Monitoring impact of recent *Sargassum* influxes on mangrove cover in the coastal bays of Bonaire, Caribbean Netherlands

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1 Wageningen Environmental Research

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Photo cover: Impact of *Sargassum* influx on fringing mangrove forest in Lagun, Bonaire on 22 April 2022 (photo credits: Tessa Haanskorf).

Contents

Summary

A change detection analysis utilizing Very High-Resolution (VHR) satellite imagery was performed to evaluate the changes in mangrove cover in two coastal bays (i.e. Lagun and Lac Bay) on Bonaire, attributable to recent coastal influxes of holopelagic *Sargassum* brown algae. A baseline Pleiades satellite image from 2014 (i.e. before the first *Sargassum* influx on Bonaire) and a Pleiades satellite image from 2020 were co-registered, pan-sharpened at a resolution of 50 cm to enable detection of small changes. Next, changes in the Normalized Difference Vegetation Index (NDVI) were used to quantify changes in mangrove cover between 2014 and 2020. In addition, Sentinel-2 (S2) satellite imagery in combination with a previously developed Random Forest model to detect floating *Sargassum* was used to map the mangrove areas within Lac Bay and Lagun that experienced direct impact of *Sargassum* influxes between 2017 and 2020. Results showed that in 2014, the total area coverage of mangroves in Lac Bay was 221 ha, of which 16 ha (7.2%) was lost in the period between 2014 and 2020. However, based on the maps that showed where *Sargassum* accumulated within Lac Bay, only 0.6 ha (3.7%) of the total mangrove area that was lost between 2014 and 2020 could most likely be attributed to the direct impact of *Sargassum* influxes (i.e. the outer edge of the mangrove forest in the West of Lac Bay), while the remaining mangrove loss of 15.4 ha (96.3%) could most likely be attributed to run-off related sedimentation in the backwaters of Lac Bay. The total area coverage of mangroves in Lagun was 2.6 ha in 2014, of which 1.2 ha (46.2%) has been lost in the period between 2014 and 2020. Of the mangrove area that was lost in Lagun, 0.4 ha (33.3%) could most likely be attributed to the direct impact of *Sargassum* influx, while the remaining mangrove loss of 0.8 ha (66.7%) was most likely the result of run-off related sedimentation. The approach presented in this study provides a quantifiable method to evaluate *Sargassum* impacts to mangrove vegetation using change detection of VHR satellite imagery and showed that, although limited, *Sargassum* influxes seem to have caused mangrove die-offs in specific areas within Lac Bay and Lagun. Obtained findings will help identify priority areas within the mangrove forests of Lac Bay and Lagoon where management of *Sargassum* influxes and run-off-induced sedimentation may be required.

1 Introduction

Floating mats of the holopelagic brown algae *Sargassum* spp. (*Sargassum* hereafter) provide an important habitat for many marine organisms and act as hotspots for biodiversity and productivity in the otherwise substrate- and nutrient-deficient waters of the open ocean (Laffoley et al., 2011). However, since 2011, there has been a significant increase in the biomass of *Sargassum* in the Caribbean Sea and tropical Atlantic Ocean. Consequently, vast quantities of *Sargassum* have periodically washed up on the shores of the Caribbean, northern and central America, and West Africa (Gower et al., 2013; Wang et al., 2019).

These recent massive *Sargassum* beaching events have led to significant environmental and ecological problems. Near the coastlines, the decomposition of the algae forms leachates and organic particles, resulting in murky brown waters known as *Sargassum* Brown Tides (SBT). These tides lead to decreased light penetration, oxygen levels, pH, and overall water quality (van Tussenbroek et al., 2017; Chávez et al., 2020). The diminished water quality and occurrences of hypoxia caused by SBT have been identified as major factors contributing to the mortality of coastal marine habitats such as seagrasses and mangroves, as well as the associated fauna (van Tussenbroek et al., 2017; Chávez et al., 2020).

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 and in coastal bays (i.e., Lagun and Lac Bay) (Dutch Caribbean Nature Alliance, 2019; van der Geest et al., 2024). In Lac Bay and Lagun, these *Sargassum* influx events were believed to have caused the sudden die-offs of fish, seagrasses and mangroves that were observed at sites where *Sargassum* accumulated (Dutch Caribbean Nature Alliance, 2019), but this has never been quantified. To fill this knowledge gap, 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 quantify the ecological impact of these recent massive *Sargassum* influxes on mangrove forest cover in the coastal bays of Bonaire. To do so, the land cover classification for Bonaire from 2014 (Mücher et al., 2020) was used to extract the mangrove-covered area for Lac Bay and Lagun with an additional buffer zone of 50 m. Next, commercial very high resolution (VHR) Pleiades satellite imagery with a resolution of 50 cm was used, to be able to monitor (small) changes in mangrove cover in Lac Bay and Lagun between 28 February 2014 (i.e., before the first *Sargassum* influx event in 2015) and 20 November 2020 (i.e. reflecting the cumulative impact of all *Sargassum* influx events between 2015 and 2020 on mangrove cover). Moreover, Sentinel-2 (S2) satellite imagery between 2017 and 2020 in combination with a previously developed Random Forest model for detecting floating *Sargassum* (van der Geest et al., 2024) was used, to map the mangrove areas within Lac Bay and Lagun that experienced direct impact of *Sargassum* influxes between 2017 and 2020. Finally, it was investigated whether sites where mangrove cover decreased between 2014 and 2020 can be related to the areas within Lac Bay and Lagun where the cumulative influx of *Sargassum* was relatively high between 2017 and 2020.

[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*, namely Lagun and Lac Bay (Fig. 1). Both areas are in the path of easterly trade winds. 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 situated on the seabed there, 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.

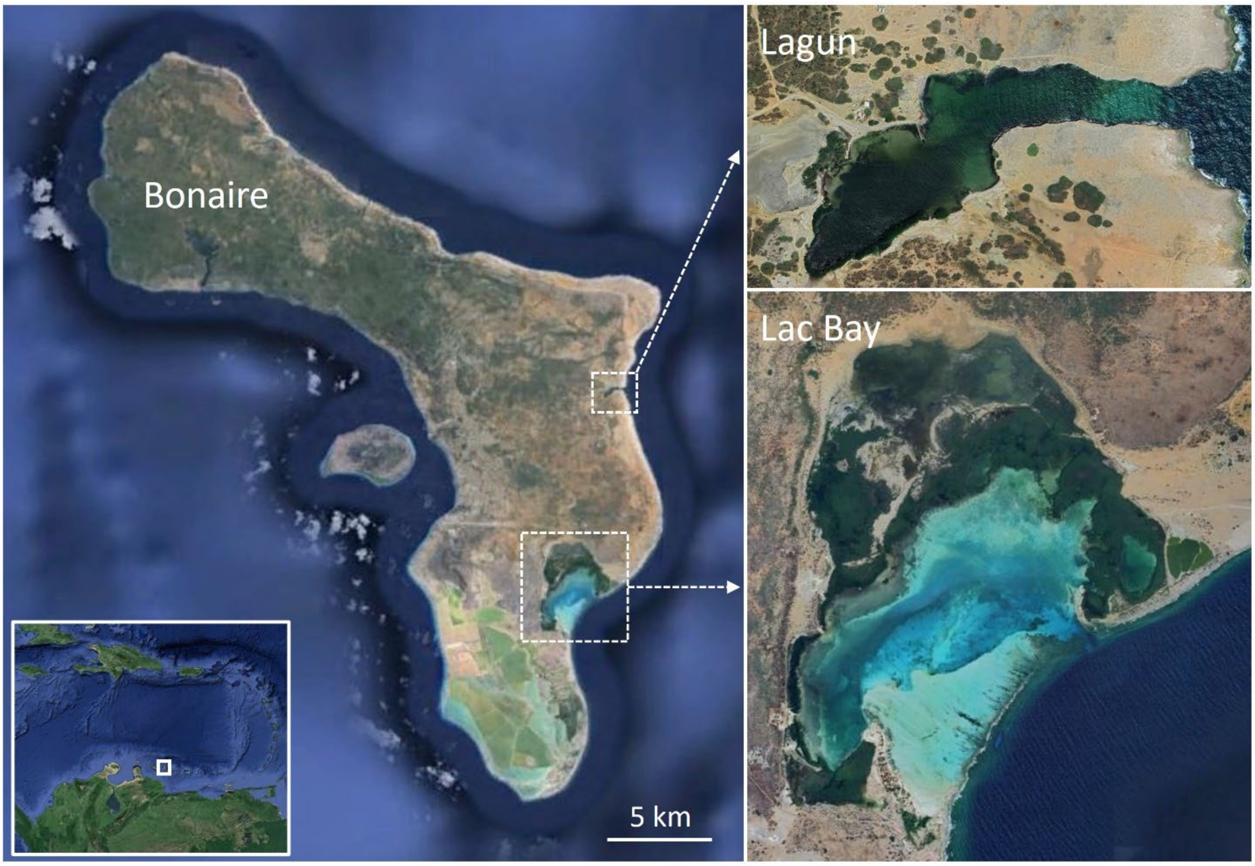

Fig. 1. *Map showing the location of Bonaire in the Caribbean Sea, Bonaire, and the two coastal bays (i.e., Lac Bay and Lagun) that were monitored for Sargassum influx and changes in mangrove cover.*

2.2 Satellite data

Most commonly used satellite data for environmental monitoring are nowadays the freely available Copernicus S2 satellite images. However, the optical S2 satellite sensors have a maximum resolution of 10 meters which hampers the detection of small changes in mangrove cover over time. This is troublesome when the aim is to investigate the impact of *Sargassum* influxes on mangrove cover in coastal bays, as *Sargassum* generally only accumulates at the outer 10 m rim of the mangrove forests, and thus may only impact a relatively small mangrove area. Therefore, it was decided to use commercial very high resolution (VHR) Pleiades satellite imagery with a resolution of 50 cm (400 Pleiades pixels fit in one Sentinel-2 pixel). Pleiades multi-spectral imagery was acquired for two acquisition dates, namely 28 February 2014 and 20 November 2020, to detect changes in mangrove cover in Lac Bay and Lagun before the first *Sargassum* influx event in 2015 and to evaluate the current effects of *Sargassum* accumulation on mangrove cover in these two bays. Note that VHR satellite imagery was selected for these two dates based on the acquisition dates (before and after the first *Sargassum* influx) and the effort to find imagery with a limited amount of cloud cover.

The identical Pleiades 1A and Pleiades 1B satellites deliver 50 cm imagery products with a repeat cycle of 26 days. Pleiades is an environmental-focused constellation from CNES (France) which was launched on 17 December 2011 (Pleiades 1A) and on 2 December 2012 (Pleiades 1B). Both satellites are currently still operational. Next to the panchromatic band (480 – 820 nm) with a 50 cm resolution, the Pleiades satellite sensor has 4 multispectral bands at 2 m resolution:

- B0= 450-530 (Blue),
- B1= 510-590 (Green),
- B2= 620-700 (Red),
- B3= 775-915 (Near Infrared (NIR))

Both the panchromatic with a 50 cm resolution and multispectral bands with a 2 meter spatial resolution were available for the selected dates: 28 February 2014 and 20 November 2020.

2.3 Pre-processing

Several preprocessing steps for the Pleiades high resolution imagery have been undertaken for a better analysis, namely:

1. Pan-sharpening
2. Co-registration
3. NDVI vegetation index calculation and calibration
4. Removal of some small cloud contaminated areas

Pan-sharpening is the process in remote sensing to achieve the highest level of visual contrasts and detail from an image. By combining the high spatial resolution of B&W panchromatic band imagery with the multispectral (colour) imagery, pan-sharpening produces a final colour image with a sharper quality at a resolution of 50 cm (Fig. 2). The original multi-spectral image has a resolution of 2 m. Figure 3 shows the result of the pan-sharpening of a selected part of the Pleiades images from 2014 and 2022, where the images are presented as false colour, which is often done in remote sensing when it concerns vegetation analysis. It means that the Near-Infrared (NIR) spectral channel is indicated in red to highlight the photosynthetically active vegetation, as vegetation reflects the NIR lights while it absorbs the red light for its photosynthetic process.

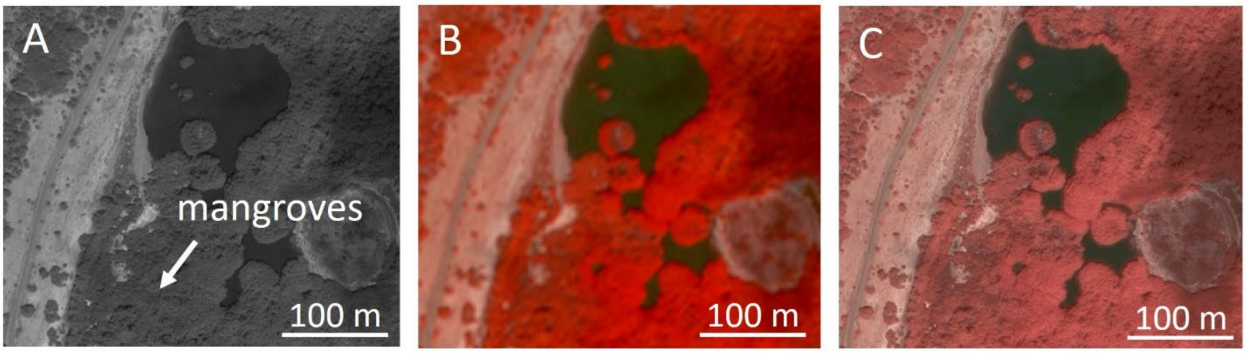

Fig. 2. *(A) Original panchromatic image of 28 February 2014 at 50 cm resolution for a small mangrove area in Lac Bay. (B) Original multi-spectral image with a 2 meter resolution. (C) Pan-sharpened multispectral image with a 50 cm resolution.*

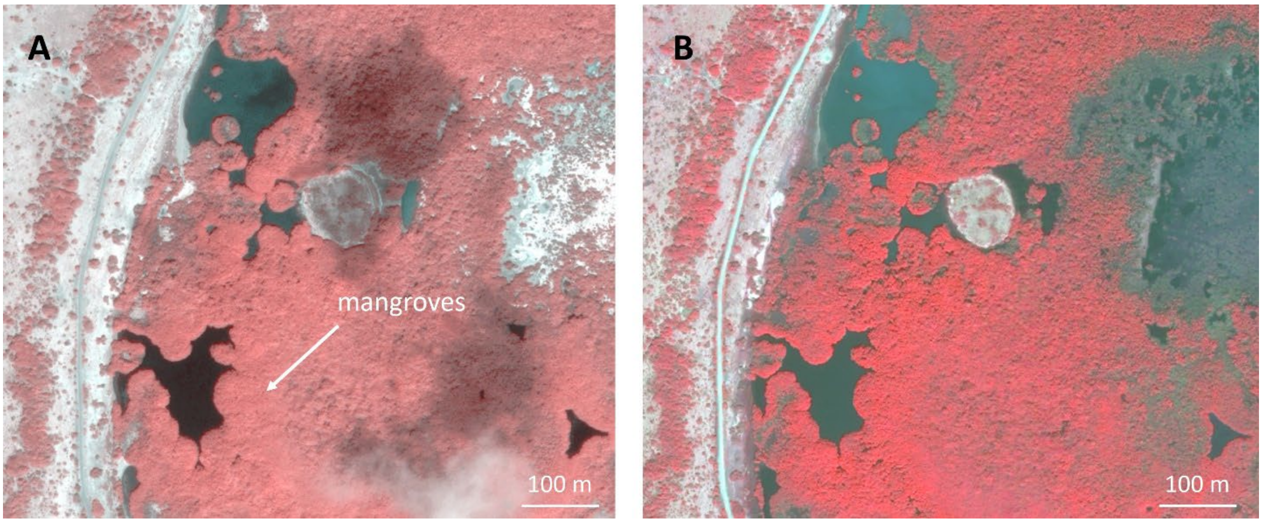

Fig. 3. *Pan-sharpened Pleiades imagery (50 cm resolution, and shown as false-colour) of a section of the mangrove forest in Lac Bay, Bonaire for (A) 28 February 2014, and (B) 20 November 2020.*

Co-registration is normally not needed with Pleiades imagery, but it was necessary due to unexpected small mismatches in geolocations of the two dates (at a very detailed level). Mismatches can occur due the fact that some imagery have been orthorectified while others have not, depending on the level of product as ordered or due to different geographic projections. After close inspection the image of 2020 was co-registered to the image of 2014, since the 2014 image was considered to be the most accurate in geometry. After the image co-registration the imagery fitted exactly together (using the georeferencing tool in ArcGIS).

NDVI stands for Normalized Difference Vegetation Index and quantifies vegetation by measuring the difference between the Near-Infrared (which vegetation strongly reflects) and the red light (which vegetation absorbs for photosynthesis), which is calculated as:

$$NDVI = \frac{NIR - RED}{NIR + RED} \tag{1}$$

A recent study by Casal et al. (2024) showed the presence of seasonality in mangroves cover in Lac Bay, Bonaire. To compensate for seasonal difference in mangrove cover and associated NDVI values between the image from 28 February 2014 and 20 November 2020, NDVI values for well-developed spots of mangrove were determined for both images and compared. Results showed that the NDVI was on average 0.2 higher for the selected mangrove patches in the image from 20 November 2020 compared to the image from 28 February 2014. To correct for this seasonality in NDVI, a value of 0.2 was added to all NDVI values for the image from 28 February 2014. As a result, a fully developed mangrove forest was reflected by a NDVI of around 0.67 in both pan-sharpened images (see also Figure 5). Note that NDVI values are not absolute in a pan-sharpened image and will be higher in the associated multispectral imagery. However, our aim is not to estimate the absolute biomass of the mangrove trees, but to detect (small) changes in the mangrove cover for which we used the pan-sharpened imagery.

2.4 Mangrove cover change detection analysis

The area of mangrove forest in Lac Bay and Lagun has been derived from the 2014 land cover database of Bonaire (Mücher et al., 2020) and was subsequently buffered with a radius of 50 meter to ensure that all mangrove forest was included in the change detection analysis over the period from 2014 to 2020. The mangrove covered area is 221 ha for Lac Bay and 2.6 ha for Lagun. Next, for the identified mangrove-covered study area in Lac Bay and Lagun, a change detection technique was used to evaluate the differences between the corrected NDVI values in the baseline image from 28 February 2014 and the image from 20 November 2020. Since we were interested in potential mangrove loss, we subtracted the NDVI value for each pixel in the 2014 image from the NDVI value for the same pixel in the 2020 image (i.e. $NDVI_{2020} - NDVI_{2014}$), so that a negative value for the difference in NDVI reflects loss in mangrove biomass. Negative changes thus reflect a decrease in NDVI pixel values in 2020 compared to 2014 due to loss of biomass and/or decrease in vegetation coverage (Morawitz et al., 2006). Temporal changes in NDVI that were larger than 0.3 were considered to reflect changes in mangrove cover, while temporal differences in NDVI that were smaller than 0.3 were assumed to be due to changes in mangrove biomass and not yet due to changes in mangrove coverage. In this study we focus on identification of areas where mangrove cover was lost between 2014 and 2020, which is thus reflected by areas with temporal differences in NDVI that were larger than -0.3. Note that the 2014 Pleiades image of the mangrove forest in Lac Bay contained some patches with cloud cover (see Fig. 4A). These cloud-covered areas were not taken into account in our analyses of mangrove loss over time (see Fig. 5A).

2.5 Mapping mangrove areas impacted by *Sargassum*

We used Sentinel-2 (S2A and S2B) satellite imagery with 10 m resolution that were collected between 2017 and 2020 (see Table 1), in combination with a previously developed Random Forest model for detecting floating *Sargassum* (van der Geest et al., 2024), to determine the degree of cumulative impact experienced by mangrove forest habitat within Lac Bay and Lagun between 2017 and 2020.

Table 1. *Number of Sentinel-2 (S2) images per year that were analyzed for the presence of Sargassum.*

Year	Satellite	Nr. of S2-images
2017	Mostly S2A (some S2B)	32
2018	S2A & S2B	67
2019	S2A & S2B	67
2020	S2A & S2B	69
Total		**235**

For each of the S2-images (N=235) we determined where *Sargassum* was present within Lac Bay and Lagun, by using the same procedure as described by van der Geest et al. (2024). Next, the number of times that a specific 10 m x 10 m pixel within Lagun, Lac Bay was classified as *Sargassum* was counted between 2017 and 2020, after which the *Sargassum* counts per pixel for this entire period were plotted. The obtained maps showing the *Sargassum*-impacted areas within Lac Bay and Lagun, were subsequently used to identify the mangrove areas that experienced direct impact of the *Sargassum* influxes.

3 Results

3.1 Changes in mangrove cover in Lac Bay

Figure 4 shows the pan-sharpened Pleiades images for Lac Bay for 28 February 2014 and 20 November 2020 that were used for quantification of NDVI per pixel as shown in Figure 5, where high NDVI values (pixels shown in red) reflect areas with relatively high mangrove cover and low NDVI values (pixels shown in green) reflect areas with relatively low or no mangrove cover. Figure 5 shows an overall decrease in NDVI (i.e. mangrove cover) between 2014 and 2020, especially in the northern part of Lac Bay.

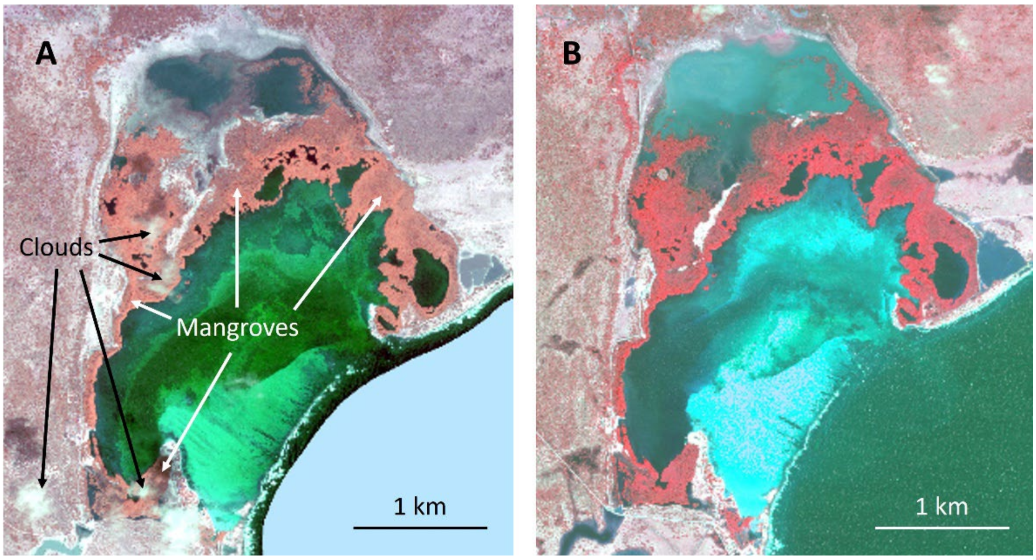

Fig. 4. *Pan-sharpened Pleiades images of mangrove forest in Lac Bay for (A) 28 February 2014 and (B) 20 November 2020. Note that there were some clouds on the Pleiades image from 2014.*

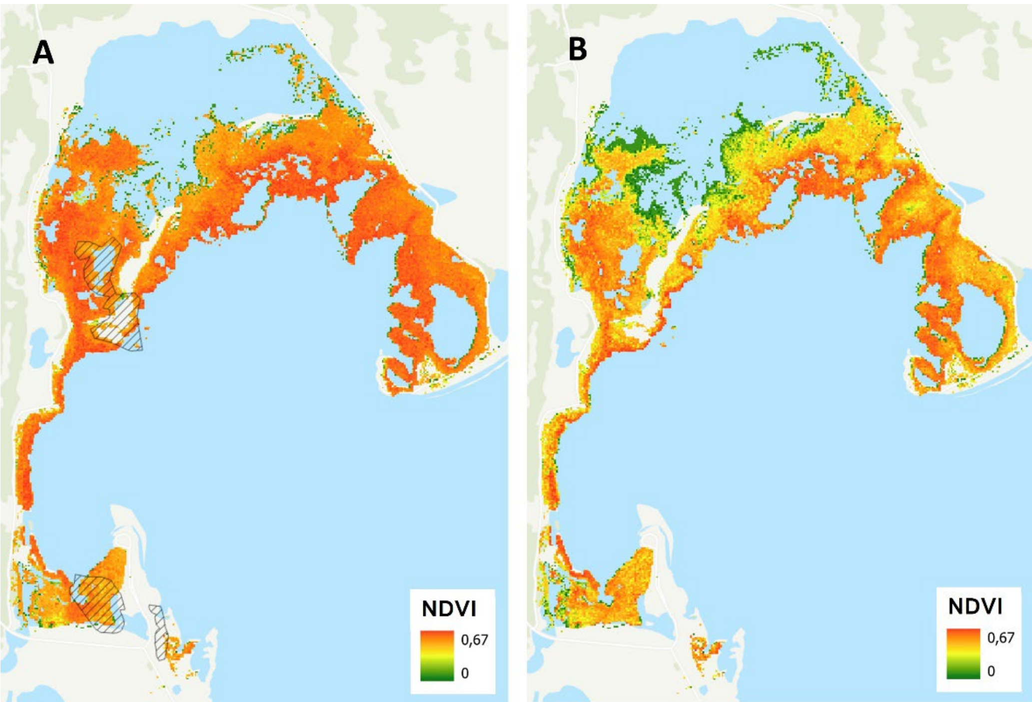

Fig. 5. *NDVI per pixel for images of Lac Bay for (A) 28 February 2014, and (B) 20 November 2020. The maximum value of the NDVI values for both dates have been harmonized and reached a value of 0.67. Areas with cloud cover (2014 image only) are indicated with dashed lines and were not taken into account in our analysis of mangrove loss between 2014 and 2020.*

Figure 6 shows the result of the change detection method used, based on differences in NDVI values between 2014 and 2020 for a mangrove-covered part of Lac Bay, with clear mangrove die-off observed at the outer rim of the mangrove forest.

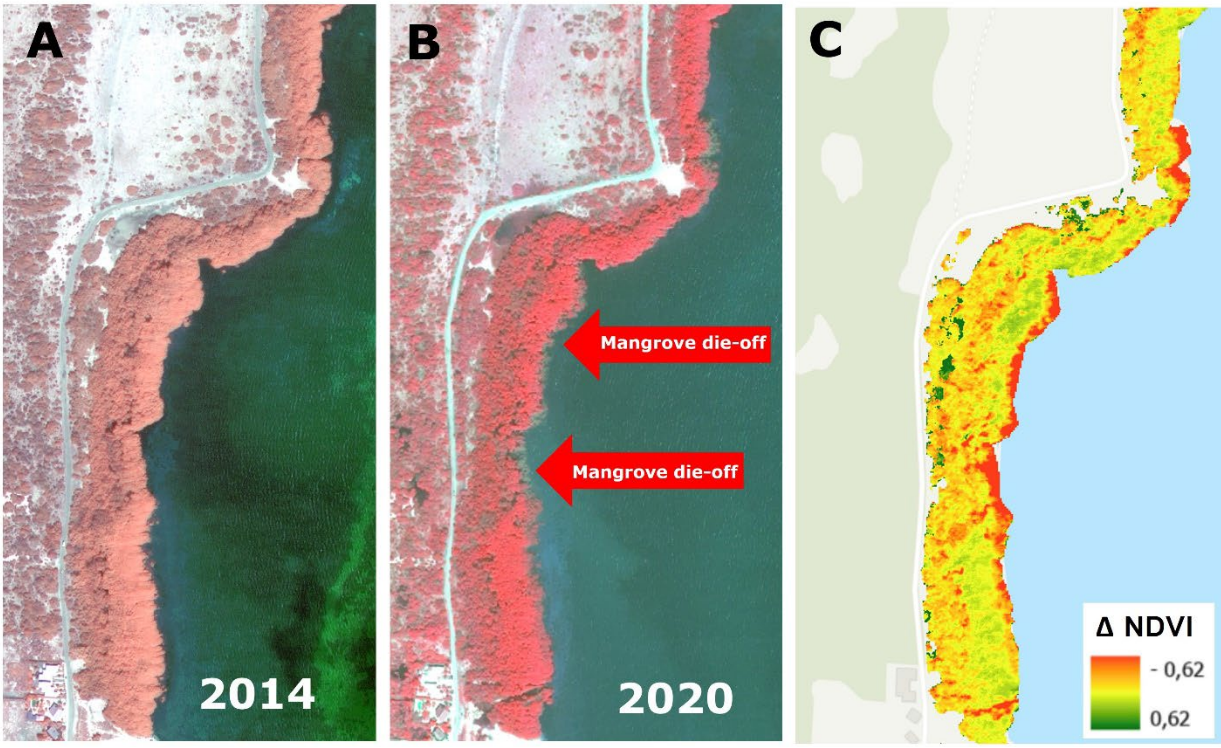

Fig. 6. *Change detection method based on differences in NDVI values. (A) Pleiades image of a mangrove-covered area within Lac Bay for 28 February 2014. (B) Pleiades image of the same mangrove-covered area as shown in (A), but for 20 November 2020. (C) The difference in NDVI between 20 November 2020 and 28 February 2014 (*$NDVI_{2020} - NDVI_{2014}$*) per pixel for the same mangrove-covered area as shown in (A) and (B), where pixels in red reflect a decrease in mangrove cover over time, and pixels in green reflect an increase in mangrove cover over time.*

In Figure 7 we have mapped the pixels in the mangrove forest of Lac Bay for which the NDVI was reduced with a value larger than 0.3 between 2014 and 2020. Using this threshold, the total mangrove-covered area lost between 28 February 2014 and 20 November 2020 was 16 ha.

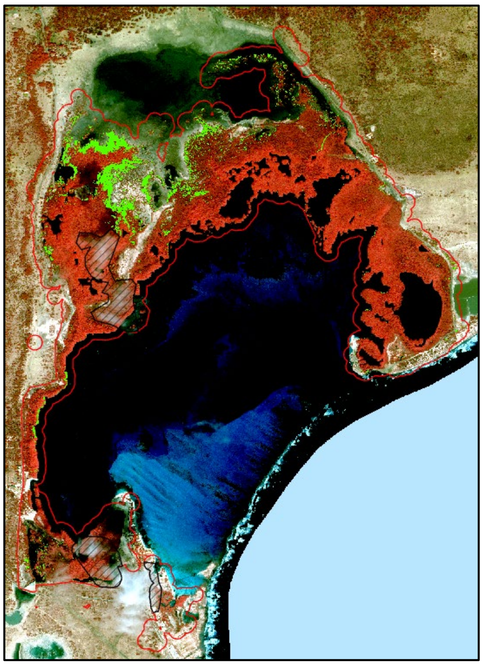

Fig. 7. *Pixels in green indicate the areas in Lac Bay where mangrove forest was lost between 28 February 2014 and 20 November 2020. The red polygons show the mangrove area with a 50 meter buffer zone, while the dashed black polygons indicate mangrove patches with cloud cover that were not taken into account in the analysis.*

Next, Sentinel-2-based monitoring of *Sargassum* presence in Lac Bay showed that between 2017 and 2020 most *Sargassum* accumulated on the western part of Lac Bay. Based on this information, a black polygon could be drawn around the part of the mangrove forest within Lac Bay that experienced direct impact of *Sargassum* between 2017 and 2020 (Fig. 8A).

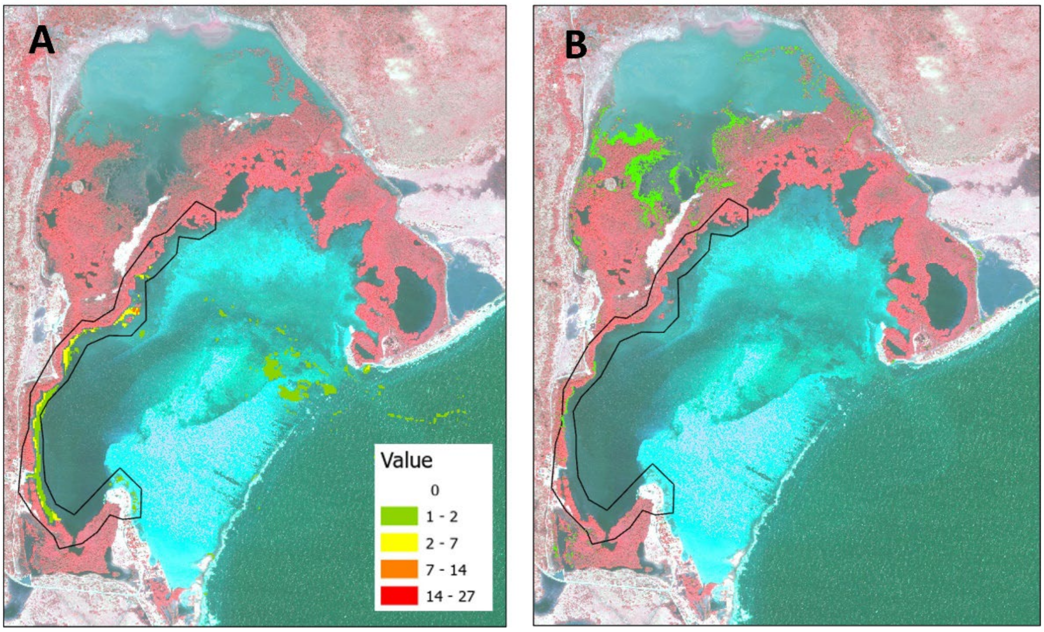

Fig. 8. *(A) Number of times that Sargassum was detected within Lac Bay per pixel on the 235 Sentinel-2 images that were analyzed between 2017 and 2020, which was used to identify the mangrove area within Lac Bay that experienced direct impact of Sargassum influxes during this period (i.e. mangrove area within the black polygon). Background reflects Pleiades image of 20 November 2020. (B) Pixels in green reflect the areas in Lac Bay where mangrove forest has disappeared between 28 February 2014 and 20 November 2020, while the black polygon reflects the mangrove area that experienced direct impact of Sargassum influxes during this period.*

Using the identified mangrove areas within Lac Bay that were exposed to direct impact of *Sargassum* (Fig. 8A), we could discriminate between mangrove loss due to *Sargassum* influxes, and mangrove loss due to other causes (Fig. 8B). So only the green pixels identified within the polygon in Figure 8B can be accounted as loss of mangrove cover due to *Sargassum* influx. The green pixels within the black polygon concern a very narrow line on the outer edge of the mangrove next to the water where *Sargassum* suffocates the mangrove trees (in detail visible in Fig. 6). The total extent of disappeared mangrove forest (green pixels) within the black polygon concerns an area of 0.6 ha over a length of approximately 3 km. This suggest that the remaining 15.4 ha of the mangrove area that was lost between 2014 and 2020, has been lost due to other reasons, mostly related to terrestrial erosion-induced sedimentation of the backwaters (see Fig. 9), which gradually turned the backwaters of Lac Bay into hypersaline anaerobic flats with high water residence times, unfavourable for mangrove growth and survival (Debrot et al., 2019; Casal et al., 2024).

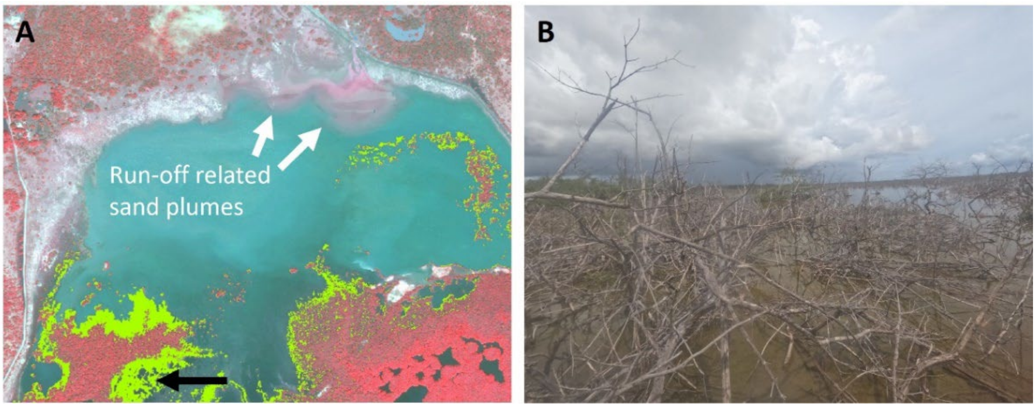

Fig. 9. *(A) Backwaters in the North of Lac Bay where significant decreases in mangrove cover occurred between 28 February 2014 and 20 November 2020 (indicated in green), which were probably caused by run-off related sedimentation (indicated by white arrows). The black arrow indicates the location where the picture in (B) was taken on 29 October 2023, which shows one of the mangrove die-off areas in Lac Bay (photo credits: Sander Mücher).*

3.2 Changes in mangrove cover in Lagun

For Lagun, the mangrove cover change detection analysis has been carried out in the same way as was done for Lac Bay. As such, Figure 10 shows the pan-sharpened Pleiades images for Lagun for 28 February 2014 and 20 November 2020, which were used for quantification of NDVI per pixel as shown in Figure 11. Next, temporal changes in NDVI were determined by subtracting $NDVI_{2020}$ from $NDVI_{2014}$ (see Fig. 12). Due to differences in phenology in February 2014 compared to November 2020, the NDVI values for each image had to be harmonized. Therefore, a value of 0.2 had to be added to the NDVI values in the 2014 image (dry season) to correspond to the NDVI values of November 2020 (wet season).

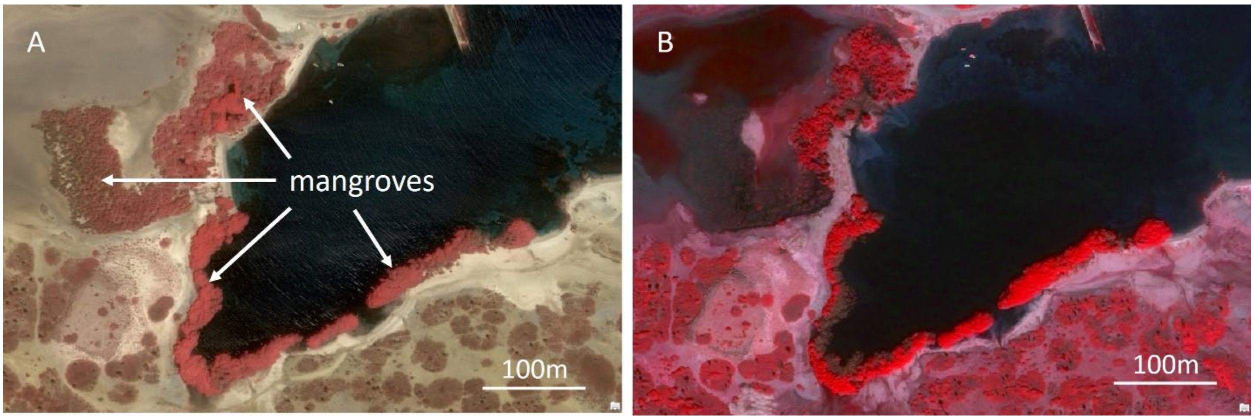

Fig. 10. *Pan-sharpened Pleiades images of Lagun in part where mangroves were present for (A) 28 February 2014, and (B) 20 November 2020.*

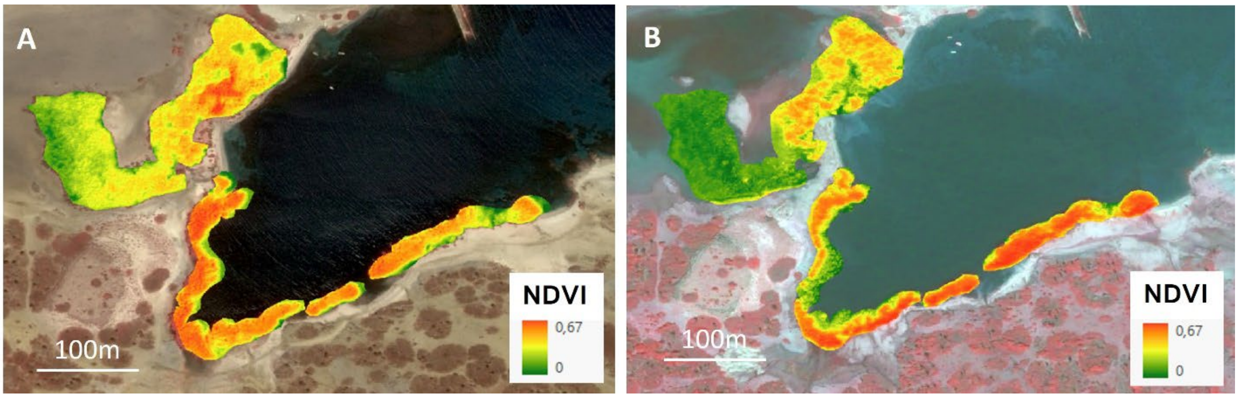

Fig. 11. *NDVI per pixel for images of Lagun for (A) 28 February 2014, and (B) 20 November 2020. The maximum value of the NDVI values for both dates have been harmonized to a value of 0.67. Pixels with high NDVI values are shown in red and reflect areas with relatively high mangrove cover while pixels with low NDVI values are shown in green and reflect areas with relatively low mangrove cover.*

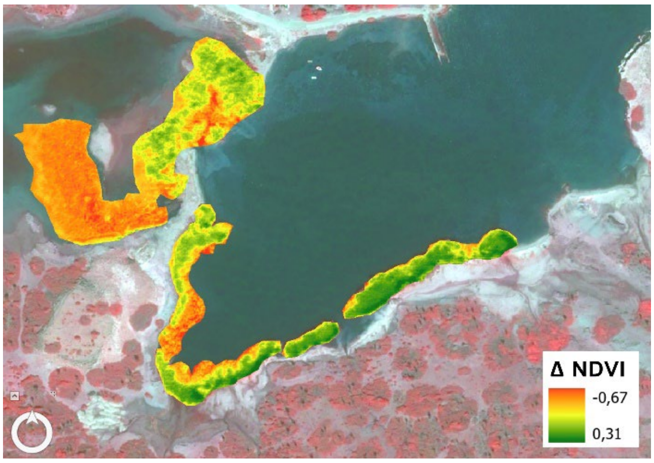

Fig. 12. *Difference in NDVI between 28 February 2014 and 20 November 2020 ($NDVI_{2020}$ – $NDVI_{2014}$) per pixel for the mangrove-covered area in Lagun. Pixels in red reflect a decrease in mangrove cover and pixels in green reflect an increase in mangrove cover.*

In Figure 13 we have mapped the pixels in the mangrove forest of Lagun for which the NDVI was reduced with a value larger than 0.3 between 2014 and 2020. Using this threshold, the total mangrove-covered area lost over this period was 1.2 ha. Since the total mangrove area in Lagun on 28 February 2014 was estimated to be 2.6 ha, this means that 46.2% of the mangrove forest in Lagun has been lost between February 2014 and November 2020.

Next, Sentinel-2-based monitoring of *Sargassum* presence in Lagun between 2017 and 2020 showed that most *Sargassum* accumulated at the outer edge of the mangrove forest in the western part of Lagun (Fig. 14). Based on this information, we could discriminate between mangrove loss that can most likely be attributed to the direct impact of *Sargassum* influxes (green pixels outside black polygon in Fig. 13, which are mainly located along the outer edge of the mangrove forest), and mangrove loss due to other causes (green pixels within the black polygon in Fig. 13). This suggest that of the 1.2 ha mangrove area that was lost in Lagun, 0.4 ha (33.3%) could be attributed to the direct impact of *Sargassum* influxes, while the remaining 0.8 ha (66.7%) has been lost due to other reasons, most likely related to run-off induced sedimentation, but potentially also due to indirect effects of the *Sargassum* influxes, including clogging of channels, which may have limited water exchange to the backwaters of Lagun.

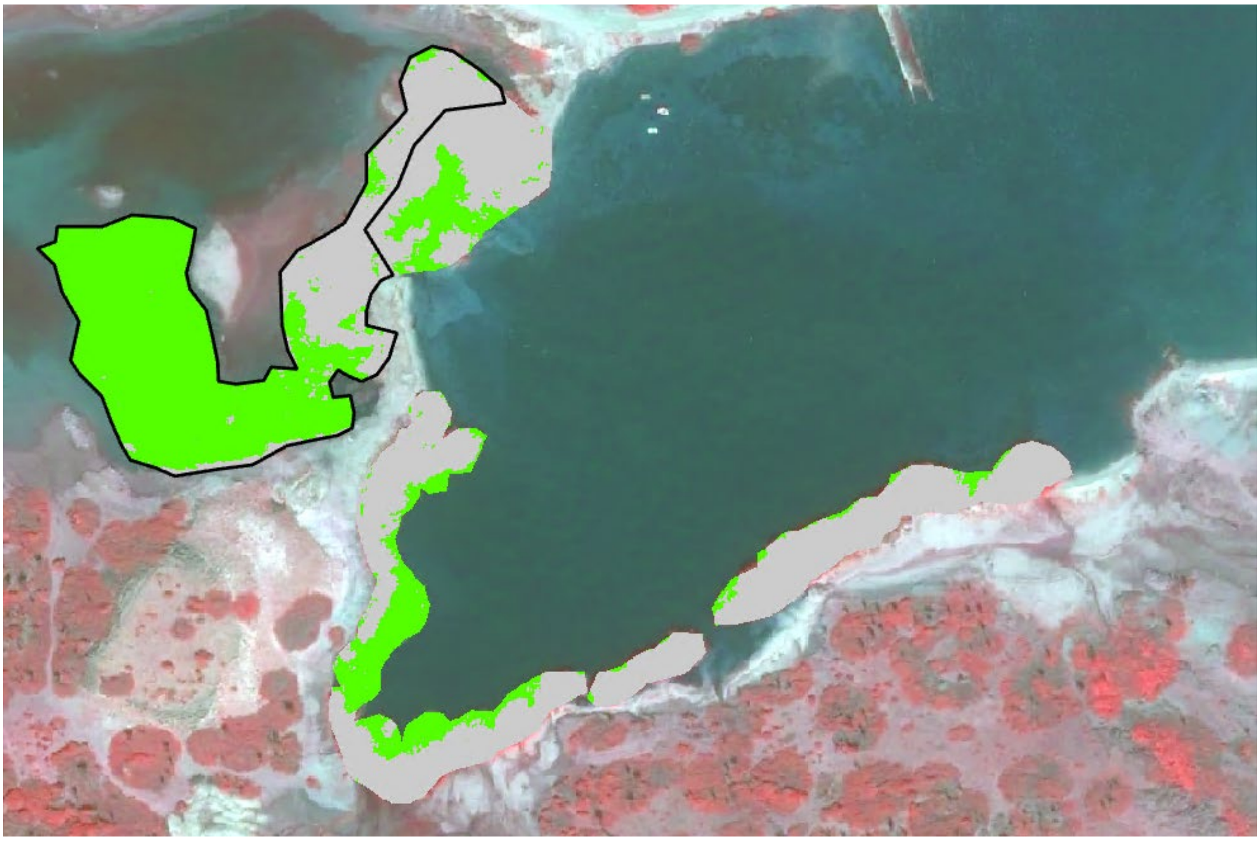

Fig. 13. *Pixels in green reflect the areas in Lagun where mangrove forest has disappeared between 28 February 2014 and 20 November 2020, which cover 1.2 ha. Mangrove loss outside the black polygon (0.4 ha) can most likely be attributed to the direct impact of Sargassum influxes between 2017 and 2020, while mangrove loss within the black polygon (0.8 ha) is attributed to other causes, most likely related to run-off-induced sedimentation.*

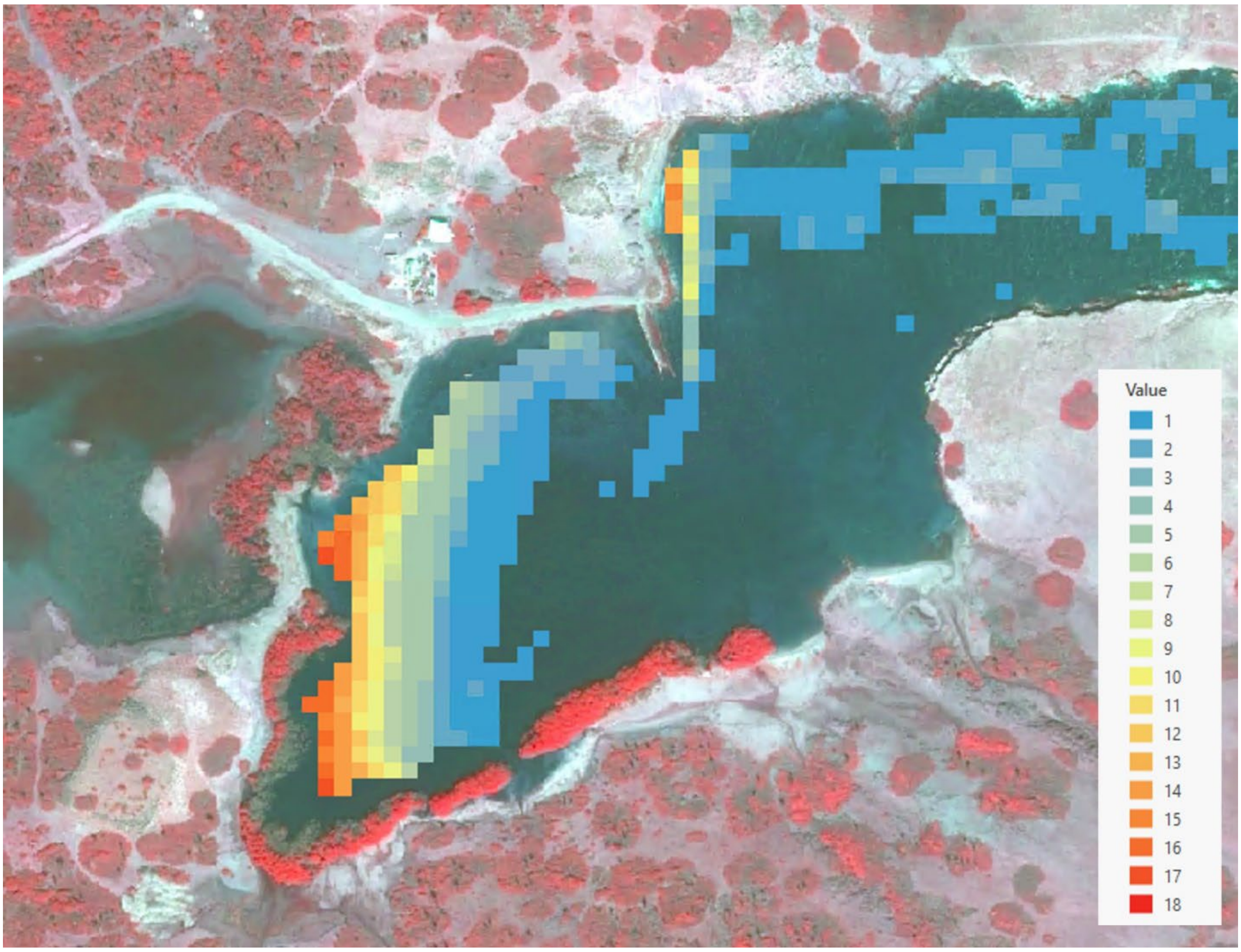

Fig. 14 *Number of times that Sargassum was detected within Lagun per pixel on the 235 Sentinel-2 images that were analyzed between 2017 and 2020 plotted on the Pleiades image of 20 November 2020.*

4 Discussion

Several limitations can be found when using NDVI for change detection analysis that include atmospheric effects, new leaf growth in crops and seasonality (Xue and Su 2017, Casal et al., 2024). In addition, tidal differences between the images at the time of image capture and image pre-processing steps (e.g., pan-sharpening, orthorectification) can affect the NDVI estimates (Hernández et al., 2022). In this study, most of these limitations were minimized in the image pre-processing steps. However, due to the limited availability of VHR satellite images of Bonaire without cloud cover in the target areas, we were forced to compare VHR satellite imagery from different period of time in the year, namely 28 February 2014 and 20 November 2020, which is not ideal. To correct for the observed seasonal differences in NDVI, a value of 0.2 was added to all NDVI values for the image from 28 February 2014. Although, this correction may have resulted in an overestimation of the NDVI values in 2014, it will not have influenced our result with regard to changes in mangrove cover between 2014 and 2020, as only a change in NDVI that was larger than 0.3 from 2014 to 2020 was considered to reflect a change in mangrove cover.

Moreover, we used spatial overlap between *Sargassum* accumulation areas and mangrove die-off areas as a proxy to study the direct impact of *Sargassum* on mangrove survival. However, field experiments are needed to validate our assumption that mangrove die-offs in *Sargassum*-impacted mangrove areas are indeed the result of *Sargassum* loading and not due to other factors. In addition, we did not collect any field-based data on mangrove biomass and mortality. Future research should therefore focus on collecting more field-based estimates on mangrove biomass and die-offs, so that the satellite measurements can be calibrated.

In this study we focused on mapping mangrove loss in Lac Bay and Lagun between 2014 and 2020, but there may also have been sites where mangrove cover increased over this period, especially at the seaward fringes of the forest. Although identification of mangrove outgrowth areas is beyond the scope of this study, we recommend future research to investigate whether mangrove outgrowth may have been suppressed by recent *Sargassum* influxes.

Major changes in mangrove forest cover in the coastal bays of Bonaire were observed which could also have negative repercussions to other highly productive and biodiverse coastal habitats, such as seagrass beds and coral reefs. The cumulative and chronic impacts of *Sargassum* influxes (van Tussenbroek et al., 2017; van der Geest et al., 2024) may not provide enough recovery time to these valuable coastal ecosystems, especially when these systems are simultaneously being impacted by terrestrial erosion-induced sedimentation (Debrot et al., 2019). The changes in mangrove cover were observed in this study occurred in a short time frame of less than 7 years. Assuming that *Sargassum* influxes (Wang et al., 2019) and erosion-induced sedimentation (Debrot et al., 2019) will continue, natural resource managers need to consider the combination of these stressors and its potential long-term impacts to the vulnerable mangrove forests of Bonaire.

5 Conclusions

This study shows that very high resolution (VHR) Pleiades satellite imagery with a resolution of 50 cm can be effectively used to evaluate the ecological impact of recent *Sargassum* influxes on mangrove cover in the coastal bays (i.e. Lac Bay and Lagun) of Bonaire. Large changes in mangrove cover between 28 February 2014 and 20 November 2020 were quantified in Lac Bay and Lagun using NDVI (a proxy for mangrove cover). In 2014, a total area of 221 ha of mangrove forest habitat was identified in Lac Bay of which 7.2% (i.e. 16 ha) was identified as lost in 2020, while in Lagun a total of 2.6 ha of mangrove forest habitat was identified in 2014 of which 46.2 % (i.e. 1.2 ha) was identified as lost by 2020. Although there may also have been sites where mangrove cover increased between 2014 and 2020, especially at the seaward fringes of the forest, mapping of mangrove outgrowth areas was not part of this study. However, as mangrove outgrowth may have been suppressed by the recent *Sargassum* influxes, this would be an interesting topic for future research.

Based on the maps showing the cumulative presence of *Sargassum* per pixel within Lac Bay and Lagun between 2017 and 2020, it was possible to differentiate between the ecological impact of *Sargassum* on mangrove cover in Lac Bay and Lagun and the impact of other stressors (e.g. run-off related sedimentation). In Lac Bay, 3.7 % (i.e. 0.6 ha) of the total area of mangrove forest that was lost between 2014 and 2020 (i.e. 16 ha) could most likely be attributed to the direct impact of *Sargassum*, while in Lagun this was 33.3% (i.e. 0.4 ha of a total loss of 1.2 ha). In both bays, the *Sargassum*-induced mangrove die-offs were restricted to the outer rim of the mangrove forest in the west, where floating *Sargassum* accumulates due to the persistent easterly trade winds. The remaining part of mangrove forest that was lost in Lac Bay (i.e. 15.4 ha) and Lagun (i.e. 0.8 ha) between 2014 and 2020, was concentrated in the backwaters of Lac Bay and Lagun, and can most likely be attributed to terrestrial erosion-induced sedimentation, which gradually turned the backwaters into hypersaline anaerobic flats with high water residence times, unfavourable for mangrove growth and survival.

Given the observed loss in mangrove cover in Lac Bay and Lagun in less than 7 years, action should be taken to reduce the influx of *Sargassum* as well as the influx of terrestrial-erosion induced sediments into the coastal bays of Bonaire.

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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

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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

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