Mapping seagrass (Zostera) by remote sensing in the Schleswig-Holstein Wadden Sea

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Abstract

The change of mapping methods for seagrass beds, here species of eelgrasses, from aerial surveys to automated classification of optical satellite data is described. Both methods are compared with respect to availability and suitability of their data. Differences in the detection capability of the methods are shown as well as results of the validation of the satellite image classification.

In North Friesia, where the largest area of eelgrass occurs in the Wadden Sea, eelgrass beds have been mapped regularly using aerial surveys since 1994. After a significant decline in the 1930s and 1960s, monitoring results show a steady increase in the size of the area covered by eelgrass beds up to 2017.

Since 2006, the aerial surveys have been complemented by ground surveys, which, however, only cover one sixth of the area of the Schleswig-Holstein Wadden Sea each year. Results show that size estimates of individual beds can vary significantly between aerial and ground surveys.

In recent years, satellite-borne remote sensing technology and subsequent analysis methods have reached a level of quality, which makes them an alternative and cost-efficient method for mapping eelgrass. The technology has advantages such as the coverage of large areas at single points in time, repeatable and transferable image analysis methods, and high spatial resolution of the satellite images, as well as frequent repetition of acquisition of data. This provides standardised results, which allow direct comparisons over time and between areas.

Keywords

Eelgrass, seagrass, Zostera, monitoring, detection of eelgrass, Wadden Sea, habitat mapping, remote sensing, Sentinel-2, Landsat-8

1 Introduction - Short history of eelgrass in the Schleswig-Holstein Wadden Sea

Two endemic species of seagrasses, more specific eelgrasses, grow in the Wadden Sea, *Zostera noltei (Hornemann 1832)* and *Zostera marina (Linnaeus 1753)*. Zostera marina occurs sporadically in patches and occurs mostly in small channels in the tidal flats. It also occurs as scattered patches in the beds of *Z. noltei*, which often forms extensive and very dense eelgrass beds on high-lying stable tidal flats.

Eelgrass beds are highly productive and bind large amounts of nutrients. They are a food source, especially for bird species, and provide spawning grounds as well as cover from predators for numerous other species (Larkum et al. 2006, Terrados & Borum 2004, Schomburg 1997) in the Wadden Sea.

Eelgrasses are perennial herbs. The leaves and stalks grow annually, the root network remains over the winter. Established eelgrass beds increase their area through root growth. The colonisation of new areas takes place by means of seeds, which usually drift together with leaf remnants.

The information on the eelgrass stocks of the nineteenth or the beginning of the twentieth century is mainly anecdotal. In The Netherlands, there is documentation of dike construction using eelgrass as a core and eelgrass used for roofing. Eelgrass mattresses were in widespread use and much esteemed (Terrados & Borum 2004). This indicates that the Wadden Sea hosted large areas of eelgrass in the eulittoral as well as in the sublittoral zones. Eelgrass then fell victim to a fungal disease in the 1930s (Den Hartog & Polderman 1975, Vergeer & Den Hartog 1994). *Labyrinthula zosterae sp. nov.(Porter & Muehlstein 1991)* infected (Vergeer & Den Hartog 1991, Muehlstein & Porter 1997) the common eelgrass *(Z. marina)*. Hughes et al. (2018) recently found a correlation between water pollution levels and the mortality of seagrass in the 1930s, which showed a significantly higher level of damage by *Labyrinthula zosterae* at higher nitrate levels. Also increased water turbidity in the industrial era is cited as a limiting factor for the sublittoral stocks of *Z. marina* (e. g. van Katwijk et al. 2010). While the long-leaved sublittoral populations of eelgrass re-established in other European coastal regions, they have not yet recovered in the Wadden Sea (de Jonge und de Jong 1992).

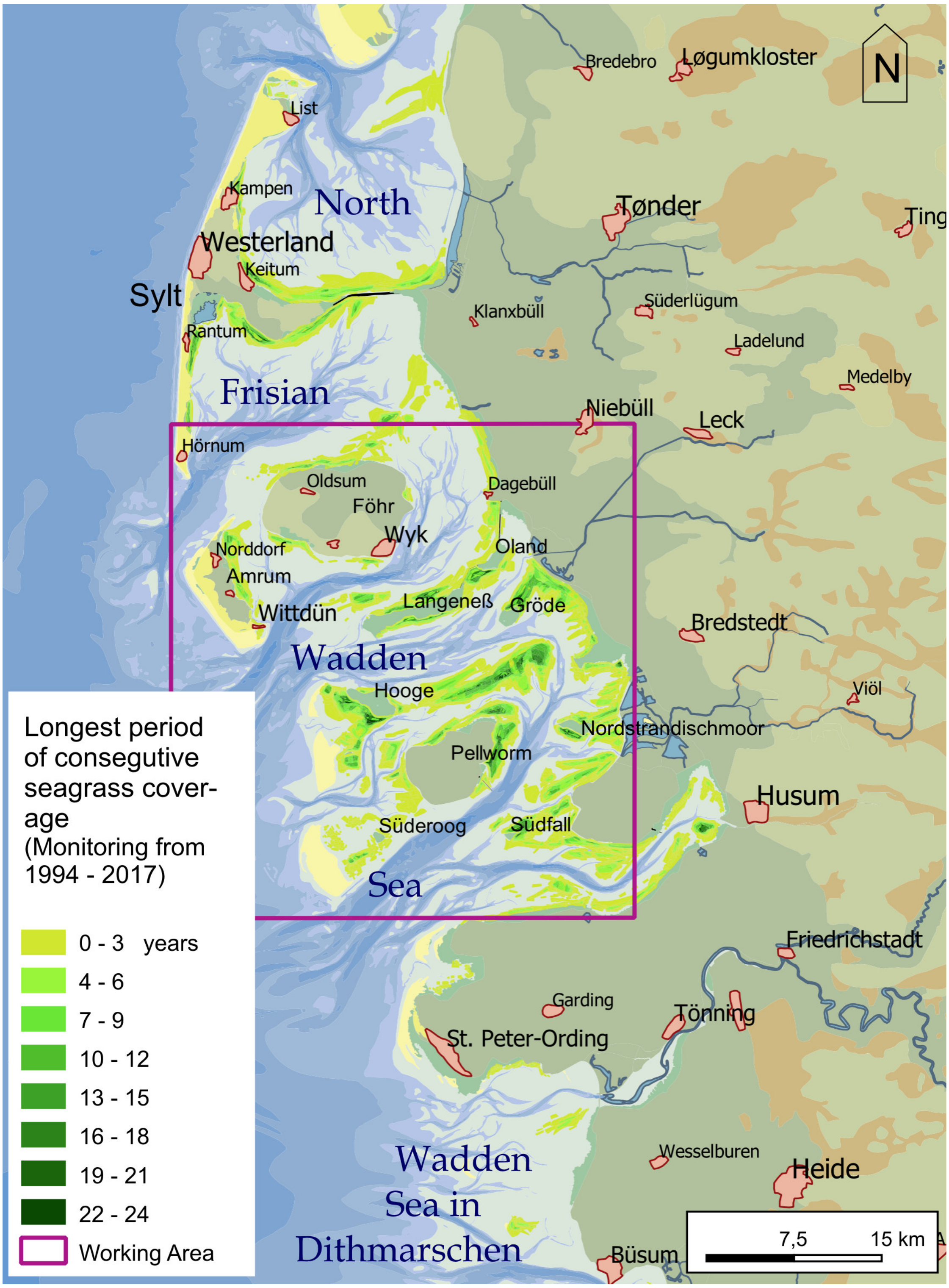


Figure 1: Temporal continuity of eelgrass beds in the Schleswig-Holstein Wadden Sea derived from aerial surveys. Pink box: working area for the development of remote sensing methods. (All maps and images are geographically projected and directed to UTM north)

The eulitoral eelgrass population, dominated by *Z. noltei*, has declined drastically since the 1960s. The decline occurred especially in the southern Wadden Sea, from the Netherlands to the Elbe Estuary and the Wadden Sea in Dithmarschen (Reise et al. 1994). Further north, in the North Frisian and Danish Wadden Sea, larger areas of eelgrass have been preserved. From the end of the 1970s until the mid-1990s, when continuous monitoring was set up, however, the area covered by seagrasses in the northern Wadden Sea had also fallen to a minimum (Reise & Kohlus 2008).

Especially the high nutrient load in the Wadden Sea is assumed to have caused the decline of seagrass since the 1960s (e.g. van Katwijk et al. 1999). There is evidence of impairment of eelgrass caused by the growth of epiphytic algae, especially in the absence of the grazing mudsnail Peringia *ulvae (Pennant, 1777)*) (e.g. Gerbersdorf 1994, Philippart 1995) or the smothering of eelgrass beds by macroalgae (Reise und Siebert 1994, Reise et al. 2008).

Since the beginning of trilateral monitoring (1994), the area covered by eelgrass in the North Frisian Wadden Sea has increased by well over 400%. The prevailing currents and transport vectors on the west coast of Schleswig-Holstein, which are towards the North, hinder the spread of eelgrass through drifting seeds from the North Frisian Wadden Sea to the southern regions of the Wadden Sea in Dithmarschen and the Elbe estuary. In the Wadden Sea in Dithmarschen, only episodic settlements have occurred so far. Spatial analyses of aerial mapping data from the last 24 years show that over 86% of the area has not been continuously colonised by seagrass for more than three successive years and no area has been continuously colonised for more than eight years (Figure 1). In the last three to four years some eelgrass areas are regrown, future monitoring will show whether a stable population is currently established.

The location of the large eulittoral seagrass beds in the lee of islands, sand banks and high tidal flats indicates that sediment dynamics and hydrology influence colonisation (Reise & Kohlus 2008, Schanz & Asmus 2003). A second indication of the importance of morphodynamic processes is that the phase of strong increase in area was during a period of reduced storm frequencies (Dolch et al. 2016b). Moreover, this is confirmed by the much rarer and episodic occurrence of the seagrass beds in the area of Dithmarschen, which is characterised by unstable tidal flats, which are exposed to high levels of marine energy.

In conclusion, the causes for the massive decline of *Z. noltei* since the middle of the 20th century – in the North Frisian Wadden Sea which occurred later and only in the 1990es (Dolch et al. 2016a) - are mainly seen in eutrophication but also in a changed hydrography. However, the reasons are not completely clear (Reise et al 2015).

The seagrass beds, shown to be sensitive to environmental influences, are protected as a biotope (Landesnaturschutzgesetz Schleswig-Holstein). The area of seagrass beds is regarded as a reciprocal eutrophication indicator and is recorded as a parameter for the European Water Framework Directive (WFD, directive 2008/32/EC). Seagrass is also a parameter for angiosperms (together with saltmarsh vegetation) for the WFD.

The ongoing monitoring of eelgrass in the Wadden Sea, described in the next chapter, was established in the 1990s, the ground mapping in 2007. Since the OFEW-project 2005 (Geißler et al. 2011), methods for monitoring of eelgrass beds in the Schleswig-Holstein Wadden Sea using optical satellite remote sensing have been improved and have now been applied for several years (Müller et al 2016). An image classification framework has been set up and the results are regularly validated. With the increasing availability of suitable sensors, the satellite-based method has become mature enough to be applied for monitoring purposes.

2 Methods

2.1 Monitoring Methods

Data acquisition over extensive areas of the tidal region of the Wadden Sea is challenging. The area that needs to be covered for ground mapping the eelgrass beds is about 140 km². The tidal basins are often separated from each other by deep channels and can only be reached with great effort. Moreover, the tidal flats are only accessible for a short time at low tide and they are often difficult walk on. Therefore, a combination of different approaches is required to assess the extent and the health of the eelgrass beds. Aerial mapping provides a large-scale overview of the extent of the eelgrass beds and their development during the growing season. Complementary to this, the perimeter of the beds is mapped on the ground using GPS loggers and a detailed characterisation of the eelgrass is carried out at a set of selected sites.

A comparison of the area covered by eelgrass beds between years is only possible, when using the data collected at the time of the maximum development during the growing season. This time can vary slightly between years depending on the weather conditions.

2.1.1 Aerial mapping

Aerial mapping of the size and the density of eelgrass beds has been carried out annually in the Wadden Sea of Schleswig-Holstein since the pilot phase of the Trilateral Monitoring and Assessment Program (TMAP) in 1994.

Aerial mapping is conducted – not least because of costs, but above all to meet the tight time frame – by sports aircraft. Mapping is carried out from a height of 300 to 500m by three surveyors, which draw independently the visually observed borders of the eelgrass beds. The results of the three surveyors are compared at the end of the flight. A distinction is made between the density categories 20-60% and >60%. The comparison from multiple surveyors allows for an estimation of methodological error, which has been estimated to be 10-20% with regard to the size of the beds (Reise 1994). Green macroalgae are mapped using a similar method during the eelgrass surveys.

The aerial mapping has the advantage that it provides a large-scale overview and enables a rapid assessment of the area. Furthermore, the timing of flights can be scheduled to match the maximum extent of the eelgrass beds. The method shows limitations in the accuracy of the position and delineation of the beds. At the beginning of the monitoring, sea charts were used for orientation and localization of the beds. Since 2007, the National Park Administration has provided georeferenced satellite image maps (Reise 2007) as a basis for the mapping. This decreased positional inaccuracies (Reise et al. 2015).

The outlines simplify the border of the seagrass beds, this generalization – e.g. loss of uncovered patches – leads to an overestimation of the area covered by eelgrass. Erroneous estimates result from the limitations of differentiating between lower densities of eelgrass cover and eelgrass free sediment, especially when the sediments are dark coloured (Reise et al. 2014). In addition, underestimation can also occur, if areas covered by macroalgae are not identified correctly.

2.1.2 Ground mapping

Several types of ground mapping are performed with different objectives.

Ground mapping has been carried out since 2007 in order to achieve qualitatively more accurate data on the size of the eelgrass beds than is obtained by aerial mapping. Within each six-year reporting period of the Habitat Directive (Council Directive 92/43/EEC) the whole area is surveyed once by mapping a sixth of the Schleswig-Holstein Wadden Sea area each year. The perimeter of the beds is mapped on foot using a GPS logger (usually < +-15m accuracy) and detailed information on species composition and health of the eelgrass is collected at a set of selected sites. In contradiction to the aerial mapping, the density classes are recorded for >5 to 20% and for >20% and there is no separation of eelgrass density at 60% (Dolch et al. 2011). Thus, the ground measurements also cover the very low densities of eelgrass, which cannot be detected during aerial mapping.

Ground mapping provides more accurate data on the borders of the eelgrass beds. The drawback with the method is the long time-period required to map the whole area. The total extent of tidal flats with eelgrass can differ between years by more than >10%. This means that the coverage measured during the annual surveys is a combination of data collected under different environmental conditions.

Ground monitoring is supplemented by transect surveys of coverage density, changes in species composition, coverage with macroalgae (mostly *Ulva lactuca Linnaeus 1753*) and the vitality of eelgrass beds (Dolch et al. 2011). The parameters are estimated optically and the position of the transects is measured using GPS.

A third type of ground mapping is performed with the focus on delivering validation data for the satellite assessment of seagrass. As close as possible to the time the satellite flies over the area, a series of up to one hundred 10X10m quadrants are surveyed along transects. The transects are not fixed, but their position is documented using GPS. The quadrats correspond to the size of one pixel of the Sentinel-2 MSI A and B sensors. The surveys include a visual assessment by experienced observers of the density of coverage of eelgrass, macroalgae and diatoms as well as a finger-test of sediment grain size. This data set is best suited for validation of the satellite classification data and is called “transect ground truth mapping” in the following text.

2.2 Development of satellite remote sensing methods for eelgrass detection

For a long time, the integration of satellite data into monitoring was not feasible, especially because the availability of suitable images was very limited. The challenge obtaining good satellite images is that the fixed acquisition schedule needs to concur with low tide and cloud free conditions.

The availability of good satellite data has increased in recent years because more satellite sensors with suitable characteristics have become available. The different satellite programmes of space agencies and commercial supplier provide suitable data for eelgrass detection in the Wadden Sea from different sensors. Free satellite data in sufficient spatial resolution is available from the European Copernicus satellites Sentinel-2, which provides spectral measurements with 10-60 m resolution (sensor MSI) since summer 2015. In combination with data from NASA (Landsat-8 OLI sensor, launched in 2013), with 30 m resolution, the Wadden Sea area is covered every 3-6 days. However, the requirement of low tide and cloud free conditions reduces the number of suitable images and there is still no guarantee for a good acquisition of data during the growing season and for the maximum spatial extent of eelgrass in each year. This limitation can be addressed by supplementing the data set with commercial satellite data that have been acquired under good conditions. Alternatively, mosaicking satellite images from different acquisitions that show different parts of the area so that the whole area is covered during the main growing season can be used. Since 2013, data for the Schleswig-Holstein Wadden Sea area was acquired with suitable conditions at least once per year during the main growing season: 15.08.2013 (Landsat-8), 17.07.2014 (Landsat-8), 21.08.2015 (Landsat-8), 08.09.2016 (Landsat-8), 05.09.2016 (Sentinel-2), and 29.08.2018 (Landsat-8). A satellite based monitoring is only possible if suitable image material is reliably available every year. 2017 was a year with generally poor remote sensing conditions, as our analysis of the indicator sunshine hours shows (Figure 2), and it became a test situation for a year with sparse data availability. This shortage was solved by combining three different satellite images from different sensors and to the full areas could be covered with suitable acquisitions.

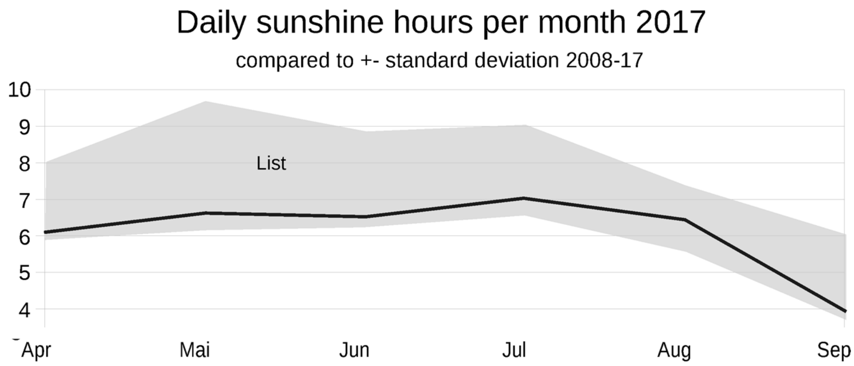


Figure 2: Daily sunshine hours in 2017 (black line) compared to the statistical long-term sunshine hours between 2008 and 2017 (analysis of data published by www.wetteronline.de)

Since 2015 satellite images have been used for eelgrass detection in parallel to the monitoring techniques described above. During a test phase, the results were compared with the results of the aerial and ground mapping. The method applied to the satellite data for detecting eelgrass beds has been developed since 2000 (started with EU FP4 and 5 projects Bioptis and Himomand has evolved over the past years in close cooperation with the stakeholders (projects OFEW, DeMarine-1, DeMarine-Environment, direct contracts). It can be applied to different sensors and is independent of the acquisition date (month or year). It is based on a number of processing steps, which include an atmospheric correction by dark objects subtraction, cloud detection with the Idepix software available in SNAP software, linear spectral unmixing and band combinations for vegetation density assessment. For the latter the Normalized Difference Vegetation Index (NDVI) is used. The classification of pixels is performed by a decision tree, which combines different indices derived from the spectral information of the different surfaces (Brockmann & Stelzer, 2006, Müller et al. 2016). In a post-processing step, incorrectly classified pixels are removed from the final maps during a visual inspection carried out by experts.

2.3 Validation methods

Different validation methods were applied in order to assess the accuracy of the satellite classification and in order to compare the different eelgrass monitoring methods. (1) Validation is performed by comparing the dedicated transect ground truth measurements (10x10m) with the satellite data. (2) Areal extent and location accuracy have been determined for individual eelgrass beds using both aerial mapping and satellite classification data with the objective of determining transfer factors that would allow the current time series, which is based on aerial mapping, to be continued using satellite classification data.

Where available, the three methods aerial mapping, ground mapping and satellite classification are compared. However, for many eelgrass beds only aerial mapping and satellite classification data is available because of the limited coverage of the ground mapping to one sixth of the area each year. The density of eelgrass coverage as well as the size of the beds are investigated.

3 Results

3.1 Validation of image classification with dedicated transect ground truth measurements

In a first step of the validation of the classification with dedicated transect ground truth measurements, the eelgrass density classes of the satellite data are overlaid with the density assessment performed at the transect points. Figure 3 shows one example of this overlay for the eelgrass bed north of Gröde (Figure 1). While the satellite image was acquired on 08.09.2016 by Landsat-8, the ground survey took place on 24.08.2016. The colour shading of both data sets are aligned for the different density classes. The characteristic structure of the meadow is visible in both data sets showing a dense bed with linear interruptions, which are small channels, in west-easterly direction.

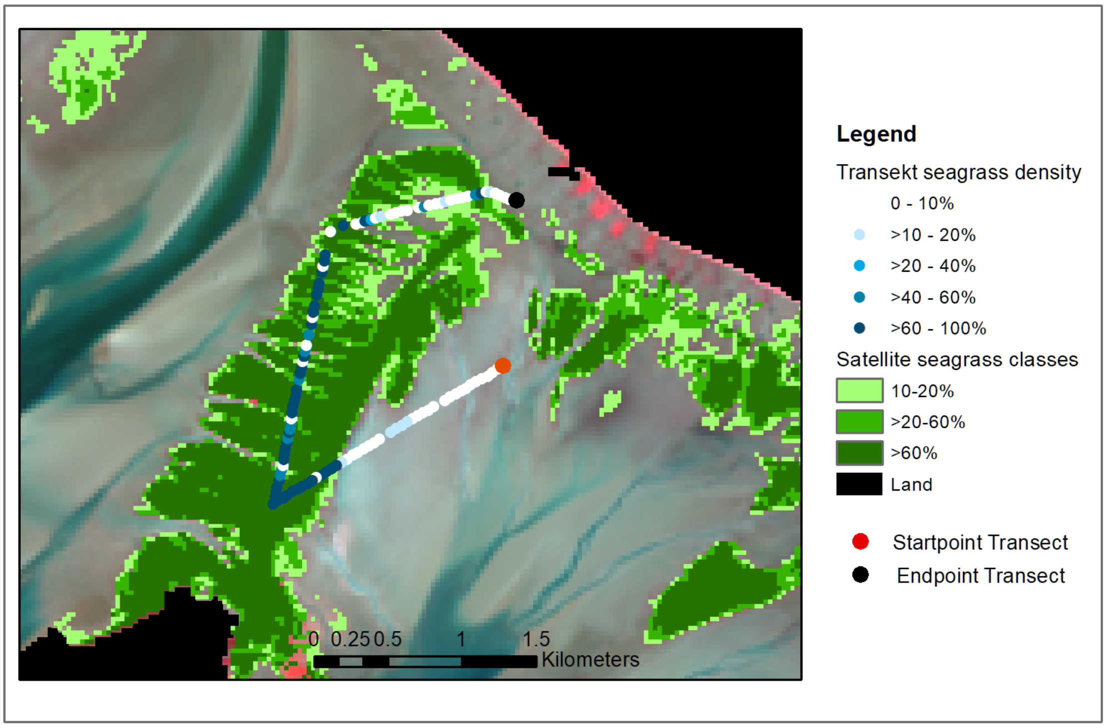
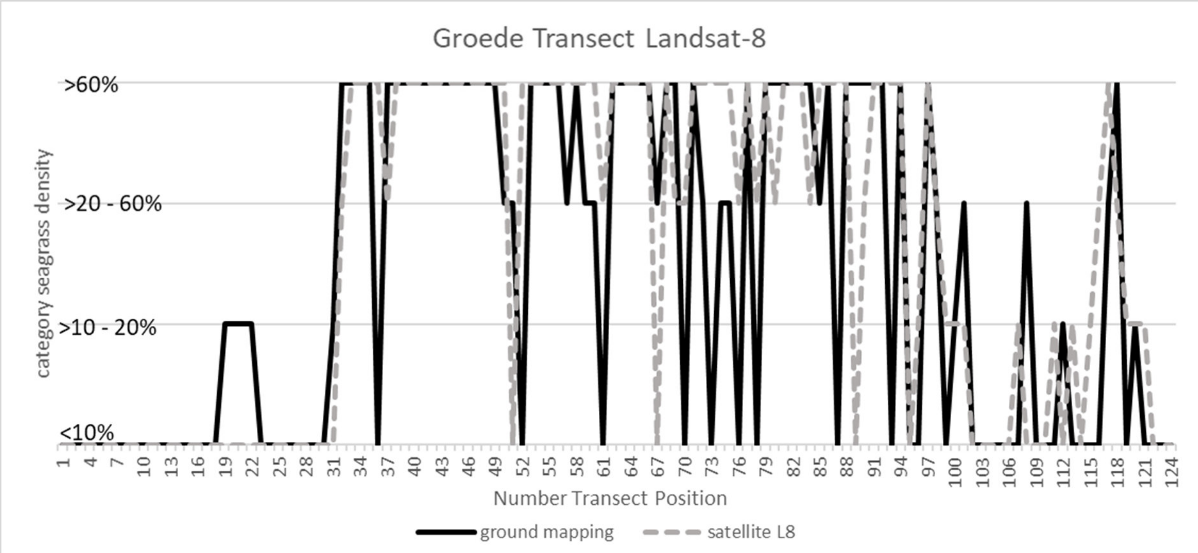


Figure 3: Classification of the seagrass meadow NE of Gröde (Landsat 8, 08.09.2016) and overlay of density assessment along transect points (28.07.2016).

In order to show how the data sets agree, the density categories along transects are shown in Figure 4, which correspond to the transect shown in Figure 3. The upper plot shows the results for the Landsat-8 classification from 08.09.2016, while the lower plot shows the results for the Sentinel-2 acquisition from 05.08.2016. For these plots, the ground-based assessment categories have been mapped to the density classes of the satellite classification. The transect plot for Landsat-8 shows that the data for eelgrass beds with dense vegetation, collected according to both methods, correspond very well. The parts of the eelgrass beds with low vegetation density, which occur along the small channels, are captured by the satellite, but not always with the correct low-density class. Often the data from the satellite images only allow for the detection of a density of 20-60%, whereas ground-based surveys allow for the mapping of areas with less than 10% eelgrass density. In some cases, the same behaviour is visible in both data sets, but is shifted by 1-2 pixels, which can be caused by slight inaccuracies between pixel and transect point position. This is different for Sentinel-2 results, where the changes in eelgrass density is shown in exactly the same positions (Figure 4 lower plot). The better results for Sentinel-2 data are due to the higher spatial resolution of the sensor (10x10m) which is the same as the area that is assessed along the transect.



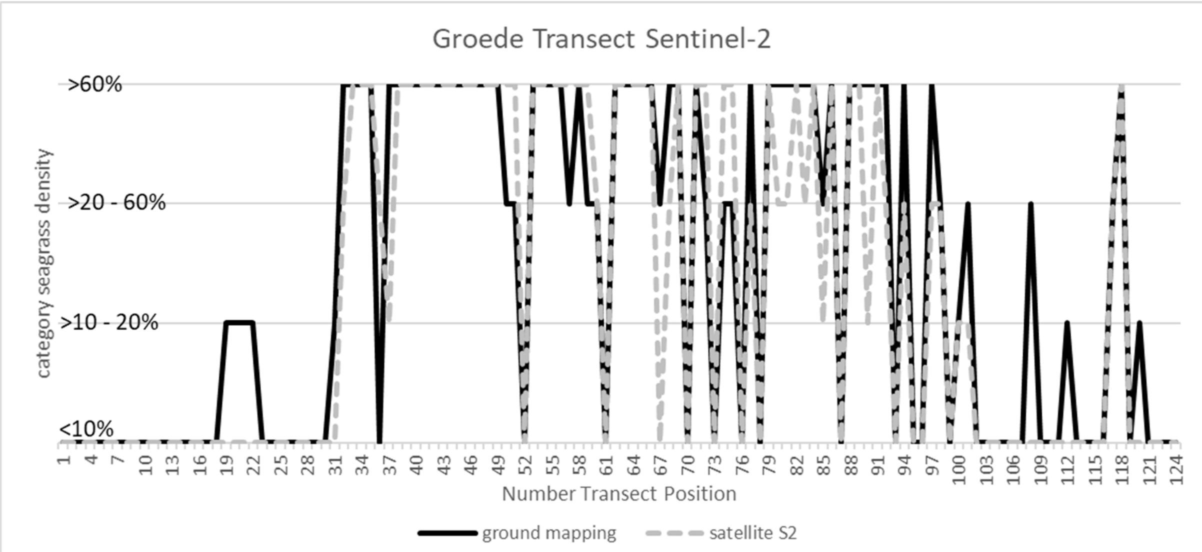


Figure 4: Eelgrass density categories along the transect (position in Figure 3) for Landsat-8 (above) and Sentinel-2 (below)

The results from two different transects mapped in 2016 (Sylt and Gröde) are compiled in a confusion matrix showing the agreement and disagreement between the field assessment and the classifications of the satellite data (Figure 5). The upper matrix shows the results for Landsat-8 classification while the lower matrix demonstrates the performance of the Sentinel-2 classification. Dense eelgrass cover (>60% density) is classified with an accuracy of 84% for Landsat-8 and 79% for Sentinel-2 while the seagrass free and sparsely covered areas (0-10% density) are classified with an accuracy of 68% (Landsat-8) and 86%(Sentinel-2). The intermediate classes have lower accuracies in both satellite types and the overall accuracy is 65% and 75%, respectively. Causes for the lower accuracy for the Landsat classification are the factors described above: the small-scale structures are less clear in the Landsat image and slight spatial shifts cause disagreement in the categories.

seagrass density Landsat-8

ground mapping	0-10%	11-20%	21-60%	>60%	
0-10%	**43**	8	5	7	68%
11-20%	6	**2**	0	0	25%
21-60%	5	4	**4**	12	16%
>60%	1	0	11	**61**	84%
	78%	14%	20%	76%	**65%**

seagrass density Sentinel-2

ground mapping	0-10%	11-20%	21-60%	>60%	
0-10%	**60**	1	1	1	95%
11-20%	7	**1**	0	0	13%
21-60%	3	6	**7**	9	28%
>60%	0	2	13	**58**	79%
	86%	10%	33%	85%	**75%**

Figure 5: Confusion matrix of seagrass density classes from classification and ground mapping at points along Sylt and Gröde transects. The above matrix shows the results for Landsat-8 classification, the lower matrix demonstrates the performance of the Sentinel-2 classification.

There is a tendency for the classifications to underestimate the eelgrass densities, especially for the Sentinel-2 classification. This aspect needs further investigation in future analyses. For Landsat-8, the misclassification can also be observed in the other direction: eelgrass is classified in the satellite data but not detected on ground. This might be caused by mixed pixels, that include eelgrass as well as bares sediments and therefore falls into a seagrass covered category.

3.2 Comparison of methods

The different methods are compared for selected eelgrass beds. In the following figures, the eelgrass beds near to Gröde are used as an example. The maps in Figure 6 show the eelgrass beds north of Gröde in August 2016 detected by satellite classification (1), aerial mapping (2) and 1/6 ground mapping (3). The Landsat-8 image from 08.09.2016 is shown as background image (false colour image). Figure 6 demonstrates that the satellite classification detects the small-scale structures of the meadow while the aerial mapping and 1/6 ground mapping show a more generalized outline. The aerial mapping does not completely cover the eelgrass bed and shows a less accurate outline. It can further be seen that aerial and 1/6 mapping cover larger areas for the sparse eelgrass density than the satellite classification.

The extent of the eelgrass areas is depicted in Figure 7, which shows the extent from the aerial mapping in June, July and August, the 1/6 ground mapping from August 2016 and from satellite classification derived from the acquisition in September 2016. The comparison of the mapped area shown in Figure 7 underlines the tendency that the satellite classifications provides the smallest eelgrass area, which is mainly due to the two facts that the small scale patches of sparse or no-eelgrass are not included and that the density categories 10-20% and 20-40% might be underestimated in the satellite data. Due to the higher resolution of Sentinel-2 and thus more detailed outline of the beds, the retrieved area is even smaller than for Landsat-8. The lower limit of detection has to be further investigated for the satellite method.

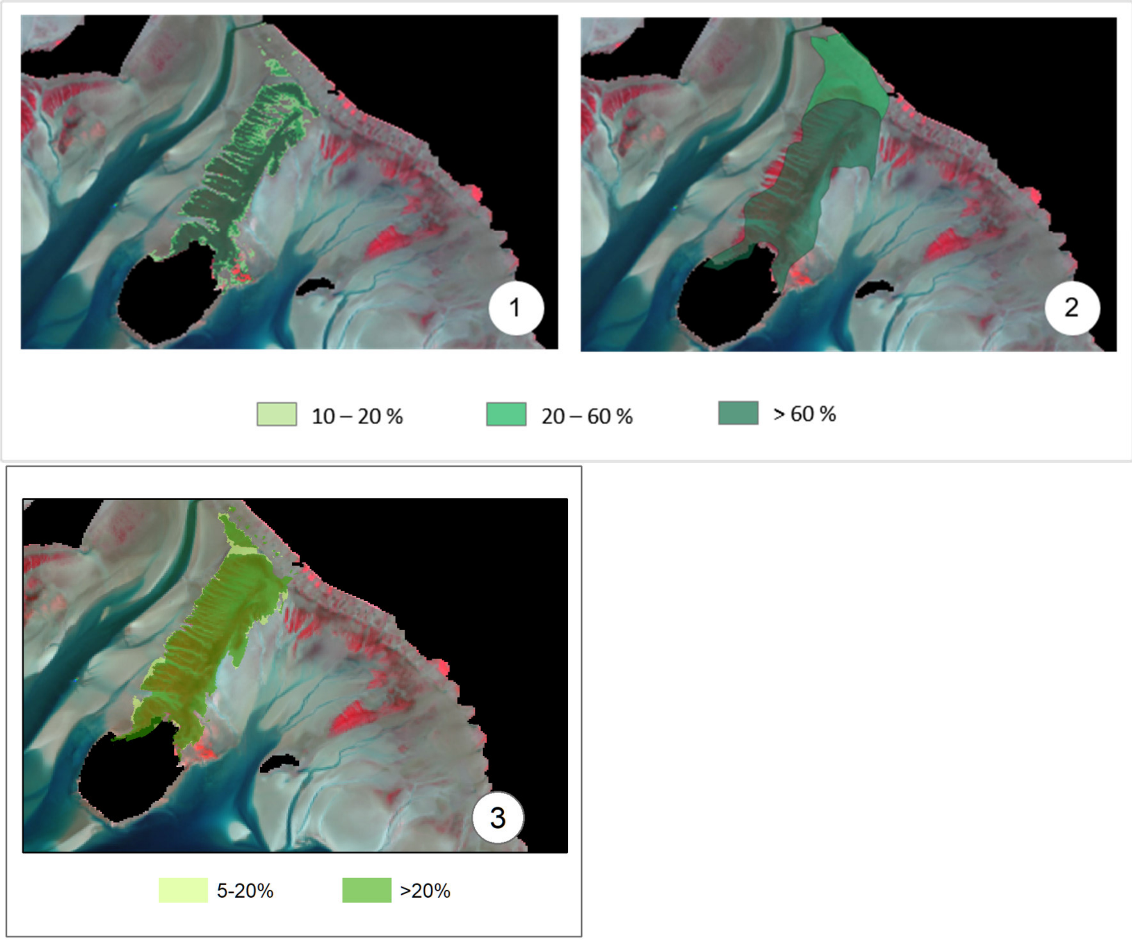


Figure 6: Results for eelgrass detection north of Gröde: (1) satellite classification (08.09.2016), (2) aerial mapping (22.08.2016), (3) ground mapping (02.08.2016). The limits for eelgrass density are different in the ground mapping (no differentiation at 60%). Only the central eelgrass meadow is regarded for this comparison. Background image: Landsat-8 08.09.2016 (false colour image)

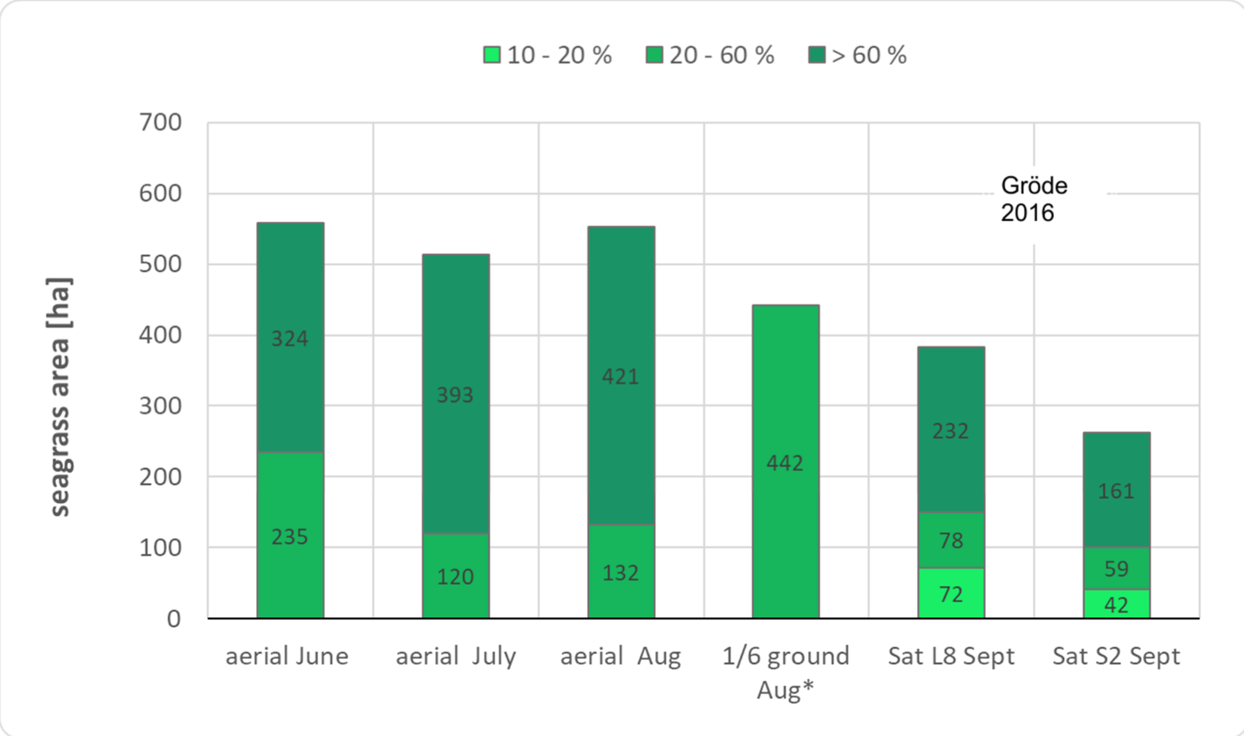


Figure 7: The eelgrass bed north of Gröde: comparison of the size of the bed from aerial mapping, 1/6 ground mapping and satellite classification Landsat-8 and Sentinel-2 for the different density classes. *The density class for 1/6 ground mapping is covering the range 20-100%; the area for 5-20% is not considered.

The comparison shown in Figure 7 is for one selected eelgrass bed, however, the same comparisons have been performed for 9 different beds. Generally, the size of the beds calculated from the satellite images is smaller than that calculated from aerial mapping or the 1/6 ground mapping. Table 1 provides an overview of the absolute differences in size (ha) and the relative differences between aerial mapping and satellite classification. Negative numbers indicate larger areas derived from the aerial mapping. In most of the cases, the aerial mapping provides larger areas. The eelgrass meadow north of Pellworm (see Figure 1) shows the largest absolute differences, which, however, are quite stable over all three years. The other beds show larger differences between the years and need to be investigated further in order to identify any systematic patterns occur. The differences between the methods that occur especially for Pellworm or Blauort are topic for future investigations about the lower limit of eelgrass detectable by satellite imagery.

Table 1: Absolute and relative differences between areas of eelgrass beds between aerial mapping and satellite classification. Negative numbers indicate larger areas derived from the aerial mapping.

	Absolute differences (ha)			Relative differences (%)		
Eelgrass meadow	**2015**	**2016**	**2017**	**2015**	**2016**	**2017**
Langeneß	22	89	-16	6	35	-6
Gröde	-186	-170	-276	-35	-31	-49
Pellworm	-1146	-1142	-1154	-67	-63	-67
Föhr-Süd	-43	-127	33	-31	-62	52
Föhr-Nord	-130	-110	-38	-52	-52	-37
Sylt-Munkmarsch	-52	-83	-81	-29	-42	-43
Sylt-Lister Tidebecken	-219	-74	-134	-46	-19	-43
Nordstrandisch Moor	-53	-43	-34	-36	-28	-28

Blauort	-47	-47	-37	-82	-62	-67

3.3 Time Series of the total area covered by eelgrass beds in the Wadden Sea

For reporting, the total area covered by eelgrass beds in the Wadden Sea is used. The sizes of individual beds are not reported. In Figure 8 the area covered by eelgrass in the North Frisian Wadden Sea derived from the aerial mapping is compared with the area derived by satellite classification. The fact that the area calculated by aerial mapping is larger than the area calculated from the satellite images is obvious in this assessment of a large area.

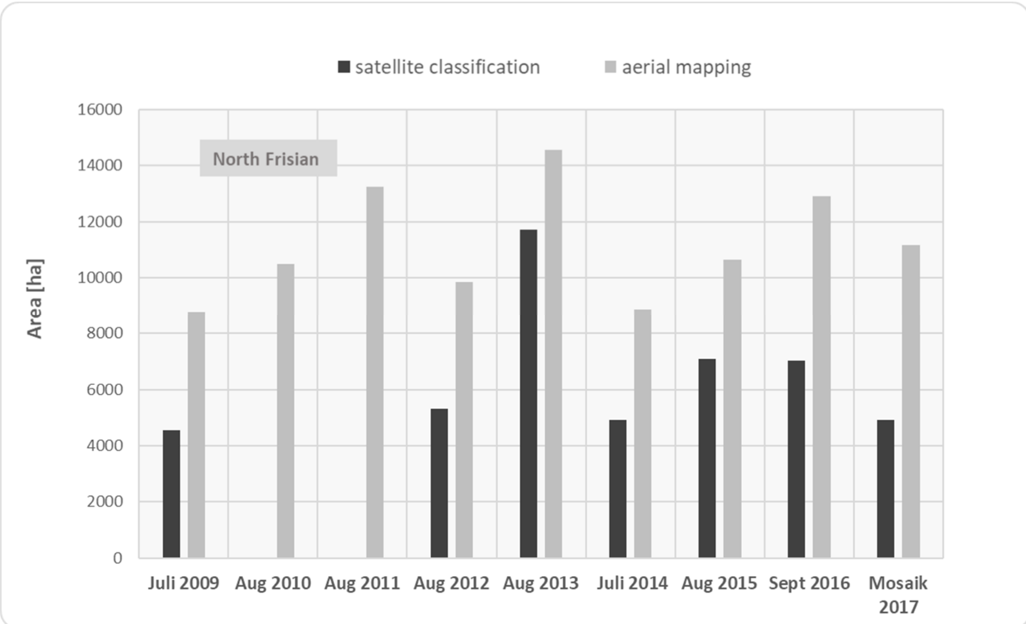


Figure 8: The total size (ha) of the area covered by eelgrass in the working area (see Figure 1) of the North Frisian Wadden Sea for the years 2009-2017 derived from aerial mapping and satellite classification

For the years 2009 to 2011, Figure 8 shows the continuation of the growth in the total area of eelgrass beds that began in the mid-1990s. The declines 2011/2012 and 2013/2014 are particularly pronounced in the working area, but less pronounced, when the total size of the beds for the whole Wadden Sea area is considered. The areas mainly affected were exposed areas to waves and currents and especially newly populated areas with eelgrass growth for the first time in 2011 or 2013.

Overall, the total size of the eelgrass beds has fluctuated at a fairly high level since 2012. Such a development is typical in situations, where suitable sites for eelgrass growth are largely occupied and, depending on the annual weather conditions, the plants spread to areas that cannot be permanently colonised. An assessment that fits in well with the observation of the decline in the areas covered rarely or for the first time by eelgrass in the two years 2011 and 2013.

4 Discussion

The direct comparison of transect ground truth data and satellite classification shows good agreement in the density assessment. The transect measurements dedicated to validation are therefore of great value and should be continued in the future. The areas of 10x10m assessed along the transect correspond exactly to the pixel resolution of Sentinel-2, thus allowing both methods to capture the same degree of detail regarding structures within the eelgrass beds.

When comparing the different monitoring methods currently in use with the satellite classification, the size of the eelgrass beds derived by the satellite imaging is clearly smaller.

The influence of the spatial resolution of data could be shown. Although the higher resolution Sentinel-2 images provided better results in terms of agreement with the transect data, they show larger differences, when comparing data from aerial mapping and 1/6 mapping. Due to the higher resolution of Sentinel-2, large numbers of (non-continuous) pixels, with no eelgrass coverage, can be excluded from the calculation of the total area – irrespective of whether they occur at the perimeter or deep within an eelgrass bed. This can only be done to a very limited degree in the other methods. Thus, it is not surprising that the satellite classification generally provides smaller estimates of the size of eelgrass beds than the other methods.

When assessing the agreement between the eelgrass density assessments from ground mapping and satellite data (e.g. Figure 5) three aspects have to be considered: the width of the (lower) density categories, the differences in the time of data acquisition, and the interaction between these two factors. An increasing time span between acquisition dates may result in significant differences in eelgrass density – particularly when starting with a low density. The lower density categories (0-10 and 11-20%) only cover 20% of the full range, while the remaining two categories cover the other 80% of the density spectrum. This means that an eelgrass patch starting at 7% and increasing by 15% moves quickly from the lowest density category to the second highest density category. However, when starting at 22%, it would take another three 15%-increases to reach the highest density category. Furthermore, the determination of low-density categories in the field is not always easy and this is also a factor, which should be taken into account.

The lower limit of eelgrass density for detection by satellite data needs further assessment in order to provide reliable information for the continuation of the time series of monitoring data.

Table 2 provides an overview of the different methods with respect to different aspects that influence the accuracy and availability of eelgrass information.

Table 2: Overview Assessment of different detection methods

	Aerial mapping	**1/6 ground mapping**	**Satellite classification**
Spatial coverage	Coverage of total area every year	1/6 of total area visited every year	Coverage of total area every year
Temporal coverage	Dedicated overflight dates depending on growing season, synoptic mapping 3x per year. Good correspondence with maximum development	Mapping during growing season (between late June and September)	Synoptic coverage (currently no guaranty of image at peak growing phase)
Outline and structure	Generalized outline; rare internal structures	Precise outline; no separation of different density areas within the meadow; no internal structures	Precise outline; separation of density areas as small as image resolution; very highly detailed structures inside the meadow
Lower density limit	20%	5%	~10% (higher uncertainties at densities below 20-40%)

Discrimination between eelgrass and macro algae	Yes	Yes	Yes (during postprocessing)
Costs	Flight costs and working hours for mapping and digitalisation	Time consuming field work; data organisation	No data costs, working hours for image processing

5 Outlook

It is planned to continue the parallel assessment of satellite derived data on eelgrass beds and ground as well as aerial eelgrass monitoring. The comparison of the data from the three methods will be performed for single beds as well as for the whole North Frisian Wadden Sea. Copernicus has committed to continue the Sentinel programme (satellite and data provision) until 2030. Sentinel-2 is currently in orbit with 2 different satellites (A and B), providing data every 5 days. The satellites C and D are already built and will be launched mid 2020, thus optimizing the possibilities of obtaining regular images during the peak growing phase.

Classifications performed in earlier years need to be redone with improvements introduced to the method, which have been applied to data since 2013.

Concepts for analysis of data from years without suitable satellite images during the maximum of the vegetation period have been developed and already tested in 2017. Besides the combination of different sensors. A gap-filling with the help of near-time data or by interpolation inside dense eelgrass beds could be a post-processing step for patches resulting from cloudy cover.

Satellite remote sensing offers an easier way to track the annual size and density of eelgrass beds. With higher density, the results are reliable, up-to-date on a large scale and spatially more precise than the previous mapping from an aircraft. In a next step, the accuracy should be determined more precisely in areas with lower density.

Ongoing monitoring shows that *Zostera marina* is establishing itself at the edge of deeper wadden areas. It is not expected that developments of this kind could be detected by remote sensing in the foreseeable future. Ground mapping will continue to be necessary for the detection of areas sparsely overgrown with eelgras, the proportion of different Zostera species, the strength of epiphytic vegetation etc., and this will also provide some verification of the remote sensing results.

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7 Declaration of competing interests

The authors declare that they have no competing interests.

ReferencesBrockmann, C.; Stelzer, K. (2008): Optical Remote Sensing of Intertidal Flats. In: Barale, V.; Gade M. (Eds): Remote Sensing of the European Seas. Springer, Heidelberg.

den Hartog, C.; Polderman, P. J. G. (1975): Changes in the seagrass populations of the Dutch Waddenzee. Aquat. Bot., 1 (1975): 141-147.

de Jonge, V. N.; de Jong, D. J. (1992): Role of tide, light and fisheries in the decline of Zostera Marina L. in the Dutch Wadden Sea. Netherlands Institute for Sea Research Publication Series 20: 161-176.

Dolch, T.; Buschbaum, C.; Reise, K. (2012): Seegras-Monitoring im Schleswig-Holsteinischen Wattenmeer 2011. AWI List, Unpublished. Research report on ground based mapping of seagrass stocks in selected areas by order of the LLUR.

Dolch, T.; Buschbaum, C.; Reise, K. (2016a): Seegras-Monitoring im Schleswig-Holsteinischen Wattenmeer 2015. AWI List, Unpublished. Research report on ground based mapping of seagrass stocks in selected areas by order of the LLUR.

Dolch, T.; Buschbaum, C.; Reise, K. (2016b): Vorkommen von Grünalgen und Seegras im Nationalpark Schleswig-Holsteinisches Wattenmeer. AWI List, unpublished. Research report by order of the national park administration.

Geißler, J; Stelzer, K.; Kohlus, J.; Farke, H.; Gade, M. (2011): Anwendung und Validierung von Fernerkundungsverfahren für ein optimiertes Wattenmeermonitoring. In: Traub, K.-P.; Kohlus, J.: Geoinformationen für die Küstenzone. Points Verlag, Norden, Halmstad: 51 - 64.

Gerbersdorf, S. (1994): Epifauna in eulitoralen Seegraswiesen des Sylter Wattenmeeres. Diploma thesis, Univ. Heidelberg.

Hughes, R. G.; Potouroglou, M.; Ziauddin, Z.; Nicholls, J. C. (2018): Seagrass wasting disease: Nitrate enrichment and exposure to a herbicide (Diuron) increases susceptibility of Zostera marina to infection. In: Marine Pollution Bulletin, Volume 134 (September 2018): 94-98.

Krause-Jensen, D.; Greve, T. M. (2004): European seagrasses: an introduction to monitoring and management. P8-11. A publication by the EU project Monitoring and Managing of European Seagrasses (M&MS) EVK3-CT-2000-00044.

Larkum, W. D.; Orth, R. J.; Duarte, C.M. (2006): Seagrasses, biology, ecology and conservation. Heidelberg, Springer.

Lozan J. L.; Rachor, E.; Reise. K.; Westernhagen, H.; von Lenz, W. (1994): Warnsignale aus dem Wattenmeer. Blackwell, Berlin: 90-100.

Muehlstein, L. K.; Porter, D. (1991): Labyrinthula zosterae sp. nov., the Causative Agent of Wasting Disease of Eelgrass, Zostera marina. Mycologia 83(2): 180-191.

Müller, G.; Stelzer, K.; Smollich, S.; Gade, M.; Adolph, W.; Melchionna, S.; Kemme, L.; Geißler, J.; Millat, G.; Reimers, H-C.; Kohlus, J.; Eskildsen, K. (2016): Remotely sensing the German Wadden Sea — a new approach to address national and international environmental legislation, Environmental Monitoring and Assessment 188: 595. https://doi.org/10.1007/s10661-016-5591-x

Reise K.; Kohlus, J. (2008): Seagrass recovery in the Northern Wadden Sea? Helgoland Marine Research 62: 77-84, DOI 10.1007/s10152-007-0088-1.

Reise, K (1994): Vorkommen von Grünalgen und Seegras im Nationalpark Schleswig-Holsteinisches Wattenmeer. Research report BMU/UBA 10802085/01, 25 p.

Reise, K. (2007): Vorkommen von Grünalgen und Seegras im Nationalpark Schleswig-Holsteinisches Wattenmeer. AWI List, unpublished. Research report by order of the national park administration.

Reise, K.; Buschbaum, C.; Dolch, T. (2015): Vorkommen von Grünalgen und Seegras im Nationalpark Schleswig-Holsteinisches Wattenmeer 2014. AWI List, unpublished. Research report by order of the national park administration.

Reise, K.; Kolbe, K.; de Jonge, V. (1994): Makroalgen und Seegrasbestände im Wattenmeer. In: Lozán, J. L., Rachor, E., Reise, K., Westernhagen, H. v., Lenz, W. (Hrsg.) Warnsignale aus dem Wattenmeer. Berlin, Blackwell Wissenschafts-Verlag, 90–100.

Reise, K.; Siebert, I. (1994): Mass occurrence of green algae in the German Wadden Sea. Deutsche hydrographische Zeitschrift, Suppl. 1: 171-180.

Schanz, A.; Asmus, H. (2003): Impact of hydrodynamics on development and the morphology of intertidal seagrasses in the Wadden Sea. Marine Ecology Progress Series 261: 123-134.

Schomburg, P. (1997): Einfluß von Seegrasbewuchs (Zostera spec.) auf das Vorkommen mobiler Epifauna im Sand- und Schlickwatt vor Kampen, Sylt. Unpublished diploma thesis FB Biologie/Chemie, University of Bremen.

Stelzer, K. (1998): Erfassung der Sedimentverteilung des Schleswig-Holsteinischen Wattemeeres mit Hilfe multispektraler Fernerkundungsdaten. Diplomarbeit Universität Trier

Terrados, J.; Borum, J. (2004): Why are seagrasses important? - Goods and services provided by seagrass meadows. In: Borum, J.; Duarte, C. M.; Krause-Jensen, D.; Greve, T. M. (Eds.): *European seagrasses: an introduction to monitoring and management*. The M, 88p.

van Katwijk, M.M.; Schmitz, G. H. W.; Gasseling, A. M.; van Avesaath, P. H. (1999): The effects of salinity and nutrient load and their interaction on Zostera marina L.. Marine Ecology Progress Series190: 155-165.

van Katwijk, M. M.; Bos, A. R.; Kennis, P.; de Vries, R. (2010): Vulnerability to eutrophication of a semiannual life history: A lesson learnt from an extinct eelgrass (Zostera marina) population. Biological Conservation 143: 248-254.

Vergeer, L. H. T.; den Hartog, C. (1991): Occurrence of wasting disease in Zostera noltii. Aquatic Botany, Volume 40, Issue 2: 155-163.