at sea and above land reflect clouds.*

Although the six images that were manually annotated, were taken on days with a significant influx of *Sargassum* along the east coast, the number of *Sargassum*-pixels on these images was still very small compared to the number of water and cloud pixels inside the study area (less than 0.025% of the total set of pixels is *Sargassum*). To have a better balance between the amount of *Sargassum* and non-*Sargassum* pixels we randomly selected 1% of the non-*Sargassum* pixels. Together with the *Sargassum* pixels this formed our ground truth dataset. In the end 80% of this dataset was randomly selected and used for training and the remaining 20% for validation, for which we used a confusion matrix. The precision and overall accuracy of the RF-model were defined as follows:

$$Precision\ (\%) = \frac{TP}{(TP + FP)} * 100 \tag{2}$$

$$Overall\ accuracy\ (\%) = \frac{(TP + TN)}{(TP + TN + FP + FN)} * 100 \tag{3}$$

where TP reflects a true positive, TN reflects a true negative, FP reflects a false positive and FN reflects a false negative. In addition, the true positive rate (TPR or *Recall*, *Sargassum* pixels successfully recognized) , the true negative rate (TNR, pixels successfully recognized as 'rest' i.e., no *Sargassum*) and F1 score were determined as follows:

$$TPR\ (\%) = \frac{TP}{(TP + FN)} * 100 \tag{4}$$

$$TNR\ (\%) = \frac{TN}{(TN + FP)} * 100 \tag{5}$$

$$F1\ score\ (\%) = 2 * \frac{Precision * TPR}{(Precision + TPR)} \tag{6}$$

## 2.5 Cloud masking

To deal with cloud-haze pixels we have tried to use an AI-model (Nimbus), developed in Python using the PyTorch library for the greenmonitor.nl. It uses a Binary Cross-Entropy (BCE) loss function, which is a method of evaluating how well the neural network algorithm models the given satellite training images. If predictions deviate too much from actual results, the loss function will produce a large error. Gradually, with the help of an Adam optimization algorithm the BCE loss function learns to reduce the error in prediction (source). In the Netherlands, Nimbus is successfully implemented for the masking of land-based clouds. To apply Nimbus for Bonaire and for sea-based clouds, we have re-trained the model for several S2-images (selected dates: March 4 and 9, 2018; March 14, 2019; February 26, March 3, and May 2, 2022) with clouds and haze, which were manually annotated similar as *Sargassum* (i.e., clouds versus non-clouds). Although the model could detect most clouds (and cloud shadows), the overall results were not satisfactory, as is demonstrated in Figure 5. As high waves along the eastern and north-eastern coastline (caused by the easterly trade winds) break on the shore, they become present as white areas that are identified as 'clouds' (see yellow encircled areas in Fig. 5A & B) by Nimbus. As a result, many of the *Sargassum* that is present directly along the coastline is masked out (Fig. 5B). In most cases the number of *Sargassum*-pixels is small and restricted to the coastline, which means that the detection of *Sargassum* (and clouds) near the coastline must be fully accurate (Fig. 5C). To get the most accurate results, it was therefore decided to do the cloud masking manually to avoid false negatives caused by clouds, haze, and image artefacts. From an operational perspective this is not ideal, but for this study it was considered to be the best option.

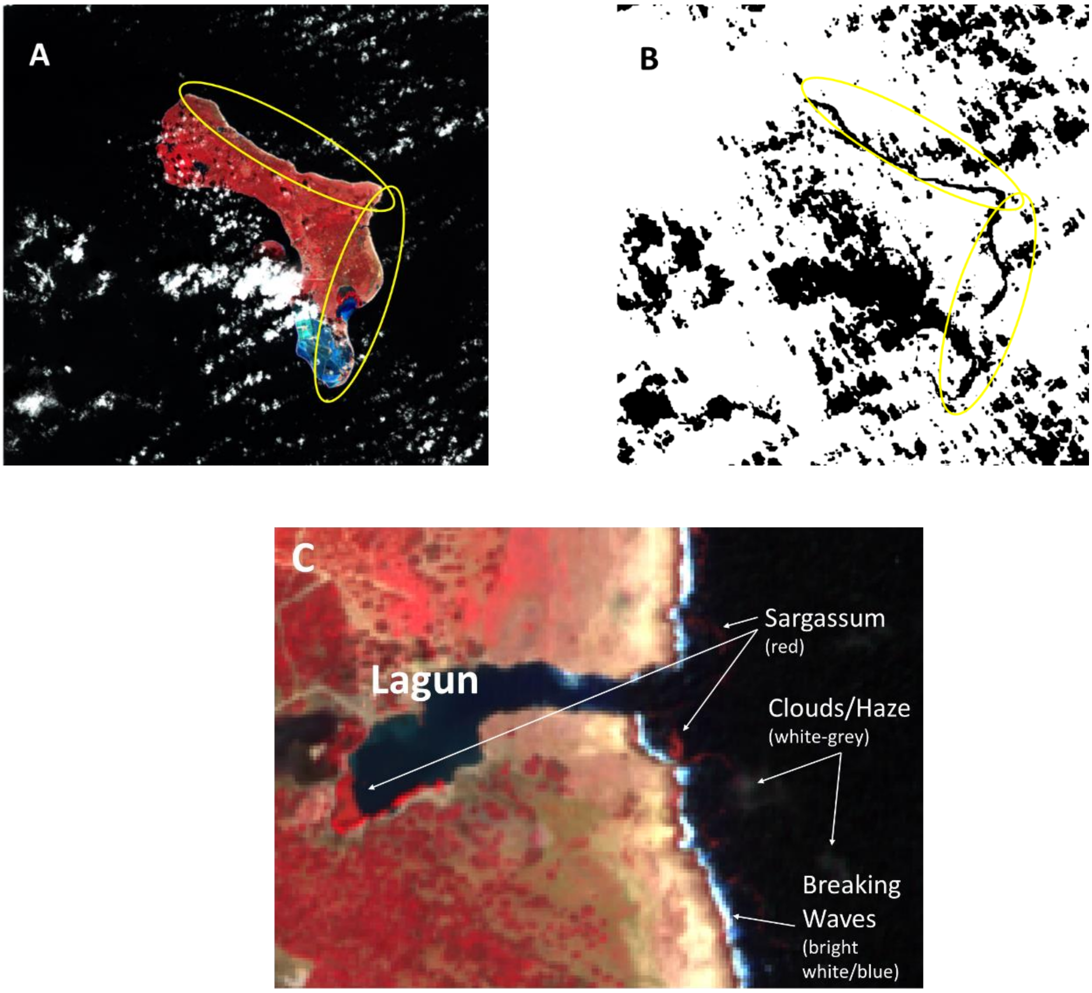


***Fig. 5.*** *False color S2-image for January 18, 2017 showing clouds in white (A) and corresponding cloud mask (in black) of Nimbus AI-model (B). The yellow encircled areas show the eastern coastline of Bonaire, which is masked out as being identified as clouds by the Nimbus AI-model. (C) Coastal area around Lagun showing the breaking waves along the shore (in bright white/blue), clouds and haze (in white-grey), and pockets of Sargassum (in red).*

## 2.6 Cloud-corrected area coverage of *Sargassum*

Due to the spatial and temporal variability in cloud cover on the S2-images, the real number of pixels checked for *Sargassum* varied per S2-image (Fig. 6). To correct for cloud cover, we therefore expressed the Sargassum area coverage as a percentage relative to the number of cloud-free pixels that were analyzed using equation (7):

$$Sargassum\ area\ coverage\ (\%) = \frac{No.\ of\ \ classified\ Sargassum\ pixels}{No. of\ cloud\ free\ pixels} * 100 \qquad (7)$$

Assuming that *Sargassum* was equally distributed in areas with and without cloud cover, we subsequently used the *Sargassum* coverage area (%) and converted it to surface area (ha) using equation (8):

$$Sargassum\ area\ coverage\ (ha) = \frac{Sargassum\ area\ coverage\ (\%) * Total\ No.\ of\ pixels}{10000} \qquad (8)$$

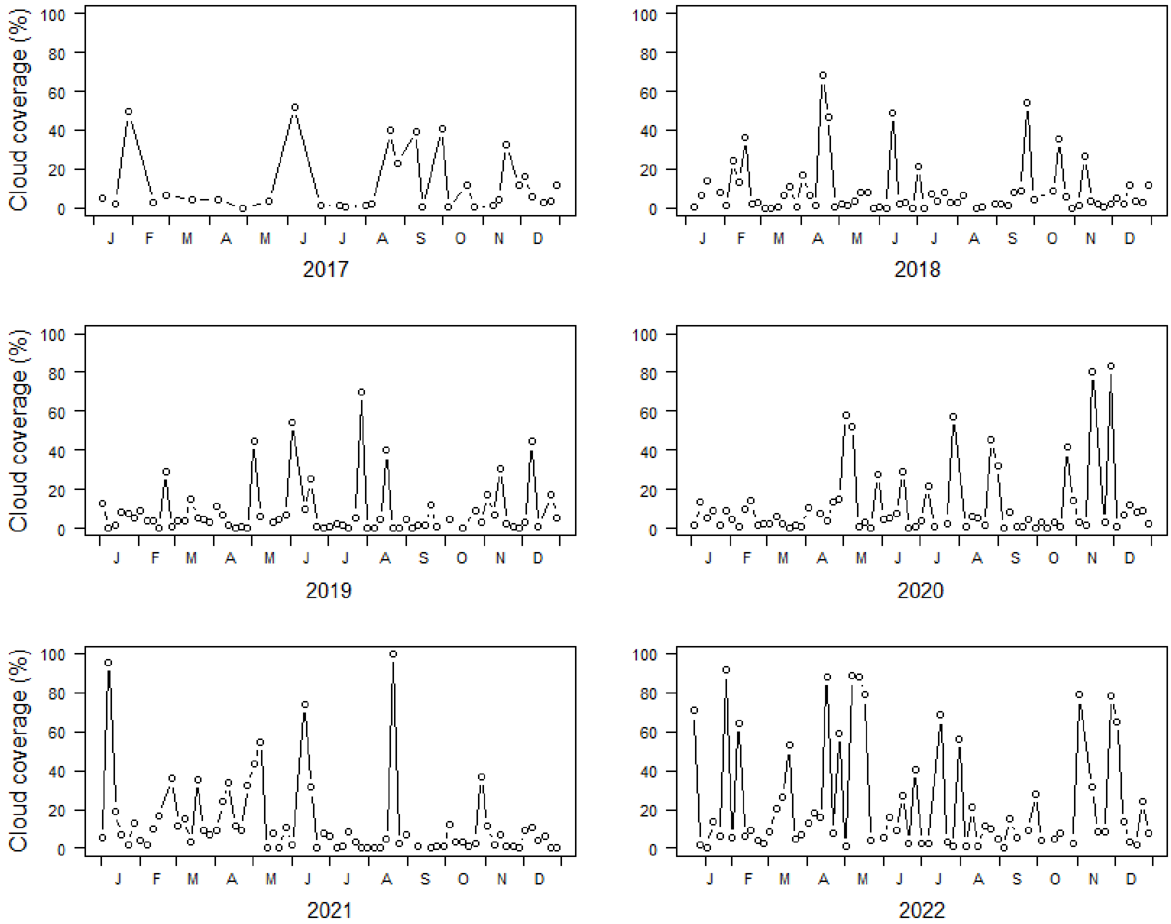


***Fig. 6.*** *Percentage cloud cover identified per S2-image between 2017 and 2022 for the total study area.*

# 3 Results

## 3.1 *Sargassum* detection model performance

The importance of the 5 predictors used in the RF-model to detect *Sargassum* was as follows: NDVI (64%), NIR (15.5%), Blue (9.4%), Red (5.8%) and finally Green (5%). This shows that the NDVI is by far the most important predictor for the RF-model to identify *Sargassum*. RF-model validation results presented in the confusion matrix in Table 2, show a model precision of 98.3% and an overall model accuracy of 99.87%, with a true positive rate (TPR or recall, *Sargassum* pixels successfully recognized) of 96.11% and a true negative rate (TNR, pixels successfully recognized as 'rest' i.e., no *Sargassum*) of 99.96%. It must be emphasized that the overall accuracy is based on 20% of the dataset and on the six manually annotated S2-images, and as such may not apply to the remaining S2-images.

***Table 2.*** *Confusion matrix reflecting the performance of the RF-model to detect floating Sargassum (validation is based on 20% of the dataset). TP = True Positive, TN= True Negative, FP = False Positive, FN= False Negative, TPR = True Positive Rate, TNR = True Negative Rate.*

| | **RF-model** | | | |
|---|---|---|---|---|
| **Truth** | Non-*Sargassum* | *Sargassum* | Total | |
| Non-*Sargassum* | **386,299** (TN) | 157 (FP) | 386,456 | 99.96% (TNR) |
| *Sargassum* | 377 (FN) | **9,326** (TP) | 9,703 | 96.11% (TPR) |
| Total | 386,676 | 9,483 | **396,159** | |
| | | 98.34% (precision) | | **99.87%** (overall accuracy)<br>97.21% (F1) |

These results show that the RF-model missed 377 pixels identified as *Sargassum* in the ground truth (False Negatives, FN). Visual inspection of the images showed that these missed pixels were mostly located along the edges of floating *Sargassum* patches, where *Sargassum* may have floated beneath the water surface, making it less detectable by the satellite. It could also be that *Sargassum* is less densely packed at the edge of a patch compared to the center. Moreover, 157 pixels were classified as *Sargassum* by the RF-model, which were not present in the ground truth (False Positives, FP). A closer look at the data revealed that these pixels were mostly cloud, cloud-shadow or haze pixels and some pixels with image artefacts (so-called inter-band parallax, caused by moving objects (e.g. clouds, airplanes and near vertical striping in the image, caused by non-uniformity near the detector boundaries (Gascon et al., 2017). In Figure 7, we have provided two examples where cloud-haze pixels and image-artefact-pixels were misclassified as *Sargassum*.

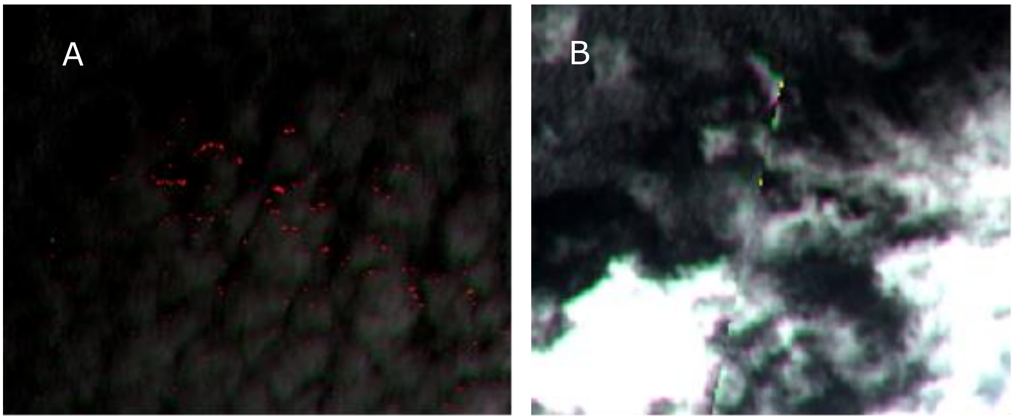


***Fig. 7.*** *Examples of false positives (i.e., pixels that were misclassified as Sargassum by the RF-model) due to (A) clouds/haze (red pixels) and (B) image artefacts (yellow pixels).*

## 3.2 Timing, distribution and scale of *Sargassum* influx events

Figure 8 shows the area coverage of *Sargassum* for the total study area between 2017 and 2022, where the area coverage is expressed in hectares (ha) based on the number of 10 m x 10 m pixels classified as *Sargassum* per cloud-corrected S2-image (see equations 7 and 8). In general, the total area coverage of *Sargassum* during an influx event is less than 25 ha, except for 4 March 2018, when an area of 352.8 ha was covered by *Sargassum*. Moreover, apart from 2017, when there was some *Sargassum* detected in January and December, *Sargassum* was primarily observed between February and July (Fig. 8).

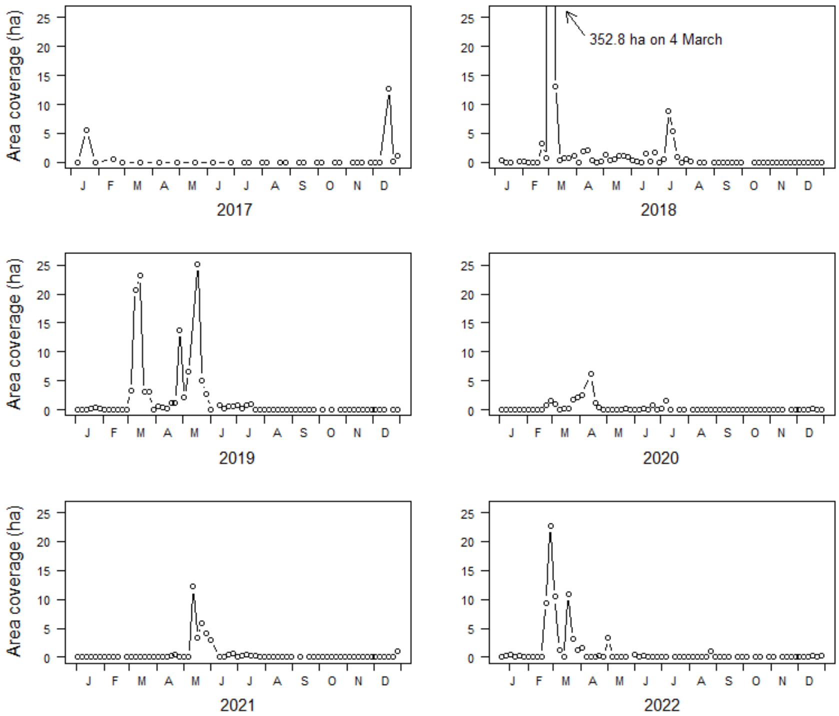


***Fig. 8.*** *Cloud-corrected area coverage (ha) of Sargassum between 2017 and 2022 for the total study area.*

When summing the cloud-corrected area coverage of *Sargassum* for all analyzed S2-images per year for the total study area, we see that the total area coverage of *Sargassum* ranged from 20.3 ha in 2017 to 405.5 ha in 2018, being on average 111.9 ha per year (see Table 3).

***Table 3.*** *Cumulative cloud-corrected area coverage (ha) of Sargassum per sub-area per year between 2017 and 2022. Note that these values are not corrected for the number of S2-images that were analyzed per year, which varied from 32 images in 2017 to either 67 or 69 images in the other years (see Table 1).*

| **Sub-area** | **2017** | **2018** | **2019** | **2020** | **2021** | **2022** | ***mean*** |
|---|---|---|---|---|---|---|---|
| Open sea | 5.3 | 347.4* | 15.5 | 0.6 | 0.4 | 2.3 | *61.9* |
| Coastline | 14.4 | 36.3 | 88.3 | 15.2 | 21.3 | 53.5 | *38.2* |
| Lagun | 0.4 | 7.1 | 10.9 | 2.2 | 5.8 | 7.5 | *5.6* |
| Lac Bay | 0.2 | 14.7 | 5.4 | 3.6 | 7.0 | 6.0 | *6.2* |
| *Total* | *20.3* | *405.5** | *120.1* | *21.5* | *34.6* | *69.4* | *111.9* |

** Value that includes 345.8 ha of Sargassum area coverage that was observed at open sea on the S2-image of 4 March 2018.*

Figure 9 shows the cumulative cloud-corrected area coverage (ha) of *Sargassum* per sub-area (i.e. open sea, coastline, Lagun, Lac Bay) per year based on the values reported in Table 3. Note that these cumulative values are not corrected for the number of S2-images that were analyzed per year (see Table 1). The cumulative area coverage is highest in 2018 at open sea, which is solely the result of the massive amount of 345.8 ha of *Sargassum* that was detected at open sea on the S2-image taken on March 4, 2018. However, in all the other years, the cumulative area coverage of *Sargassum* is highest in the "coastline" sub-area, being on average 38.2 ha per year.

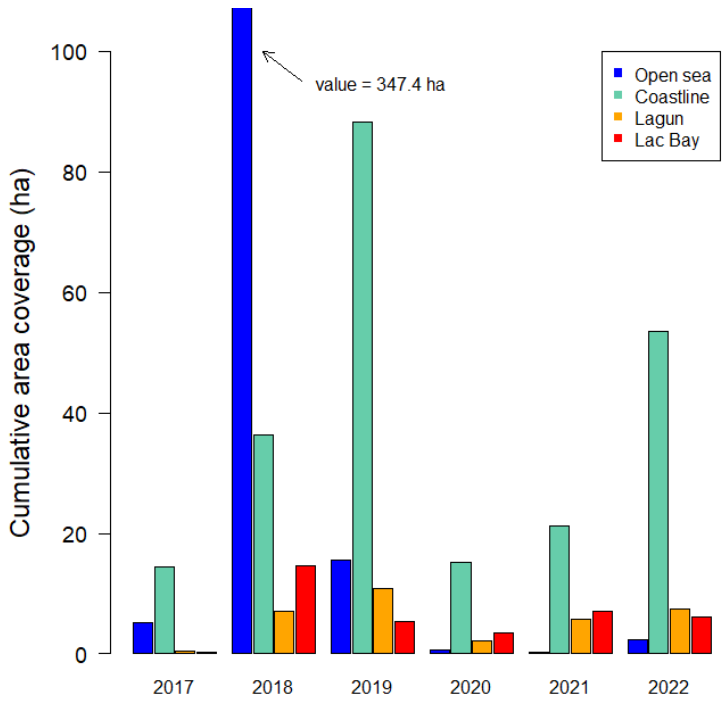


***Fig. 9.*** *Cumulative cloud-corrected area coverage (ha) of Sargassum per sub-area (i.e. Open sea, Coastline, Lagun, Lac Bay) per year between 2017 and 2022. For visual purpose, one data point is not plotted (i.e. cumulative Sargassum area coverage of 347.4 ha at open sea in 2018).*

To illustrate the seasonal presence of *Sargassum* in more detail, we have calculated the mean cloud-corrected area coverage (ha) of *Sargassum* for each month between 2017 and 2022 for the total study area. Next, we plotted these monthly mean values for each year in a boxplot (Fig. 10), which shows that the area coverage of *Sargassum* builds up from December to peak in March, after which it stays relatively high up to May to rapidly decrease again from May to September, with no *Sargassum* being present anymore in our study area from September to November.

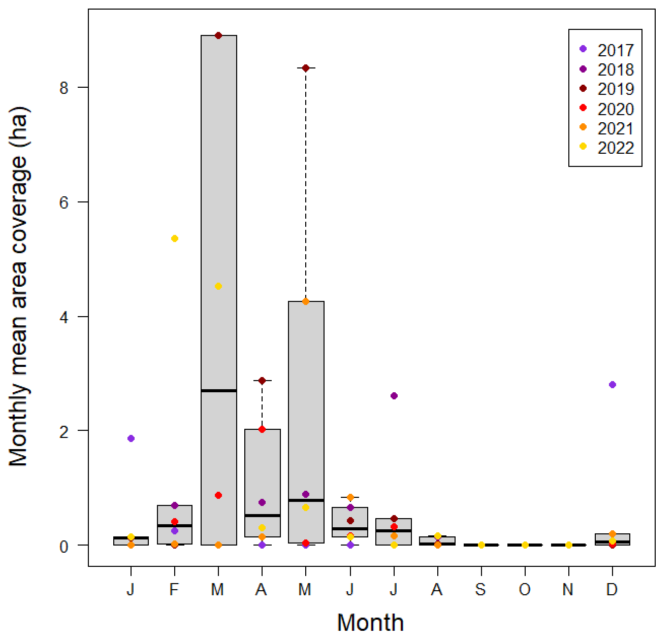


***Fig. 10.*** *Boxplot of monthly mean area coverage (ha) of Sargassum between 2017 and 2022 for the total study area. Midline in box; median; box: 25$^{th}$ and 75$^{th}$ percentiles; whiskers: 1.5 × interquartile range; colored dots: monthly mean area coverage (ha) of Sargassum for a specific year (note that dots can overlap). For visual purpose, one data point is not plotted (i.e. monthly mean Sargassum area coverage of 61.4 ha for March 2018).*

In Table 4 we have also provided the mean area coverage (ha) of *Sargassum* per month (± standard deviation (SD)) for the total study area, based on the monthly means that were calculated for each year between 2017 and 2022 (see Fig. 10).

***Table 4.*** *Monthly mean (± SD) area coverage (ha) of Sargassum based on the cloud-corrected monthly means that were calculated for each year between 2017 and 2022 for the total study area.*

| | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Mean area coverage (ha)** | 0.38 ± 0.73 | 1.13 ± 2.09 | 12.62 ± 24.16 | 1.02 ± 1.17 | 2.37 ± 3.33 | 0.37 ± 0.33 | 0.60 ± 1.00 | 0.06 ± 0.08 | 0.00 ± 0.0 | 0.00 ± 0.0 | 0.00 ± 0.0 | 0.52 ± 1.12 |

To identify where the *Sargassum* was located over time, we have plotted the cloud-corrected area coverage of *Sargassum* for each sub-area (i.e., Open sea, Coastline, Lac Bay, Lagun) between 2017 and 2022 (Fig. 11).


***Fig. 11.*** *Cloud-corrected area coverage (ha) of Sargassum between 2017 and 2022 per sub-area (Open sea, Coastline, Lagun, Lac Bay). For visual purpose, one data point is not plotted (i.e. Sargassum area coverage of 346 ha at open sea on 4 March, 2018).*

Apart from the major *Sargassum* influx event that was detected on 4 March 2018, when almost all *Sargassum* was located at open sea (346 ha), *Sargassum* area coverage was much higher near the coast (i.e. 10-200 m from the east coast of Bonaire) and in the coastal bays (i.e. Lac Bay and Lagun), despite that these sub-areas were much smaller than the "Open sea" sub-area. The fact that *Sargassum* is mostly detected when already near the coast, which is the result of the current and prevalent easterly winds pushing the floating *Sargassum* rafts quickly from the open sea to the coastline, indicates that the 5-day revisit time of S2 satellites is insufficient to be used as an early warning system for *Sargassum* influxes for Bonaire. This suggests that for early warning of *Sargassum* influxes, satellite data with a higher temporal frequency (e.g., daily, like Planet Scope) are required, also because some of the S2-images will be obscured by clouds, which will make them unsuitable for detection of *Sargassum*. However, Figure 11 also shows that *Sargassum* was often first detected at open sea or along the coast, while only a few days later it was also detected in Lagun or Lac Bay. For example, in 2018 Lac Bay experienced a severe *Sargassum* influx on March 9, which is 5 days after a major influx was detected at open sea and near the coast (Fig. 11). This suggests that our *Sargassum* detection method based on S2-images with a 5-day revisit time, can be used as an early warning system for potential *Sargassum* influxes into the bays, allowing local authorities to have 1 to 5 days to put measures in place to protect their coastal bays against a potential *Sargassum* influx.

Table 5 shows the result of a more detailed analysis of the number and duration of *Sargassum* influx events per year between 2017 and 2022 for the sub-areas "Coastline", "Lagun" and "Lac Bay". First we determined "*Sargassum*-influx periods", which were defined as the period with consecutive S2-images with more than 2 *Sargassum*-pixels within the sub-area "Coastline", and the corresponding start and end date, and total length in days per influx period. Results show that the duration of an influx period varied between 5 and 135 days (Table 5). For each coastal influx period, we have also provided the total cloud-corrected area coverage (ha) of *Sargassum* for sub-areas "Coastline', "Lac Bay" and "Lagun", which was based on the sum of cloud-corrected area coverage (ha) detected on all S2-images that were analyzed within a specific influx period per sub-area. This shows that the maximum total cloud-corrected area coverage of *Sargassum* observed along the coastline was 55.50 ha during the 2$^{nd}$ influx-period in 2019 (Table 5). Moreover, we also determined the number of *Sargassum* influx events in Lagun and Lac Bay during these 'coastal-influx' periods, where the start and end of an influx event was also defined by the number of subsequent images in time with at least 2 pixels being classified as *Sargassum*. Results from this analysis showed that the maximum number of influx events in Lac Bay and Lagun happened during the 2$^{nd}$ coastal-influx' period in 2019, which lasted from 4 March to 17 July (136 days), when there were 5 influx events in Lac Bay and 3 in Lagun (Table 5).

***Table 5.*** *Timing and duration of coastal Sargassum influx periods between 2017 and 2022, the cumulative cloud-corrected area coverage (ha) of Sargassum per defined influx period per sub-area (i.e. coastline, Lac Bay, Lagun), and the number of Sargassum influx events in Lac Bay and Lagun per coastal influx period.*

| | Coastal | | | | | | Lac Bay | | Lagun | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Year** | Influx period | Start date | End date | Length (days) | nr. S2-images | Total (ha) | Influx events | Total (ha) | Influx events | Total (ha) |
| **2017/2018** | 1 | 29-Dec-17 | 8-Jan-18 | 10 | 2 | 1.32 | 1 | 0.02 | 1 | 0.09 |
| **2018** | 1 | 28-Jan-18 | 2-Feb-18 | 5 | 2 | 0.47 | 0 | 0 | 1 | 0.01 |
| **2018** | 2 | 22-Feb-18 | 29-Mar-18 | 35 | 8 | 14.89 | 4 | 9.56 | 1 | 1.79 |
| **2018** | 3 | 8-Apr-18 | 18-Apr-18 | 10 | 3 | 3.82 | 0 | 0 | 1 | 0.76 |
| **2018** | 4 | 28-Apr-18 | 7-Jun-18 | 40 | 9 | 4.70 | 2 | 1.57 | 2 | 0.04 |
| **2018** | 5 | 22-Jun-18 | 27-Jun-18 | 5 | 2 | 0.22 | 1 | 1.47 | 1 | 0.18 |
| **2018** | 6 | 7-Jul-18 | 22-Jul-18 | 15 | 4 | 11.18 | 1 | 0.55 | 1 | 4.25 |
| **2018** | 7 | 1-Aug-18 | 6-Aug-18 | 5 | 2 | 0.77 | 1 | 0.01 | 1 | 0.02 |
| **2019** | 1 | 18-Jan-19 | 28-Jan-19 | 10 | 3 | 0.79 | 0 | 0 | 0 | 0 |
| **2019** | 2 | 4-Mar-18 | 17-Jul-19 | 135 | 25 | 55.50 | 5 | 5.38 | 3 | 10.91 |
| **2019** | 3 | 21-Aug-19 | 26-Aug-19 | 5 | 2 | 0.15 | 0 | 0 | 0 | 0 |
| **2020** | 1 | 22-Feb-20 | 3-Mar-20 | 10 | 3 | 3.12 | 0 | 0 | 0 | 0 |
| **2020** | 2 | 13-Mar-20 | 22-Apr-20 | 40 | 8 | 11.06 | 1 | 1.83 | 2 | 2.15 |
| **2020** | 3 | 1-Jul-20 | 6-Jul-20 | 5 | 2 | 0.18 | 1 | 1.13 | 0 | 0 |
| **2021** | 1 | 17-Apr-21 | 22-Apr-21 | 5 | 2 | 0.77 | 0 | 0 | 1 | 0.07 |
| **2021** | 2 | 12-May-21 | 1-Jun-21 | 20 | 5 | 16.56 | 2 | 7.04 | 1 | 5.76 |
| **2021** | 3 | 21-Jun-21 | 26-Jun-21 | 5 | 2 | 1.23 | 0 | 0 | 0 | 0 |
| **2021** | 4 | 6-Jul-21 | 21-Jul-21 | 15 | 4 | 1.12 | 0 | 0 | 0 | 0 |
| **2021** | 5 | 31-Jul-21 | 10-Aug-21 | 10 | 3 | 0.15 | 0 | 0 | 0 | 0 |
| **2021/2022** | 6 | 23-Dec-21 | 12-Jan-22 | 20 | 4 | 1.93 | 0 | 0 | 0 | 0 |
| **2022** | 1 | 21-Feb-22 | 7-Apr-22 | 45 | 9 | 47.41 | 2 | 4.88 | 2 | 7.30 |
| **2022** | 2 | 1-Jun-22 | 11-Jun-22 | 10 | 3 | 0.79 | 1 | 0.27 | 0 | 0 |

## 3.3 Coastal locations of *Sargassum* accumulation per year

To identify the coastal locations where *Sargassum* is accumulating over time, we counted the number of times that a specific 10 m x 10 m pixel within the coastal sub-areas (i.e., Coastline, Lagun, Lac Bay) was classified as *Sargassum* for each year between 2017 and 2022, after which the *Sargassum* counts per pixel per year were plotted.

Results show that the main *Sargassum* wash-up sites between 2017 and 2022 were located in and near Lagun (Fig. 12) and Lac Bay (Fig. 13). Clearly visible is that the *Sargassum* accumulated in small 'inlets' along the coastline north and south of Lagun (Fig. 12, red areas with 5 or more events), which is caused by the prevailing easterly winds. Once entering the Lagun inlet, most of the *Sargassum* washed up at the beaches on the westside of Lagun, especially in 2019 and 2022 (see also photos taken in 2022 in Fig. 12).

In Lac Bay *Sargassum* entered the bay from the east through an opening in the coral dam that separates the bay from the Caribbean Sea, after which the easterly trade winds transported most of the floating *Sargassum* to the mangrove-covered western shoreline of the bay, where it accumulated, especially in 2018 (Fig. 13). Note that no *Sargassum* was detected in Lac Bay in 2017.

*Sargassum* is also regularly detected along the northeastern coastline of Bonaire, however here there are no permanent wash-up sites, as the strong currents and wind pushes the *Sargassum* northwards along the coast.

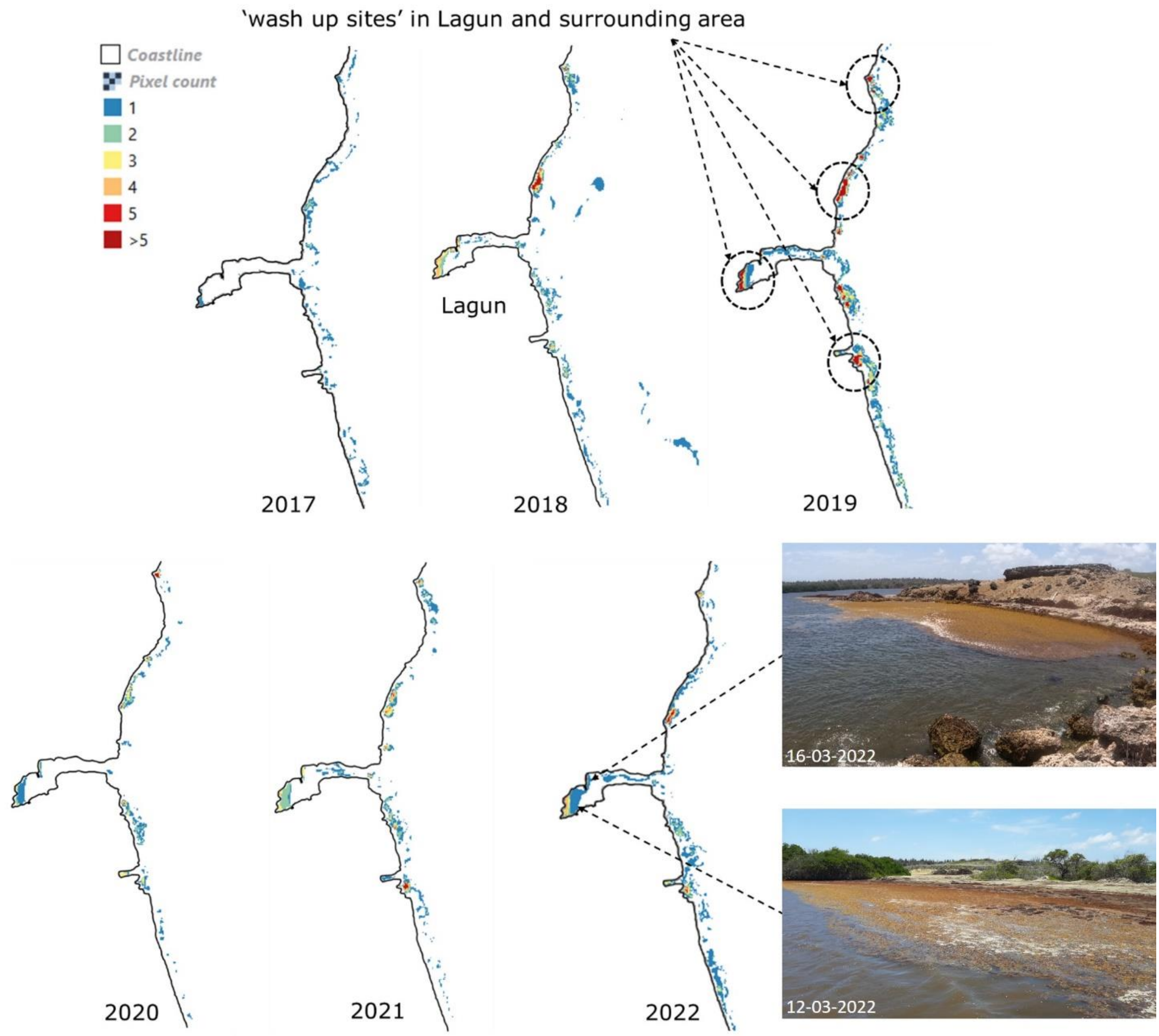


***Fig. 12.*** *Wash-up sites in and near Lagun for the years 2017 to 2022.*

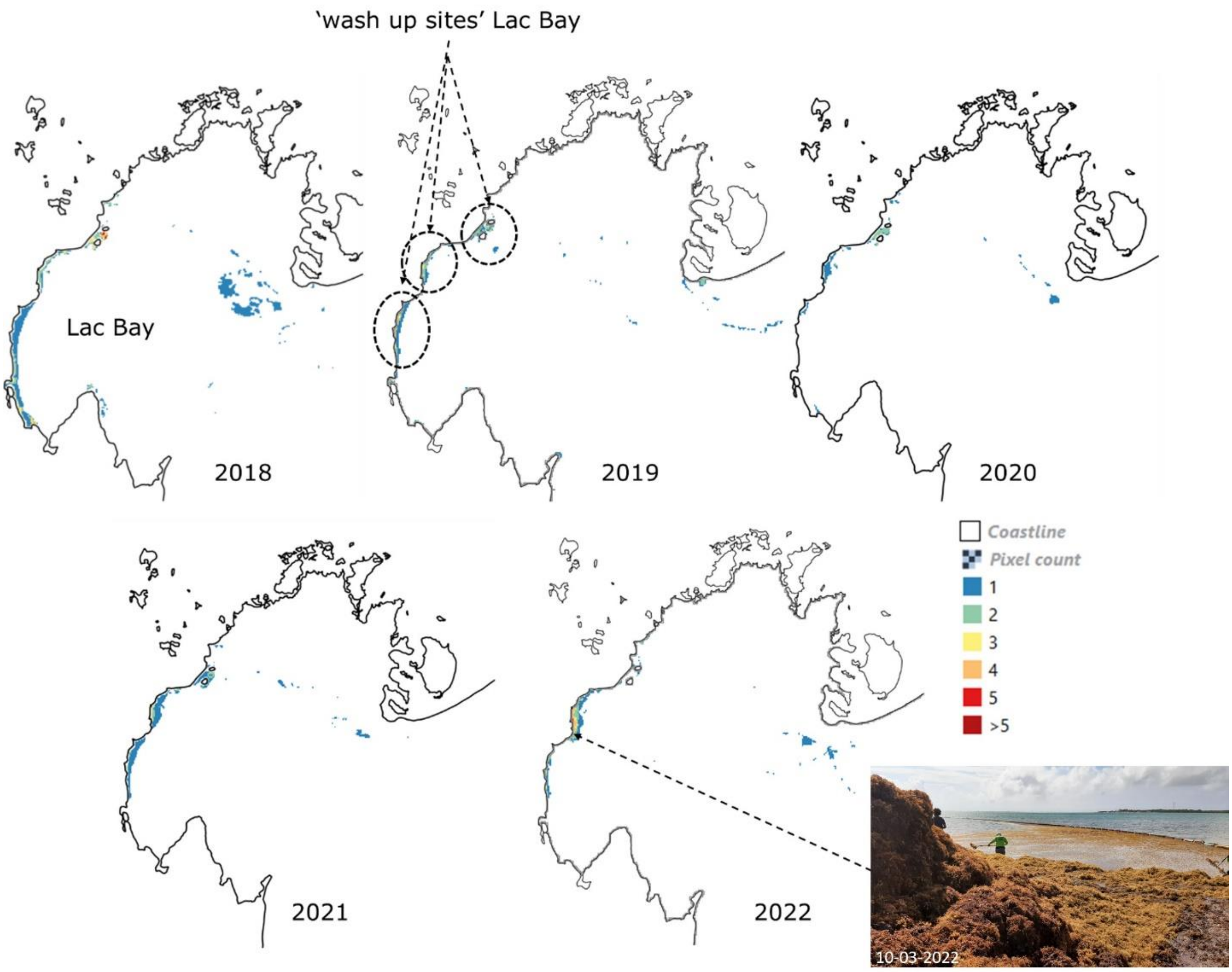


***Fig. 13.*** *Wash-up sites in and near Lac Bay for the years 2018 to 2022. Note that no Sargassum was detected in Lac Bay in 2017.*

## 3.4 Harvestable *Sargassum* biomass per year

On Bonaire, there is a growing interest towards potential opportunities for *Sargassum* reuse and valorization (López-Contreras *et al*., 2021). However, identification of suitable uses of *Sargassum* and the right scale of potential enterprises on Bonaire, requires knowledge about approximate volumes of *Sargassum* arriving at specific harvestable locations over time, which is currently lacking. To fill this knowledge gap, we have developed a method to identify *Sargassum* in time and space using open-source Sentinel 2 satellite data, in combination with specific conversion factors published in the scientific literature to convert areal coverage to volume and subsequently to total annual wet and dry weight of *Sargassum* that could potentially be harvested in the coastal waters of Bonaire. To do so, we first converted the detected areal coverage ($m^2$) of *Sargassum* per sub-area on a specific S2-image from square meter to cubic meter by multiplying the value with 0.4 m, which is the median thickness of drifting *Sargassum* aggregations reported by Gulick *et al.* (2023). Next, we used the conversion factor from *Sargassum* volume to biomass provided by Desrochers *et al.* (2022) who stated that one cubic meter of loosely packed fresh wet *Sargassum* weighs approximately 122 kg, in order to convert *Sargassum* volume in $m^3$ per sub-area to *Sargassum* wet weight (kg). Finally, the following equation (9) from Desrochers *et al.* (2020) was used to convert *Sargassum* wet weight (kg) to *Sargassum* dry weight (kg) per sub-area for each S2-image:

$$Sargassum\ dry\ weight\ (kg) = 0.1651 \times Sargassum\ wet\ weight\ (kg) + 0.0184 \quad (9)$$

Based on this procedure we could estimate the wet and dry weight per sub-area for every S2-image between 2017 and 2022. Next, we summed the obtained values per sub-area per year to get an estimate of total wet and dry weight (in ton) per sub-area per year between 2017 and 2022 (Table 6, 7). Note that these totals are not corrected for the number of S2-images that were analyzed per year.

***Table 6.*** *Total Sargassum wet weight (ton) estimated per sub-area per year between 2017 and 2022.*

| Sub-area | 2017 | 2018 | 2019 | 2020 | 2021 | 2022 | *mean* |
|---|---|---|---|---|---|---|---|
| Open sea | 2503.4 | 169404.3 | 7349.3 | 278.2 | 170.8 | 1102.9 | 30134.8 |
| Coastline | 6714.9 | 15903.9 | 38786.2 | 6568.5 | 9320.8 | 21350.0 | 16440.7 |
| Lagun | 190.3 | 3440.4 | 5324.1 | 1049.2 | 2845.0 | 3664.9 | 2752.3 |
| Lac Bay | 117.1 | 7119.9 | 2581.5 | 1678.7 | 3406.2 | 2810.9 | 2952.4 |
| *Total* | 9525.8 | 195868.6 | 54041.1 | 9574.6 | 15742.9 | 28928.6 | 52280.3 |
| *Total Lagun & Lac Bay* | 307.4 | 10560.3 | 7905.6 | 2727.9 | 6251.3 | 6475.8 | 5704.7 |

***Table 7.*** *Total Sargassum dry weight (ton) estimated per sub-area per year between 2017 and 2022.*

| Sub-area | 2017 | 2018 | 2019 | 2020 | 2021 | 2022 | *mean* |
|---|---|---|---|---|---|---|---|
| Open sea | 424.0 | 27991.2 | 1250.6 | 46.5 | 28.2 | 188.6 | 4988.2 |
| Coastline | 1163.9 | 2925.8 | 7113.7 | 1222.3 | 1718.7 | 4311.0 | 3075.9 |
| Lagun | 31.4 | 568.0 | 879.0 | 173.2 | 469.7 | 605.1 | 454.4 |
| Lac Bay | 19.4 | 1183.8 | 433.8 | 288.0 | 567.2 | 487.0 | 496.5 |
| *Total* | 1638.7 | 32668.9 | 9677.1 | 1730.1 | 2783.8 | 5591.7 | 9015.0 |
| *Total Lagun & Lac Bay* | 50.8 | 1751.8 | 1312.8 | 461.3 | 1036.9 | 1092.0 | 950.9 |

However, due to logistical restrictions, not all of the *Sargassum* biomass that is present in the coastal waters of Bonaire can be harvested. For, example, Fig. 11 and Table 3 indicate that most of the *Sargassum* gets washed up on the extremely exposed eastern coastline of Bonaire, where it is very difficult to harvest *Sargassum* due to strong currents and high wave activity. In contrast, when *Sargassum* enters the sheltered bays of Lagun and Lac Bay where it generally aggregates on the west coast of these bays (Fig. 12, 13), it can be harvested relatively easily. Especially when physical barriers (i.e. booms) are placed inside the bays to direct the floating *Sargassum* to accessible sites where it then concentrates and can be harvested, as is currently done by coastal managers from STINAPA (see photo in Fig. 13). Assuming that floating *Sargassum* can only be harvested when located in Lagun or Lac Bay, the harvestable biomass (i.e. biomass in Lagun and Lac Bay) per year can be determined, which for the period between 2017 and 2022 was on average 5704.7 ton wet weight and 950.9 ton dry weight per year (Table 5 & 6; Fig 14). Although these estimates should be taken with care, they do provide a first rough indication of harvestable *Sargassum* biomass per year, that can be used by local entrepreneurs and policy makers on Bonaire to determine suitable uses of *Sargassum* and the right scale of potential enterprises.

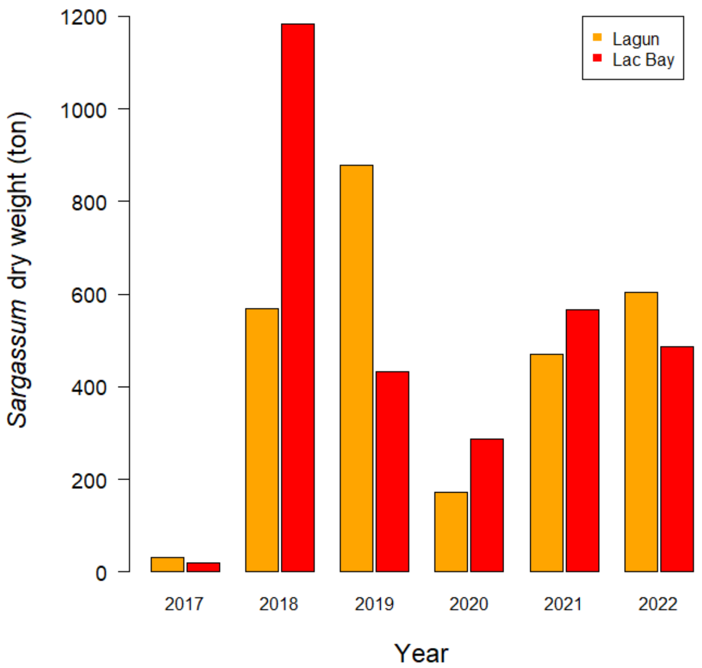


***Fig. 14.*** *Sargassum dry weight (ton) detected in Lagun and Lac Bay per year between 2017 and 2022.*

# 4 Discussion

## 4.1 Limitations of the *Sargassum* detection model

In this study it was decided to monitor the influx of *Sargassum* between the east coast of Bonaire up to 20 km seaward (see Fig. 15) with the intention to follow the movement of *Sargassum* up to the eastern shoreline and into the coastal bays (Lagun and Lac Bay). This puts pressure on the performance of the RF-model to detect *Sargassum*, as in most cases *Sargassum* is present in very small amounts. The variable environmental conditions in the study area, which lead to larger variation in spectral reflectance, complicated the detection even further, as the RF-model needed to detect *Sargassum* in shallow waters in coastal bays (Fig. 15A), in deep waters at open sea (Fig. 15B), near the coastline where waves break along the shore (Fig. 15C), under rough and calm sea conditions, and with variable presence of clouds, cloud shadows and haze (see Fig. 5 & 9). As a result, the model performance is limited (see False Positives and False Negatives in Table 2) and is a compromise between detecting *Sargassum* for shallow waters in the bays and along the coastline and the detection of *Sargassum* at open sea. Therefore, it is expected that the RF-model can be improved when trained for shallow nearshore and deep offshore search areas separately.

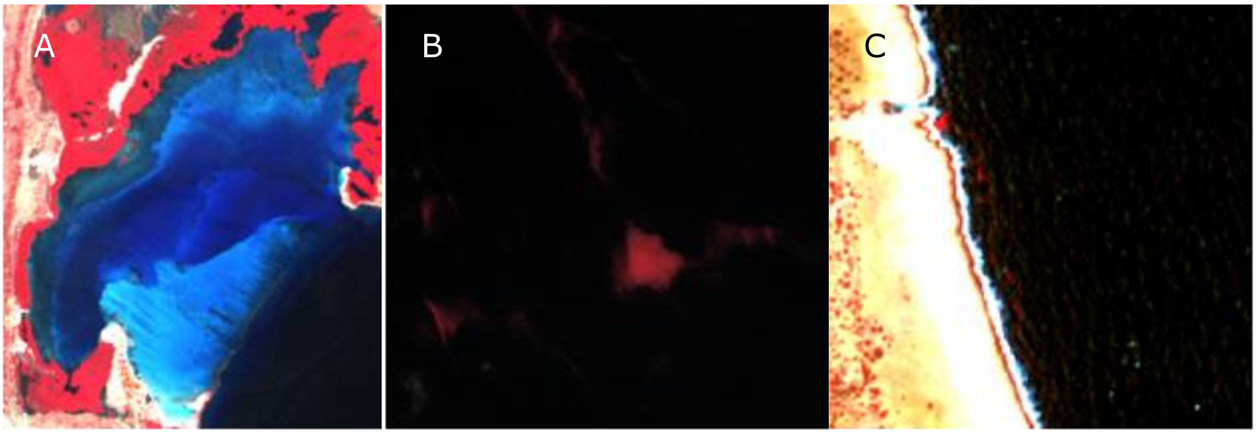


***Fig. 15.*** S2-images of different sub-areas within the study area to illustrate the variability in environmental conditions and related spectral reflectance within the study area (A) Lac Bay, a sheltered shallow bay, (B) deep waters at open sea, and (C) along the exposed east coast of Bonaire with high wave activity.

## 4.2 *Sargassum* area coverage and harvestable biomass

Given the revisit time of 5 days of S2 satellites, it is theoretically possible that a *Sargassum* patch that is detected on a S2-image is still present on the subsequent S2-image, when it was taken 5 days later. If this happened, it would cause an overestimation of the cumulative area coverage (ha) of *Sargassum* per year (see Table 3). However, due to the strong currents and easterly trade winds, we assume that most floating *Sargassum* will not reside along the coast for 5 days. Obviously, double counting of *Sargassum* could also occur when *Sargassum* accumulates on shore, where it may stay floating for 5 or more days, after which it will start decomposing to eventually sink. However, as the first 10 m from the shore was masked out from our study area, any *Sargassum* that accumulated within 10 m from the shore, was not mapped in this study. In this study we used several conversion factors that were published in the scientific literature to convert the observed area coverage of *Sargassum* in the coastal waters of Bonaire into *Sargassum* wet and dry weight. For example, we assumed that the thickness of the *Sargassum* raft was on average 0.4 m as reported by Gulick *et al.* (2023) for *Sargassum* rafts in the Sargasso Sea. However, it could well be that the average thickness of the floating *Sargassum* rafts in the coastal waters of Bonaire may have deviated from this value, so care must be taken when interpreting our estimates of *Sargassum* biomass.

# 5 Conclusions

This study shows that Sentinel-2 (S2) satellite imagery can be effectively used to map floating *Sargassum* in the coastal waters of Bonaire, providing valuable information on the timing, distribution and scale of *Sargassum* influx events between 2017 and 2022. Results showed that floating *Sargassum* could be well detected with our Random Forest model (overall accuracy 99.9%). However, to get the best classification results, good cloud masking is a prerequisite. The cloud masking for our study area was done manually, since the cloud masking results using AI-techniques was still unsatisfactory. *Sargassum* influxes were primarily observed by the S2 satellites between February and July, although there was some variability between the years. The cumulative area coverage (ha) of *Sargassum* ranged from 20.3 ha in 2017 to 405.5 ha in 2018, and was on average 111.9 ha per year. Most of the floating *Sargassum* was detected near the east coast (i.e. 10-200m from the shore) and in the west part of two coastal bays (i.e. Lagun and Lac Bay), which is mainly the result of prevailing easterly trade winds pushing *Sargassum* from open sea towards these locations. Moreover, between 2017 and 2022 the annual dry weight of *Sargassum* that washed up in Lac Bay and Lagun, the only 2 sites where *Sargassum* could potentially be harvested due to relatively calm waters in these bays, was on average 950.9 ton (range 50.8 − 1751.8). Although the seasonal presence and limited abundance of harvestable *Sargassum* on Bonaire, may limit its commercial use, this study provides the first assessment of the approximate volumes of *Sargassum* biomass arriving at specific locations at Bonaire over time.This will aid identification of suitable uses of *Sargassum* and the scale of potential enterprises on Bonaire, while it also allows assessments of economic feasibility and sustainability for proposed ventures. In addition, the obtained information will help identify priority areas for coastal management of these *Sargassum* influxes.

# 6 Acknowledgement

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# 7 Quality Assurance

Wageningen Marine Research utilises an ISO 9001:2015 certified quality management system. The organisation has been certified since 27 February 2001. The certification was issued by DNV.

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# Justification

Report C023/24
Project Number: 6224132500

The scientific quality of this report has been peer reviewed by a colleague scientist and a member of the Management Team of Wageningen Marine Research

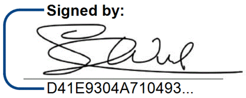
Approved: Dr. E.H.W.G. Meesters
Researcher

Signature:


Date: 16 July 2024

Approved: Dr. C.J. Wiebinga
Business Manager Projects

Signature:

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