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Indicators of Expansion and Retreat of *Phragmites* Based on Optical and Radar Satellite Remote Sensing: a Case Study on the Danube Delta

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Abstract

Reed is an important wetland species. In some places it provides valuable ecosystem services, while in other places it poses a threat as an invasive species. Thus, monitoring and predicting reed dynamics is crucial. We not only detected changes in reed area using remote sensing, but also developed indicators for the stability of reed wetlands based on remote sensing that would allow to predict its future development. We used satellite imagery to study reed development in the Danube Delta in Romania over a period of 22-years and identified expanding, stable and retreating reedlands. We then compared optical vegetation indices and radar backscatter among those three different reed development categories. We found clear spatial differences in long-term reed dynamics. We also revealed a clear difference in radar backscatter, but no difference in the optical signal of expanding, stable and decreasing reed areas. The radar data showed the largest seasonal variation in locations where reed was expanding and smallest seasonal variation where reed was decreasing. Overall, our study shows that the stability of reed ecosystems, and their services, can be monitored by quantifying seasonal changes in backscatter of reed-lands using radar satellites. This principle looks promising for monitoring other ecosystems as well.

Keywords Reed · Reed development · Marsh · Wetland · Remote sensing · Radar · Danube delta

Introduction

Wetland ecosystems provide valuable services. For example, they provide habitats for unique plant species and animal communities which may in part serve as food (Henderson and Lewis 2008; de Groot et al. 2011). They also provide economic benefits (Henderson and Lewis 2008; Chmura 2011) and a nursery for fish, thereby supporting local fisheries (Boesch and Turner 1984; Deegan et al. 2002; Chmura 2011). In addition, wetlands may reduce nutrient loading in the coastal waters (Chmura 2011) and serve to mitigate waves and reduce flood risk (Möller 2006; Barbier et al. 2008; Koch et al. 2009; Morgan et al. 2009; Chmura 2011; de Groot et al. 2011). Monitoring the stability and edge dynamics of wetlands, and thereby the ecosystem services they provide, is thus important to enable suitable management.

Here, we focus on the stability of reed wetlands. Reed (*Phragmites australis*) is a common plant in wetlands and is well known for its phytoremediation (Guo et al. 2014), but is also recognized as an important species for shoreline protection, and protection of arthropods, birds and mammals (Ostendorp et al. 2003; Cerri et al. 2017). Reed also provides raw materials, and can provide food for livestock (Stanica et al. 2012). The function of reed as a buffer between aquatic and terrestrial ecosystems makes reed one of the most important wetland species (Brix 1999). Since the 1950's, reed has shown a severe die-back in eastern, central and northern Europe. This phenomenon was named the Reed Die-Back Syndrome (RDBS). The warmer Mediterranean region did not seem affected, and reed here even seemed to expand rapidly (Van Der Putten 1997). However, more recently reed die-

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back was also detected in Italy (Fogli et al. 2002; Cerri et al. 2017).

In contrast to the reed die-back in northern Europe, in the United States reed is rapidly expanding and commonly treated as an unwanted invasive species. In the US reed eradication programs are a common part of management (Chambers et al. 1999; Silliman and Bertness 2004). Recently it has been suggested that the European subspecies of reed is outcompeting the North American subspecies, with large potential effects for the ecosystem, as reed can have a large effect on the nitrogen balance of a system (Findlay et al. 2002; Volesky et al. 2018). Rapid expansion of reed lands in North America could indicate replacement by the European subspecies.

Many possible causes of reed die-back or reed expansion have been suggested (Van Der Putten 1997; Fogli et al. 2002; Cerri et al. 2017), but as of yet it is unclear which set of conditions are linked with these developments. Hence, we lack reliable methods to predict where die-back or expansion may occur. Remote sensing is a promising technique for both monitoring long-term reed dynamics as well as obtaining indicators for predicting future reed development.

In this study we aim to take the first steps towards developing remote sensing techniques to both monitor and predict future reed development. We will do this for the Danube delta along the Black Sea coast in South Eastern Europe, one of the worlds` largest area naturally covered by wetlands. Here, reeds have been continuously harvested for centuries and local communities greatly depend upon their many ecosystem services (Stanica et al. 2012). The Razelm Sinoe Lagoon System, in the Danube Delta in Romania was chosen as the study area. This lagoon system at the end of the Danube river, along the Black Sea provides a massive coastline covered almost exclusively by reed, which is very important for local communities (Stanica et al. 2012). It is unclear if the Danube delta follows the southern European trend of rapid expansion, or if there are signs of vegetation die-back like sites in Italy (Fogli et al. 2002; Cerri et al. 2017) and Hungary (Van Der Putten 1997).

To effectively monitor the vast area of the Razelm Sinoe Lagoon System (± 1000km^2), we use space borne remote sensing. Several studies have already looked into detecting reed using remote sensing to support management; reed and other vegetation can be distinguished using optical (Pengra et al. 2007) or radar data (Bourgeau-Chavez et al. 2013). In the south of France, an extensive model was used to model reed height, diameter, flower head density, stem density and cover based on six optical satellite (SPOT 5) images covering a single growing season (Poulin et al. 2010). They found that although the Normalized Difference Vegetation Index (NDVI) performed poorly, the Soil Adjusted Vegetation Index (SAVI) worked well. Space borne X-band radar has been applied to differentiate between reed, *Suaeda japonica*, and mudflat (Lee et al. 2012). C-band radar has been shown to be useful to classify wetlands into six different classes (forested and nonforested peat bogs, marsh, open water, clearing and forests) (Baghdadi et al. 2001). Sentinel 1's C-band Synthetic Aperture Radar (SAR) is expected to be very useful for wetland analyses (Reschke et al. 2012). A study (Brisco et al. 2011) using airborne C-band radar found that reed produces backscatter patterns similar to other grasses. Following the Freeman-Durden model (Freeman and Durden 1998), they distinguished between double bounce scattering, volume scattering and surface scattering and considered *Phragmites* a volume scattering object (Brisco et al. 2011). In other words, they expect most of the signal to be scattered by the vegetation layer. Both optical and radar remote sensing have been applied with success to reed monitoring before (Poulin et al. 2010; Lee et al. 2012). Several studies have thus demonstrated the (change) detection of reed using remote sensing data, but without predicting how this situation will develop in future. In this study we ultimately aim to identify a remote sensing based indicator of future development, i.e., to signal where changes could be expected.

In this study, we will use a large historical optical satellite data set (the Landsat archive) to establish reed development over a period of 22 years, and distinguish between increasing (lateral expansion), decreasing (lateral loss) and stable reed areas. We detect differences in the state of reed areas, by comparing the signals of optical (Sentinel 2 Multi Spectral Instrument) and radar (Sentinel 1 C-band Synthetic Aperture Radar) in the three categories of reed development. Additionally we investigate the effect of the fetch (the length of the open area the wind and waves have to build), as it has been suggested to influence expansion (Coops et al. 1994) and we establish the effect of seasonal development patterns, as we expect that a stressed system might have a smaller lateral expansion of reed in spring. Seasonal in situ measurements in the Razelm Sinoe Lagoon System were taken to establish the underlying physical characteristics of the reed beds.

Summarizing, the overarching aim of this study is to establish an indicator to help monitor reed dynamics, and hence the stability of the ecosystem services the reed provides. We do so by focusing on indicators that can be derived from satellite remote sensing data, and that distinguish between areas with die-back versus expansion. We subsequently apply this indicator to a major coastal reed land in the Razelm Sinoe Lagoon System in Romania, to establish if reed wetlands are dying back or expanding. This will directly support monitoring efforts in Romania, but might also be a first step towards mapping reed die-back or expansion in other areas.

Materials and Methods

In this section we first describe the study area followed by the protocol for the in situ measurements. We then establish where expansion, minor change and retraction of reed has taken place, by comparing two satellite images from the Landsat archive, 22 years apart. This is followed by an explanation on how we established reed development within these 22 years every 2–4 years. Subsequently, we describe how we calculated the fetch length. Finally, we describe how we use indices from recent optical (Sentinel 2 MSI) and radar (Sentinel 1 SAR) satellite images to compare expanding, stable and eroding reed areas in winter, spring and summer.

Area Description

The primary study site is the Razelm Sinoe Lagoon System, in Romania. This is the southern part of the Danube Delta Biosphere Reserve. The entire system covers about 1000km^2, and consists of a series of lakes, former lagoons transformed into lakes and present-day lagoons with engineered inlets, as well as other ponds, wetlands, former coastal sandbars, fossil and present day littoral barrier beaches. The coastal vegetation consists mainly of reed (*Phragmites australis*) which can grow up to six meters, before dying in winter (Hanganu et al. 2002). The lagoon has seen major human influences over the last century. The connection with the nearby fresh water system, the Danube, was increased by cutting new canals and dredging existing channels, followed by closing down of the main inlet in 1974 (at Gura Portitei) and replacement of the natural connections with the sea with engineered inlets (for Sinoe Lagoon). This caused the system to move towards a fresh water system. This also meant an increase of Danube-born nutrient and sediment inflow in the lagoon system. The limited connection with the sea causes the system to accumulate both organic and non-organic matter (Stanica et al. 2012; Dinu et al. 2015). The climate of the Lagoon System is continental, with hot dry summers and very cold winters. The Lagoon System is located in one of the windiest areas in Romania. The water bodies of the lagoon system are partly or entirely frozen during winter, the freezing periods vary from days to weeks, but complete ice cover for long periods is rare.

Seasonal in Situ Measurements of Reed Characteristics

At two locations in the Razelm Sinoe Lagoon System, in situ measurements were taken, the first site, Jurilovca (see Fig. 1), is located at latitude: 44.75°, longitude: 28.94°, the second site, Histria, is located at latitude: 44.55°, longitude: 28.78°. Site Jurilovca was sampled in March, May and July 2015. Site Histria was sampled in the same months in 2016 (see Appendix Fig. 8 for a detailed map of both sites). Five destructive plots and six non-destructive plots of 1 × 1 m were placed at both sites. The position of each plot was recorded with a GPS. In each plot, the number of reed stems was counted by placing a 0.5 × 0.5 m frame and counting all stems with a length > 30 cm, stems with a shorter length were ignored. In each plot, 20 representative stems are selected, their diameter is measured approximately 10 centimeter above the ground. These stems were harvested and their length was recorded. They were weighed, dried for > 3 days at 60° and reweighed to establish wet and dry biomass.

Fig. 1 the first field site, Jurilovca. Picture taken by D. van der Wal at the 29th of April 2015

Categorizing Long-term Vegetation Development from Landsat Imagery (22 years)

To establish vegetation development in the Razelm Sinoe Lagoon System we used two Landsat images 22 years and 4 days apart (Landsat 5 TM at 1995-07-04 and Landsat 8 OLI at 2017-06-30). We used the surface reflectance images provided by the United States Geological Survey (USGS), made available through EarthExplorer. The rough outlines of the lagoon were manually drawn, to ensure we only have vegetation and water in the area of interest and all roads and other human structures are excluded. This outline was made manually, and is of variable width. The aim of this outline is to exclude anything that is not reed or water e.g., inland vegetation, roads etc.), thus retaining only the wetland area. Within this rough area of interest we established the land line by applying a threshold of 0.3 on the Normalized Difference Vegetation Index (NDVI). This is done for both images (1995 and 2017). Both water lines were visually checked and the NDVI threshold performed well. In the Razelm Sinoe Lagoon System, a small section at the southern tip of Sinoe lake was removed from analyses, as it proved difficult to distinguish between water and vegetation here in the 2017 image, likely due to a mix of dead vegetation, water and sediment. This small section was not taken into consideration for any of the consecutive analyses. In addition, some areas were excluded due to clouds and cloud shadows in the imagery. Appendix Fig. 9 provides the outline of the applied masks.

This study is focused on reed retraction or expansion by looking at vegetation stress at the seaward edge of the wetland vegetation. If we include the broader reed land, any signal of stress caused by edge effects may not be detectable. Therefore we extract a small strip that can reasonably be expected to show this stress. We used the water edge of 2017 to extract a strip of 60 m (i.e. 2 Landsat pixels) of reed vegetation. For pixels in this strip, the lateral development of the reeds (stable, increase or decrease) was established. Within this strip, values were extracted every 30 m, which is the spatial resolution of the Landsat imagery. The distance to the water was calculated for each pixel in each image; this distance was used to distinguish between increasing, stable and decreasing pixels. A pixel with an unchanged distance to water or a pixel where this distance is larger than 45 m in both 1995 and 2017 was classified as stable (see Fig. 2). We use 45 m because this is roughly the diagonal of one Landsat pixel (42.43 m), so in this case there is at least a full pixel in front of this vegetation pixel that can absorb any stress that originates from the water-vegetation border.

The remaining pixels were divided as: decrease < 0 < increased. Note that the pixels that were in the area with decreased reeds were still vegetated (as by definition pixels with vegetation in 2017 were selected).

Establishing Long-term Reed Development from Landsat Imagery (2–4 Year Steps)

To gain further insight into the long-term reed development, we analyzed six additional Landsat images (of: 1999, 2001, 2005, 2008, 2011 and 2015, see Table 1). We processed these similarly to the previous Landsat images and calculated the distance to the water for each sampling point. We tested the performance of our manual threshold of NDVI (as used to establish the development categories from the 1995 and 2017 images), by applying the ArcGIS tool 'Iso Cluster Unsupervised Classification' (using 2 classes) to the sequence of NDVI maps. This consistently estimated the land water threshold at an NDVI between 0.25 and 0.3. We used the unsupervised clustering threshold analyses to distinguish between land and water.

We used images from the same season (June/July) and used a compounding cloud mask (i.e. pixels that were covered by clouds or cloud shadows in any year were completely removed from the analysis). For the pixels in the selected strip along the shoreline, we then analyzed the position of the pixels relative to the shoreline, for the three reed development categories (retreat, stable and expansion). We used the development categories established between 1995 and 2017 to compare the distance to the water edge between categories. This provided insight into the persistence of the reed development.

Establishing Wave Exposure of Reeds, Using Fetch Length from Landsat Imagery

Based on the established vegetation edge for the Landsat 8 image of 2017-06-30, the so-called fetch was calculated, indicating the length over which wind-waves can build up over water. To establish the fetch, we determined the angle towards the water using the direction raster of the Euclidean Distance tool in ArcGIS. The fetch was then calculated as the distance in that direction until land (on the opposite side of the lagoon)

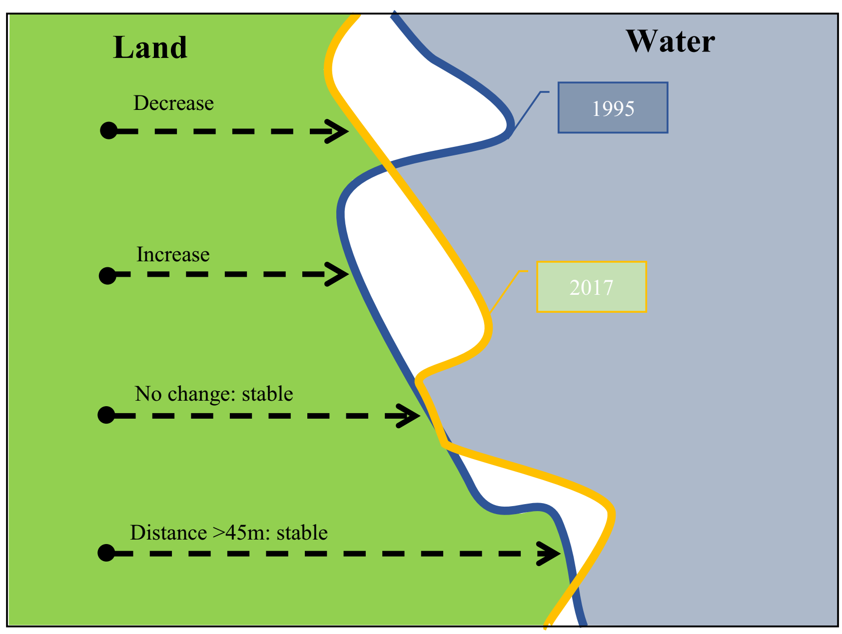

Fig. 2 Schematization of assigning the reed development categories (decrease, stable, increase) based on shoreline changes between 1995 and 2017

Table 1 Landsat images of the Razelm Sinoe Lagoon System for multi-year analysis

Satellite	Date
Landsat 5	1999-06-29
Landsat 5	2001-07-04
Landsat 5	2005-06-29
Landsat 5	2008-07-07
Landsat 5	2011-07-16
Landsat 8	2015-07-11

Table 2 Dates of in situ sampling and corresponding Sentinel-1 SAR (S1) and Sentinel-2 MSI (S2) images of the Razelm Sinoe area

In situ date	Location	Season	S1 date	S2 date
2015-3	Jurilovca	Winter	2015-01-12	2016-01-09
2015-5	Jurilovca	Spring	2015-05-12	2016-05-22
2015-7	Jurilovca	Summer	2015-07-23	2016-06-07
2016-3	Histria	Winter	2015-01-12	2016-01-09
2016-5	Histria	Spring	2015-05-12	2016-05-22
2016-7	Histria	Summer	2015-07-23	2016-06-07

was reached. Given the jagged shoreline, land closer than 100 m was not considered as the opposite side of the lagoon, and was ignored. Note that in this study, fetch was calculated for the onshore direction only (i.e., perpendicular to the coastline), and it is thus independent of actual wind direction. For each of the reed development categories (increase, stable, decrease) the mean fetch length was established to test whether shoreline change depended on the exposure of the reed to wind-waves.

Analyzing Seasonal Remote Sensing Indicators of Long-term Reed Development

The Copernicus Sentinel satellite constellation (including, among other sensors, Sentinel-1 SAR and Sentinel-2 MSI) was used as primary data source to examine how vegetation development could be observed remotely. All preprocessing was done with the SNAP toolbox (v5.0) provided by the European Space Agency. Sentinel-1 SAR multi-look, dual polarized (VV and VH) level-1 Ground Range Detected (GRD) interferometric wide swath (IW) images were used, these data are already multi-looked. We preprocessed these images by first removing thermal noise, followed by the application of an orbit file. Then data were calibrated to sigma nought, and a range Doppler terrain correction was applied. We did not apply speckle reduction filters as this would have decreased the spatial resolution, increasing the probability of including mixed pixels (with land and water). As we are in a very flat area, at sea level we did not require additional terrain corrections, hence a digital elevation model (DEM) based correction was not applied. Sentinel-2 MSI images, with 10 m resolution, were atmospherically corrected to Bottom Of Atmosphere using a dark pixel approach with the Sen2Cor tool set in SNAP. The ozone content were auto determined from the auxiliary information, the aerosol determination was set to 'rural, maritime', and cirrus correction was turned off. We used Sentinel images of winter, spring and summer. The seasonal timing of these images matched the in situ measurements, see Table 2. We focused on the RGB and NIR bands of the Sentinel images, as these are required to calculate the desired vegetation indices, but also because including other Sentinel 2 bands, such as vegetation red edge (bands 5–7), would have degraded our pixel size (to 20 m). This would have increased the chance of including mixed pixels. A single cloud and cloud shadow was removed from the Sentinel-2 images of 2016-06-07; the cloud stretched over approximately 700 m of coast. Where the cloud partially or completely covered the reed bed, the entire reed bed perpendicular to the water was removed from the analysis. The average VV backscatter and VH backscatter from Sentinel-1 SAR and average NDVI from Sentinel-2 MSI were compared between increasing, stable and decreasing reed beds.

To analyze seasonal effects, the water line was individually established for each Sentinel-2 MSI image, for the first 2 images (2016-01-09 and 2016-04-28) a NDVI threshold of 0 was used (NDVI $<$ 0 was assigned water). This threshold performed poorly in the July image, where water had a positive NDVI value, possibly due to phytoplankton. For this image a threshold of 0.3 was used (NDVI $<$ 0.3 was assumed water). The difference in NDVI between vegetated and unvegetated foreshore is typically distinct, the established thresholds were checked visually and found to perform well. To exclude potential mixed pixels, we only used pixels found to be vegetation in all Sentinel-2 images.

In addition to the NDVI, the Soil Adjusted Vegetation Index (SAVI), with a default L value of 0.5, was also used as this was found to perform better than NDVI when analyzing reed vegetation (Poulin et al. 2010).

The NDVI, VV and VH backscatter of Sentinel images were compared between reeds established to be declining, stable or expanding (as retrieved from the Landsat imagery). This was done for the Sentinel-1 SAR and Sentinel-2 MSI images of winter, spring and summer, respectively.

To establish which biophysical properties had a large effect on remote sensing imagery, we compared in situ biophysical measurements with seasonally matching remote sensing images. In situ measurements of biomass, vegetation height, stem diameter and stem density were compared with VV, VH backscatter and NDVI at that location (the values of the corresponding pixel was extracted) using separate linear regressions. The three different seasons were tested separately. Locations of the in situ stations are provided in Appendix Fig. 8.

Results

Long-term Reed Development from Remote Sensing

From the Landsat optical data of 1995 and 2017, we found a vegetation loss of 38 ha (426 pixels), whereas the vegetation was found to be stable in 265 ha (2944 pixels) and increased (expanded) in 1946 ha (21,627 pixels) in a period of 22 years. The multi-year analysis showed a strong linear increase in locations labelled as expanding reed (see Fig. 3). There was an overall decrease in reeds in locations marked as such; the rate of decrease was especially large in the period 2008–2011. The water distance of stable areas also increased, likely because points where the water distance was larger than 45 m were also labelled as stable.

Seasonal Remote Sensing as Indicators of Long-term Reed Development

The Sentinel-2 optical data showed that the NDVI was lowest in winter, increases in spring and was highest in summer. Although the NDVI seemed higher in stable and increasing sites in summer, the differences between decreasing, stable and increasing reeds were small (Fig. 4). SAVI showed the same pattern as NDVI, with clear differences between seasons, and small differences between eroding, stable and expanding reed sites. Decreasing, stable and increasing sites could not be distinguished using optical satellite data (NDVI or SAVI).

The Sentinel-1 SAR data showed low values for the backscatter, and hence likely "smooth vegetation" (canopy largely of the same height) in winter, relatively high backscatter, and hence "rough vegetation" (canopy variable in height) in spring and an intermediate backscatter and roughness in summer. Interestingly, in sites with decreasing reed beds, the backscatter was low (suggesting smooth vegetation), while in stable reed beds the backscatter was intermediate, and in increasing reed beds the backscatter was highest (suggesting the roughest vegetation structure). This pattern (i.e., a strong contrast in backscatter between the different reed development categories) was especially clear in spring, but was also visible in summer. The winter backscatter was similar between decreasing, stable and increasing sites, but in spring large differences had developed (see Fig. 4). VV and VH polarized radar showed a similar pattern, the largest seasonal changes were found in the expanding reed beds, whereas the decreasing reed beds showed least seasonal changes.

Established vegetation appeared to be able to persist in areas with a long fetch, but an increase (reed expansion) mainly occurred in relatively sheltered locations (see Fig. 5). Areas which had a decrease in reed beds, had on average an intermediate fetch but with a large spread, suggesting that die-back of reed can occur regardless of fetch length. These decreasing sites also showed limited seasonal expansion, but with large variation. Increasing and stable sites showed a larger seasonal expansion (see Fig. 6).

Seasonal Variation in Properties of Reed Vegetation Measured in Situ

The in situ data of both field sites show a slow reed development in spring. Biomass seemed lowest in spring, possibly indicating that the vegetation had only just started to develop. However, biomass was not significantly different between seasons. The stem diameter was highest in spring. This might be due to a quicker disappearance of smaller stems. However this was not indicated by the stem density, which was not significantly different between seasons. Only vegetation height was significantly higher in winter, indicating that dead stems were still present in winter. All vegetation properties measured in situ showed great variation (see Fig. 7).

Relating Seasonal Remote Sensing Indicators to in Situ Patterns

We compared the in situ measurements with radar backscatter to explain which vegetation properties cause patterns in backscatter,

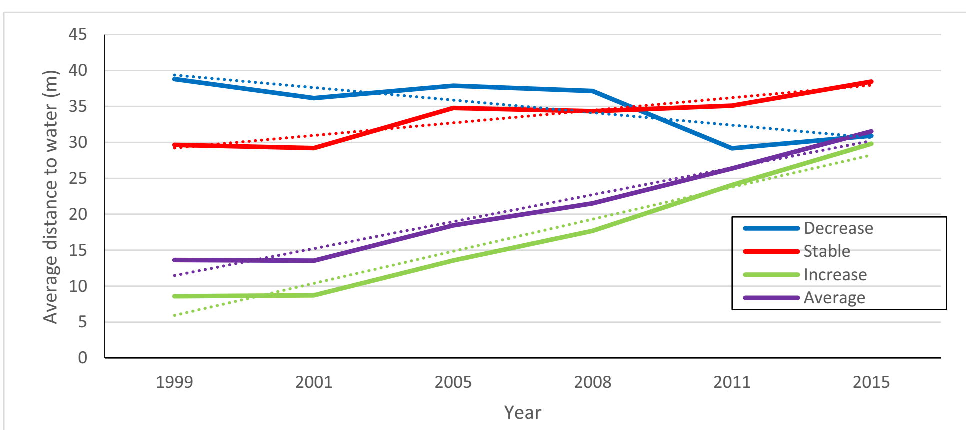

Fig. 3 The multi-year development of locations with decreasing, stable and increasing reed vegetation. This figure shows the development of the average distance to the water (shoreline) of the different development classes (decrease n = 631, stable n = 4064 and increase n = 16,108) based on Landsat images. The development class was determined over the entire period (comparing 1995 and 2017)

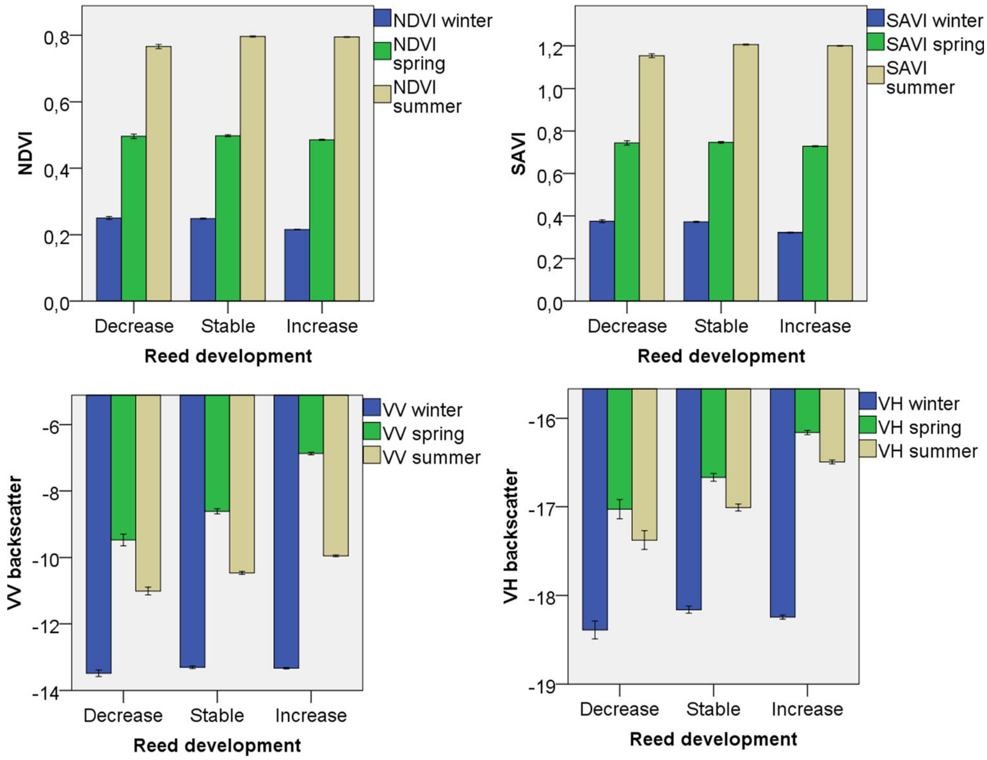

Fig. 4 Seasonal patterns in optical and radar signals of decreasing, increasingand stable reed sites, in the entire Razelm Sinoe Lagoon System. Error bars: ± 1 se

and hence which underlying processes can explain the seasonal differences in backscatter. However, the in situ measurements showed no clear relation with backscatter.

We tested 36 hypotheses simultaneously, hence according to the Bonferroni correction our p-value should be < 0.0014 to be statistically significant, none of the tested variables met this threshold (see Table 3; Fig. 7). The in situ data did not show a strong effect on backscatter. We can therefore not definitively conclude what property or process underlies the seasonal changes in backscatter.

Discussion

The aim of this study was to (1) establish an indicator to enable monitoring of reed-wetland dynamics and thereby the ecosystem service stability, and (2) apply it to the Razelm Sinoe Lagoon System in Romania to establish the stability of these reed wetlands. We used optical and radar satellite data to compare increasing, decreasing and stable reed edges of wetlands and found that especially the seasonal differences in radar backscatter provides valuable insight into the long-term vegetation stability. That is, indicators based on optical data showed no difference between the areas, but indicators based on SAR data showed large differences between decreasing, stable and increasing reed lands. All sites are roughest in spring, smoother in summer and smoothest in winter. In general, the expanding sites are roughest, the decreasing sites are smoothest. In addition, the differences between winter, spring and summer are largest in expanding sites, intermediate in stable sites and smallest in decreasing sites.

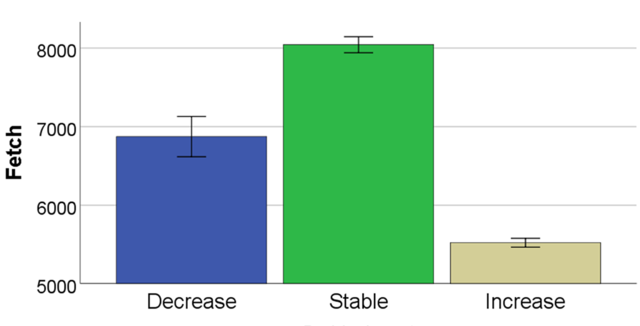

Fig. 5 The fetch (length of open water in front of vegetation) in decreasing,increasing and stable reed locations. Error bars: ± 1 se

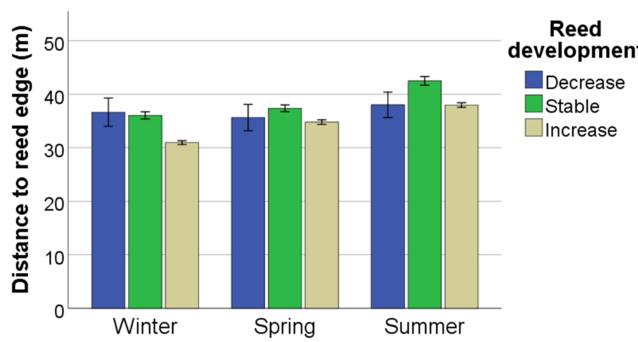

Fig. 6 The seasonal expansion of decreasing, increasing and stable locations.Error bars: ± 1 se

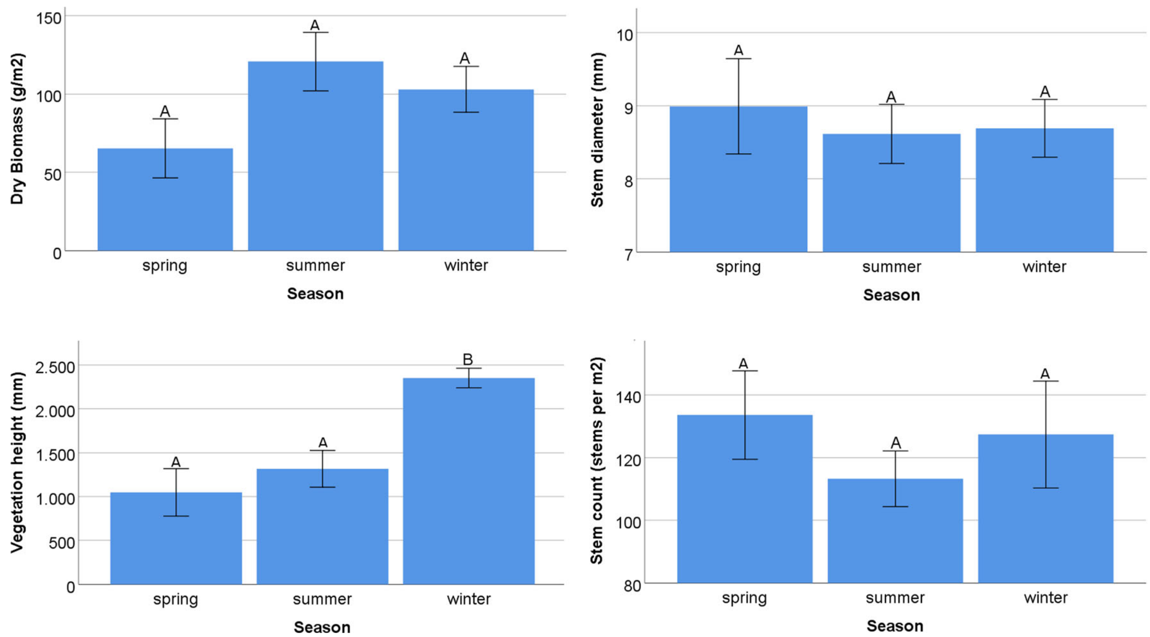

Fig. 7 Seasonal differences between in situ measured properties of reed vegetation

When analyzing vegetation stress near the waters edge using remote sensing, mixed pixels that contain both land and water potentially affect the results. We tried to reduce their influence as much as possible by selecting only pixels that are classified as land in all images. Any remaining mixed pixels in the analysis are expected to affect all classes equally and therefore would not cause the differences between classes. It could be argued that decreasing sites have decreased further and will therefore contain more mixed pixels. However, we established increasing and decreasing states of reed development based on a 2017 image, and calculated the backscatter on earlier images (2015 and 2016). Therefore, continued development cannot have increased the number of mixed pixels. Finally, if mixed pixels significantly affected our results, this would have been detected by our optical indicators (NDVI, SAVI), which are known to be sensitive towards vegetative vs. non-vegetative states. These indicators showed no differences between increasing and decreasing areas. It is therefore unlikely that the detected difference is due to the effect of mixed pixels.

Table 3 The seasonal relation (with linear regression statistics n, F, P and R2adj) between in situ measurements of the biophysical properties of reed vegetation and remote sensing signals (NDVI, and VV and VH backscatter)

			NDVI			VV			VH		
Season	Biophysical properties	n	F	P	R2adj	F	P	R2adj	F	P	R2adj
Spring	Biomass	9	1.547	0.254	0.064	0.010	0.925	-0.141	1.471	0.265	0.056
Spring	Density	14	0.564	0.467	-0.035	0.120	0.735	-0.073	1.494	0.245	0.037
Spring	Diameter	15	2.146	0.167	0.076	2.973	0.108	0.124	0.769	0.396	-0.017
Spring	Height	9	2.613	0.150	0.168	0.021	0.889	-0.139	0.013	0.914	-0.141
Summer	Biomass	15	1.468	0.247	0.032	0.003	0.960	-0.077	0.182	0.677	-0.062
Summer	Density	30	0.021	0.887	-0.035	1.309	0.262	0.011	0.336	0.567	-0.023
Summer	Diameter	37	0.067	0.797	-0.027	0.349	0.558	-0.018	0.151	0.700	-0.024
Summer	Height	15	0.865	0.369	-0.010	0.384	0.546	-0.046	2.455	0.141	0.094
Winter	Biomass	17	1.156	0.299	0.010	1.740	0.207	0.044	0.184	0.674	-0.057
Winter	Density	23	0.003	0.955	-0.047	0.491	0.491	-0.022	1.544	0.227	0.022
Winter	Diameter	29	0.025	0.877	-0.036	2.175	0.152	0.040	0.109	0.744	-0.033
Winter	Height	18	0.436	0.518	-0.034	0.192	0.667	-0.050	0.046	0.836	-0.119

Seasonal Remote Sensing as Indicators of Long-term Reed Development

We expect that the magnitude of the observed patterns in seasonal development of roughness to be site specific, due to climatological differences and site-specific differences in local environmental conditions. However, the seasonal pattern of a slower development and smaller seasonal differences in retreating sites is expected to be more general. A decrease in development and recovery speed after disturbance at vulnerable sites is also described by the critical slowing down theory (Scheffer et al. 2001). This theory indicates that as resilience decreases, the system takes longer to recover from disturbance. This could explain the limited and lower seasonal expansion at decreasing sites, which would have a lower resilience. However, although the first experimental evidence of this theory in wetlands is starting to emerge (van Belzen et al. 2017), the application of this theory to reed-lands has yet to be tested. This theory also indicates that plants can remain seemingly healthy up to a collapse, and that optical measurements related to biomass (such as NDVI) are ineffective for measuring resilience. In our study, we also found little response to lateral change in the reed beds in the optical data. However it is unclear if the observed differences in radar backscatter are related to a decrease in resilience or caused by another biophysical process. Notably, the large seasonal variation in backscatter at the expanding site should not be misinterpreted as flickering, which is often regarded as an indicator of nearness of collapse (Dakos et al. 2013). The seasonal variation seems to rather indicate growth vigor.

A multi-seasonal approach is known to be important when studying reed vegetation (Poulin et al. 2010; Lee et al. 2012). Hence seasonal changes were expected to hold information on potential lateral increase or decrease of the reed. There was a clear seasonal trend in the lateral extent of the reed bed, with reed beds protruding into the lake in summer. However the seasonal difference in backscatter in the reed bed vegetation between decreasing stable and increasing reed beds has not been described before. The early growing season is known to be very important for reed, as reed particularly depends on its initial growth to establish competitive dominance (Yamasaki and Tange 1981). The differences in backscatter between decreasing, stable and increasing sites could therefore be due to an earlier start of growth at more favorable locations. However, this would likely also create a difference in biomass, which would have been detectable by optical satellites. A previous study also found little use for NDVI in reed vegetation, but SAVI performed well (Poulin et al. 2010). However, in our study SAVI performed very similar to NDVI; neither of them showed a difference in reed vegetation between expanding, retracting and stable sites.

Radar data is able to provide valuable information on roughness that we could not derive from optical remote sensing. However it remains unclear what the underlying processes are. Graham and Harris (Graham and Harris 2003) created a water cloud model to simulate radar backscatter. They identified the most important factors in radar backscatter as the thickness of the vegetation layer (the vegetation height), the internal properties of the vegetation layer (leaf area index or leaf properties), the vegetation moisture content and the soil moisture content. We expect that if the seasonal differences in backscatter between increasing and decreasing locations were caused by thickness or the properties of the vegetation layer we would have detected it in the NDVI. Although indices such as NDVI are known to become insensitive at higher values (Baret and Guyot 1991; Zhang et al. 2013), the NDVI did show seasonal differences, indicating it was not saturated in all seasons. However, we cannot rule out properties of the vegetation layer, such as internal leaf structure, that do not affect NDVI but could have affected radar backscatter.

Vegetation and soil moisture content are major contributors in the water cloud model. The water cloud model is often used to simulate radar backscatter of land based vegetation (Graham and Harris 2003). The additional water layer in case of flooded vegetation is expected to have an even larger effect on backscatter than soil moisture content, even though the reed vegetation above it is over 2 m. This water layer is likely largely affected by elevation, as reed at lower elevations has to highest chance of being flooded. Retraction and expansion of the reed may also be a function of elevation. However, a large difference in suitability of conditions for reed growth would likely also have been visible in the optical data. Further study, likely combining remote sensing with an extensive field measurement campaign, will be required to establish which biophysical or environmental factors causes the seasonal difference between radar backscatter of decreasing, stable and increasing reed beds.

Long-term Reed Development from Remote Sensing

Our analysis showed that in the Razelm Sinoe Lagoon System reed is, overall, expanding. We found an average expansion of 87 ha per year between 1995 and 2017, clearly showing that the massive reed die-back found elsewhere in Europe does not extend to the Danube - Black Sea System. Although reed die-back has been found in southern Europe (Fogli et al. 2002; Cerri et al. 2017) our findings support earlier notions that reed is expanding (Van Der Putten 1997). The reed expansion although large in surface area is still relatively small when compared with the area of the entire lagoon system. On average the expansion is about 1.1 m per year. A study in the United States, where reed is considered to expand rapidly and management is focused on removing reed, found an invasion rate between 0.1 and 0.7 m per year, depending on which species it was competing with (Silliman and Bertness 2004). It is important to note that these are invasion and not expansion rates. In this light the expansion rate found in Romania can be considered rapid. However, it should be kept in mind that this long-term analysis was done using the Landsat satellites; the relatively low resolution of this satellite makes precise estimates difficult. Yet, our Landsat time-series demonstrated that the trends are persistent, with the strongest decrease in the period 2008–2011.

Given the large reed area that is persistently present, it is clear that the ecosystem services are clearly not threatened by reed die-back. However, a too strong reed expansion might still be a risk for service stability. Anthropogenic influences have increased influence of the Danube river and limited exchange with the Black Sea during the past century (Hanganu et al. 1999, 2002; Stanica et al. 2012). As a result the lagoon system has become mainly a fresh water system and is collecting organic and non-organic matter (Stanica et al. 2012), with the Sinoe Lagoon the only notable exception, as it has turned towards natural evolution and a trend towards brackish waters since mid 2000 s, when the previously controlled engineered inlets were left in natural flow. Reed is known for its capability to absorb nutrients such as nitrogen from water (Findlay et al. 2002), because of this ability it is often applied in helophyte filters. This means it will clean water passing through the lagoon, but also trap many nutrients there.

If the system continues to accumulate sediments and the elevation increases to the point where it offers suitable growing conditions to reed throughout the lagoon, a sudden explosive reed expansion could threaten open water dependent ecosystem services and the corresponding economic benefits. To ensure long term service stability, this situation will have to be monitored carefully.

Our analyses showed that reed expansion mainly occurred in sheltered areas, whereas exposed areas were mainly stable or decreasing. An increased establishment at sheltered sites was also indicated by Coops et al. (1994) in the Netherlands. In contrast, Weisner (1987) found a rapid expansion of reed at exposed sites in Sweden. However, Weisner (1987) pointed out that an elevation difference likely created by a different grazing regime might be the underlying cause for the rapid expansion. In general, Weisner (1987) too expected a more rapid expansion at sheltered sites. This may be associated with wave forcing, which is known to have a large influence on reed development (Haslam 1970; Coops et al. 1991), and has been shown to effect seedling establishments in other marsh species (Cao et al. 2019).

Conclusions and Outlook

We developed an indicator that can help predict the stability of reed wetlands, based on the size of seasonal differences in radar backscatter. We found that decreasing areas had smaller seasonal changes than stable or increasing areas. Radar backscatter signals showed differences among expanding, stable and retracting reed beds, where optical data did not. Although further study to pinpoint the biophysical processes underlying the radar signal would be recommended, its application has already proven to be very useful. It would also be interesting to incorporate a higher temporal resolution, i.e. analyse multiple images per season to better assess variations within and among seasons. We expect that our technique can easily be adapted to similar ecosystems such as salt marshes, but can also be applied to terrestrial systems such as heathlands or grasslands. In heathlands, SAR is also known to contribute new information not obtainable through optical data alone (Schmidt et al. 2018) and heathlands are known to adjust their seasonal development based on local conditions (Specht et al. 1983). This technique might even be applied to forests, where SAR is already often used to establish biomass (Luckman et al. 1998), but seasonal variation has not yet been used to assess the service stability. However, the great difficulties associated with mapping foliage dynamics in forests using SAR (Proisy et al. 2000), suggests that the radar backscatter indicator identified in the current study is likely best suited to characterize highly dynamic systems, which produce large seasonal differences.

Appendix

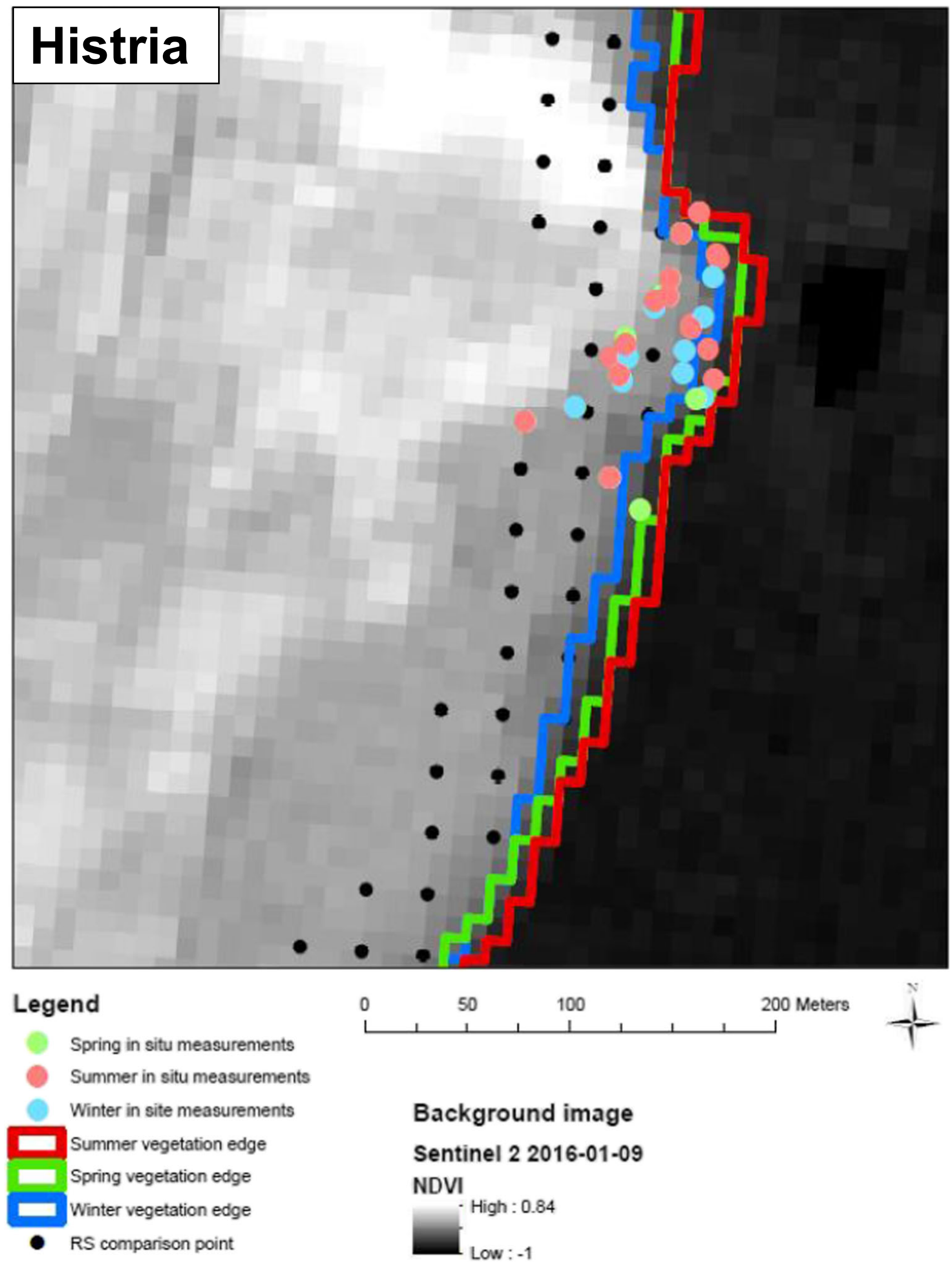

Fig. 8 Map of Romanian sample sites

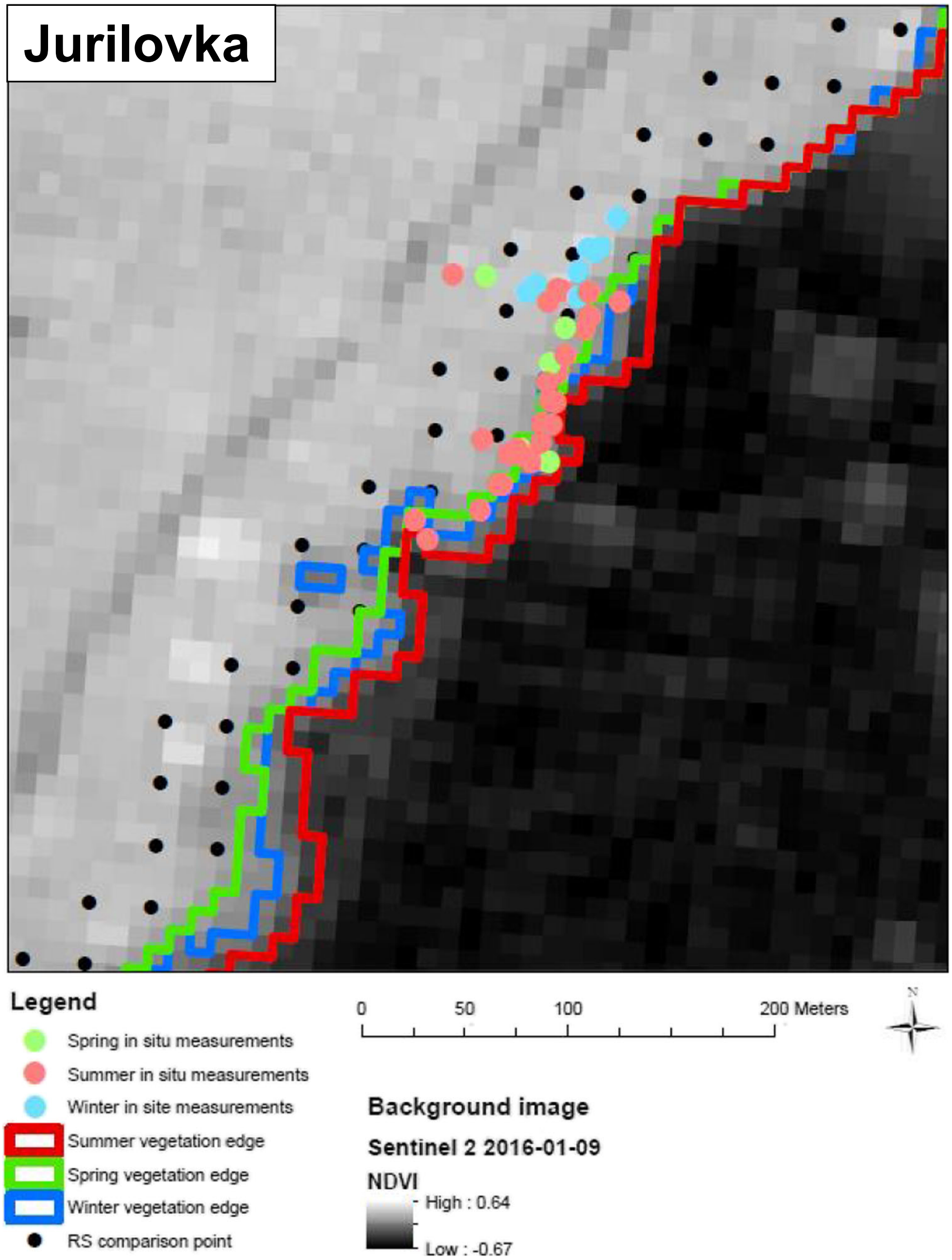

Fig. 8 (continued)

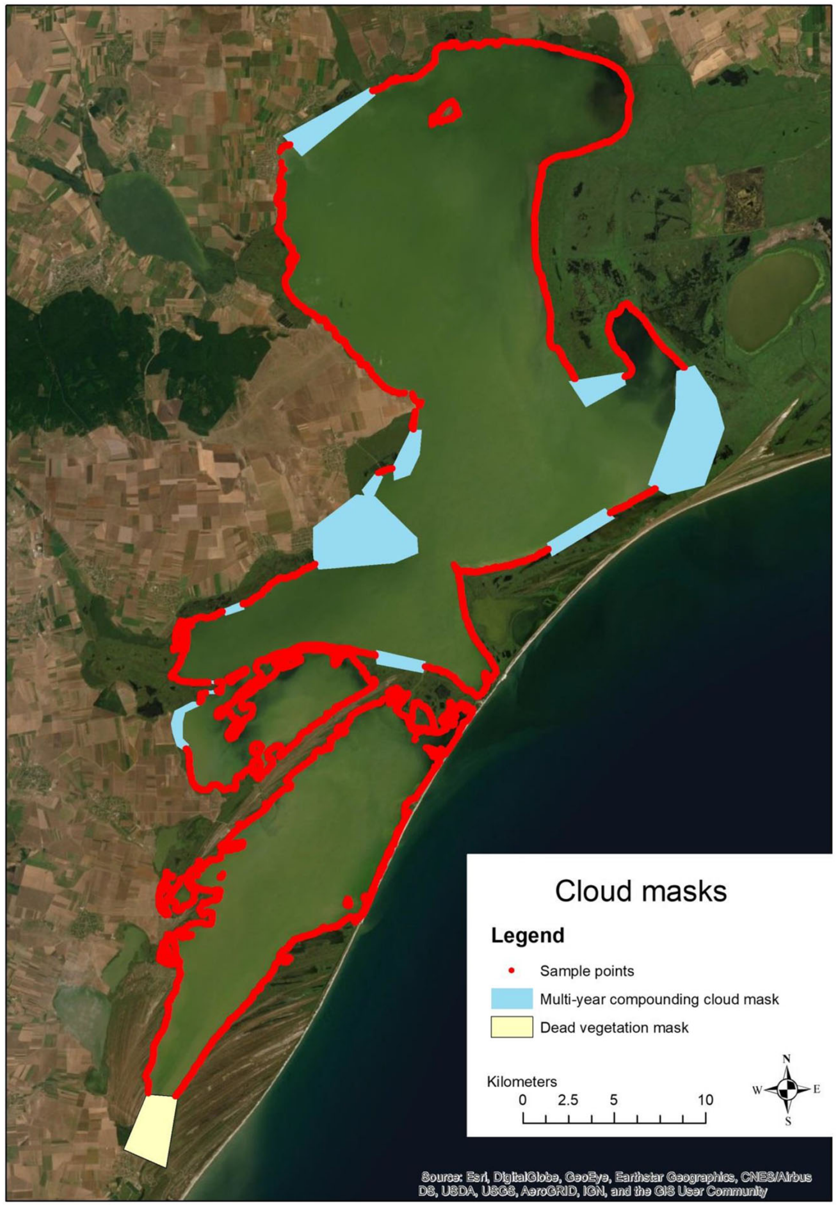

Fig. 9 Cloud masks

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Author Contributions BO and DvdW planned the research. ASC, supported by local staff, collected the field data. BO and ASC processed and analyzed the data. BO and DvdW wrote the paper. BO, ASC, TJB, AST and DvdW refined the paper. All authors read and approved the final manuscript.

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Data Availability Fully available through: https://easy.dans.knaw.nl/ui/home.

Code Availability Fully available through: https://easy.dans.knaw.nl/ui/home.

Declarations

Conflicts of Interest/Competing Interests Not applicable.

Consent to Participate Not applicable.

Consent for Publication Not applicable.

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