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Article

Advanced Land Observing Satellite Phased Array Type L-Band SAR (ALOS PALSAR) to Inform the Conservation of Mangroves: Sundarbans as a Case Study

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Abstract: Mangroves are an important bulkhead against climate change: they afford protection for coastal areas from tidal waves and cyclones, and are among the most carbon-rich forests in the tropics. As such, protection of mangroves is an urgent priority. This work provides some new information on patterns of degradation in the Sundarbans, the largest contiguous mangrove forest in the world, which are home to more than 35 reptile species, 120 commercial fish species, 300 bird species and 32 mammal species. Using radar imagery, we contrast and quantify the recent impacts of cyclone Sidr and anthropogenic degradation on this ecosystem. Our results, inferred from changes in radar backscatter, confirm already reported trends in coastline retreat for this region, with areas losing as much as 200 m of coast per year. They also suggest rapid changes in mangrove dynamics for Bangladesh and India, highlighting an overall decrease in mangrove health in the east side of the Sundarbans, and an overall increase in this parameter for the west side of the Sundarbans. As global environmental change takes its toll in this part of the world, more detailed, regular information on mangroves' distribution and health is required: our study illustrates how different threats experienced by mangroves can be detected and mapped using radar-based information, to guide management action.

Keywords: climate change; SAR; remote sensing; conservation; habitat degradation; coastline retreat

1. Introduction

Anthropogenic activities and their consequences, including climate change, are negatively impacting biodiversity and ecosystem services, with ecosystem loss and degradation occurring at an alarming rate [1]. To mitigate these losses, a better understanding of how ecosystems interact with the environment and how they respond to anthropogenic impacts is required. One ecosystem type which is particularly sensitive to environmental change is the coastal mangrove ecosystem. Mangroves are unique intertidal forested wetlands confined to tropical and subtropical coastal environments, supporting a diverse range of organisms that have developed unique adaptations by living at the interface between the terrestrial and marine biomes [2,3]. Their total area is estimated at 137,760 km^2 globally [4], which equals only 0.1% of the earth's continental surface. Mangroves are known for their floral diversity of vascular plants specially adapted to dynamic coastal environments [5], and high biodiversity of fish, birds and numerous species of phytoplankton, fungi, bacteria, zooplankton, benthic invertebrates, molluscs, reptiles, amphibians and mammals [6,7]. But mangroves also provide societal and ecological goods and services, including food and sustenance, fuel, raw building materials for local populations, and safe breeding and nursing grounds for marine and pelagic species [7–9]. Moreover, mangroves are a particularly important ecosystem in the context of climate change, providing protection and stabilization for coastal areas from tsunamis and cyclones [4,10]. A study recently estimated that 'mangrove forests and soils could sequester approximately 22.8 million Mg of carbon each year' [4]. Alongside being important biodiversity harbours [11] and carbon stores [12], mangroves have been estimated to provide at least US $1.6 billion each year in ecosystem services while their economic value is thought to be equating to US $200,000 to US $900,000 per km^2 [13,14].

The low global cover and high sensitivity of mangroves to environmental change, including climate change [15–17], have led them to be amongst the most threatened biomes [11]. Valiela and Bowen [18] report that in just over the past two decades, mangrove cover has decreased by 35% worldwide and there have been an increased incidence of cases of mangrove vegetation degradation at a rate of 2.1% per year. It has been recently reported that as much as 11 of the 70 known species of mangroves (16%) are at elevated threat of extinction [19]. Future predictions suggest that 30–40% of coastal wetlands, and 100% of mangrove forests could be lost in the next 100 years if current rates of decline continue [20,21]. Protection of mangroves is therefore an urgent conservation priority. To be effective, protection and restoration of mangroves require information on the exact geographic distribution of these ecosystems and the extent to which they have been and are degraded: this can be problematic as mangroves tend to be found in remote, relatively inaccessible areas, and degradation in these ecosystems tend to be sporadic [9,22]. Because remote sensing can allow the gathering of information on inaccessible areas at relatively high temporal resolution, it is an effective tool for the monitoring of mangrove forest degradation [9,23].

Table 1. Overview of previous remote sensing based research on the Sundarbans.

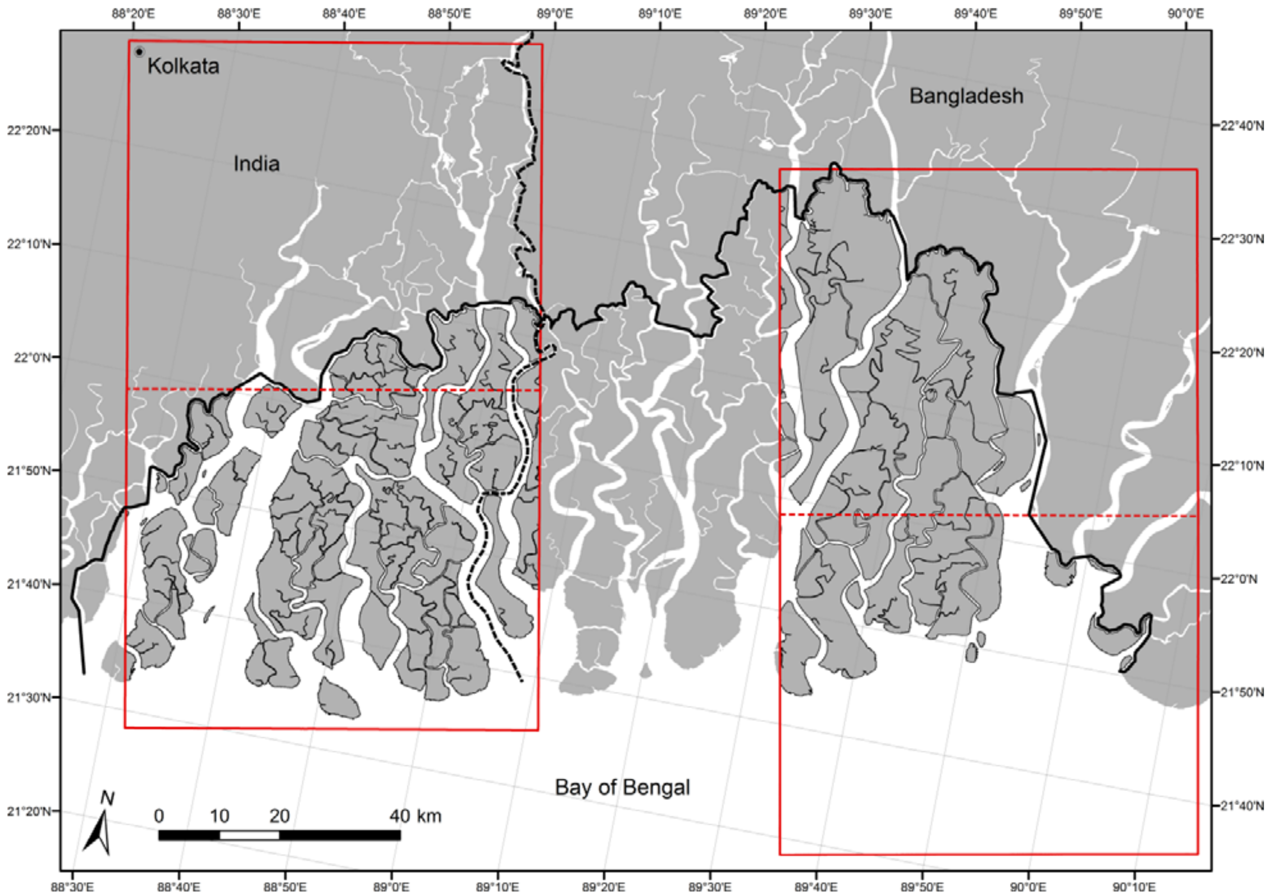
Parameters Studied	Technique	Location	Period of study	Reference
Edge detection, habitat fragmentation	Optical and radar	Bangladesh: 89°03' to 89°15'E and 21°55' to 22°09'N	1996–2000	[57]
Change detection	Optical	Bangladesh	1989, 2000	[37]
Land cover, vegetation type	Optical and radar	India: 21°30'–22°45'N and 88°–89°E	1992–1993	[12]
Change detection	Optical	Sundarbans	1973–1983; 1989–1993; 1997–2000s	[8]
Land cover, vegetation type	Optical	Bangladesh	1985–1986; 1992–1993	[58]
Forest canopy characterization	Radar	South-east Bangladesh	1984	[59]
Forest characterization	Optical	Sundarbans 8°00'–22°00'N, 88°00'–110°00'E	1999	[60]
Land cover	Optical	Sundarbans	1975, 1990, 2000, 2005	[61]
Change detection	Optical	Bangladesh 21°'40–22°30'N, 89°00'–89°55'E	1933, 1960, 1985	[22]
Change detection	Optical	Bangladesh	November 2007	[49]
Wetland mapping	Radar	India 21°30'–22°45'N, 88°0'–89°0'E	October 1992 and September 1993	[62]

In this paper, we make use of such capabilities to assess recent habitat degradation in the Sundarbans Mangrove forest in India and Bangladesh. The Sundarbans (Figure 1) is the largest contiguous mangrove forest in the world [24], covering 10,000 km^2 [8], and is situated in both India (~40%) and Bangladesh (~60%) [7,25] at the delta formed by three major rivers: the Ganges, Brahmaputra and Meghna. Both the mangrove itself and its biodiversity have been and continue to be well studied as a result of their importance and the dramatic changes it has been facing (see Table 1; [7,26,27]). In 2007, a considerable area of the Sundarbans was affected by Cyclone Sidr (the cyclone struck on the 15th November; [28–30]). Damages on the ground were reported, and degradation resulting from Sidr has been assessed for part of the ecosystem using remote sensing approaches relying on optical sensors and inferring degradation based on imagery collected shortly after the event (see Table 1; [28–30]). However, optical imagery for degradation assessment in mangroves is associated with several limitations that radar is unaffected by, such as cloud cover [23]. This meant that for any area of the Sundarbans there was usually no more than one freely available 30 m resolution cloud-free image for the entire year (sources checked: Landsat and ASTER, Advanced Spaceborne Thermal Emission and Reflection Radiometer). Anthropogenic degradation such as over-exploitation of timber and pollution moreover remains a recurrent problem in the Sundarbans [31], and recent changes in the intensity and location of these degradations have not been assessed. We consequently decided to make use of recently available Synthetic Aperture Radar (SAR) imagery from Advanced Land Observing Satellite Phased Array type L-band SAR (ALOS/PALSAR), as opposed to optical imagery, to assess ecosystem degradation in the Sundarbans over the period 2007–2009. While doing so, we tested the two following hypotheses:

(H1) Cyclone Sidr's path indicated that the cyclone went through the Bangladeshi side of the Sundarbans [32]. It can therefore be expected that it resulted mainly in mangrove degradation in Bangladesh.

(H2) Based on previous work [33], we expect coastline retreat to be continuing along the entire coastline of the Sundarbans.

Figure 1. Map of the Sundarbans, detailing recent available PALSAR scenes. The thick black line delimits the Sundarbans, while the black dotted line represents the border between Bangladesh and India. The PALSAR data used for change detection are represented by the red boxes. These are (**a**) 2 scenes for the western part of the Sundarbans (collected on 11 July 2007 and 13 July 2008), (**b**) 2 scenes for the Eastern part of the Sundarbans (collected on 7 June 2007 and 12 June 2009). Each scene is composed of two tiles; the red dotted line represents the seam.



2. Material and Methods

2.1. Study Area

The Sundarbans can be characterized as a region that comprises a vast network of small islands, formed by the deposition of alluvial sediments eroded and transported down from the drainage basins of the three aforementioned rivers [7]. The presence of mangrove vegetation is key to the formation of these islands, playing an important role in the ecosystem morphology [24]. Climate in the region is atypical of sub-tropical climes with mean maximum annual temperature varying between 29.4° and

31.3 °C and high humidity of >80% [7,34]. Characterized by sub-tropical monsoon precipitation of 1,600–1,800 mm, and frequent tidal inundation, the region is also periodically affected by severe cyclonic tropical storms [7]. Altogether, the area is ecologically dynamic, including processes such as the annual monsoon rain and subsequent flooding, delta formation, tidal influence and mangrove colonization [8]. Maximum elevation in the region does not exceed 10 m a.s.l. but is mostly between sea-level and 3 m a.s.l. [7,31], which contributes to the ecosystem's vulnerability to coastal erosion, salt-water intrusion and storm surges. The Sundarbans boasts a rich biodiversity, supporting more than 120 species of fish, 32 species of mammals, over 300 species of bird, 35 species of reptile and over 300 species of plants representing 245 genera [35]. The region provides a safe haven for species including the critically endangered Royal Bengal Tiger (Panthera tigris), amongst others which are now considered extinct elsewhere [24]. As well as being a biodiversity hotspot, the Sundarbans is of great socio-economic value, providing ecosystem services for its dense population, who exploit the area for resources such as shrimp farming, food sustenance, fuel, and timber. It has been estimated that the mangrove provides a livelihood for over 300,000 people working within a range of seasonal areas including fisherman, honey collectors and wood cutters [8].

2.2. Remote Sensing Data and Change Detection Analysis

Change detection using both optical and radar data has previously been applied to mangroves, including those in the Sundarbans, Australia, South and Central America and southeast Asia [9,36–38]. In this study, we use horizontal emitted, vertical received (HV) SAR data from ALOS/PALSAR scenes for change detection. ALOS/PALSAR is expected to provide a better depiction of mangrove forest degradation and canopy structure than methodologies based on optical sensors of comparable acquisition and processing cost [9,39]. A combination with optical imagery was tested but due to the lack of overlapping imagery and inherent georeferencing issues this was not pursued. The HV polarization of ALOS/PALSAR was considered as it is more sensitive to vegetation structure and biomass than the horizontal emitted, horizontal received (HH) polarization [40]. The HV polarization backscatter has indeed been previously described as having a high positive correlation with mangrove forest parameters such as zonation, basal area, height and growth stages, whereas HH polarization is sensitive to various soil and water parameters [23,39]. Due to this reported correlation, we can use HV backscatter as a proxy for above ground biomass (herein referred to as biomass) and hence for forest degradation [41].

Level 1.5 ALOS/PALSAR fine beam dual-polarization (HH & HV) backscatter data at 12.5 m resolution were downloaded from the Alaska Satellite Facility (ASF) Distributed Active Archive Center's User Remote Sensing Access website. We processed the data with ASF's MapReady software and consecutive tiles were subsequently mosaicked. Accessible PALSAR data from comparable times of the year included (a) 2 scenes for the western part of the Sundarbans (collected on 11 July 2007 and 13 July 2008), (b) 2 scenes for the eastern part of the Sundarbans (collected on 7 June 2007 and 12 June 2009); their coverage is shown in Figure 1. From these scenes, nearly all the areas that would have been impacted by the cyclone are covered [32,42], in addition to most of the Indian Sundarbans. However, the total land area covered by these scenes (4,434 km^2) is just under half of the entire area of the Sundarbans. Therefore the possible existence of recent habitat degradation in the central and westernmost parts of the Sundarbans could not be assessed.

The latter PALSAR scenes (2008 & 2009) were georeferenced to their corresponding 2007 scene, mostly using small rivers' intersections. Reliable ground control points are absent for a majority of the Sundarbans, however, error is estimated at a radius of less than 2 pixels (25 m) for the whole area based on an independent verification (difference for twenty randomly selected ground control points: 10.97 ± 6.17 m for the west side and 9.39 ± 6.64 m for the east side). For change detection, an accurate georeference is essential; a few pixels off gives misleading results. The percentage change from the 2007 scenes were calculated for both sides after a 5 × 5 Refined Gamma Maximum-A-Posteriori (RGMAP) filter was used to minimize speckle effects [43] and reduce the impact of any georeferencing error while minimizing loss of spatial resolution. Areas of at least 10% increase and 10% decrease in HV backscatter were extracted as such changes in HV backscatter can correspond to a significant change in biomass [9,39,44]. Waterways show lower levels of backscatter for L-band SAR because they reflect microwaves specularly which allows for the reliable removal of rivers. They were determined using a threshold value on a 7 × 7 RGMAP filter [43] on the squared difference between the scenes. This method allowed areas that were land in one scene, and water in the other to be included so that changes such as coastline retreat can be identified and quantified. As highly degraded or bare land also has lower backscatter levels for the same reason as waterways do, inland areas below this threshold were selected and kept. Contiguity of islands was based on the results of the 7 × 7 filter. Overall changes for the islands were calculated (Figure 2), and for visualization purposes, regions with less than 10% change were assigned a change class based on the nearest area with over 10% change (Figure 3).

Figure 2. Spatial distribution of the overall percentage change in backscatter, considering only areas with increases and decreases of at least 10%, between 2007 and 2008 (for the west side of the Sundarbans) and 2007 and 2009 (for the east side of the Sundarbans), for each contiguous island as determined by the 7 × 7 filter. The red line represents the trajectory of cyclone Sidr, which struck Bangladesh on 15 November 2007.

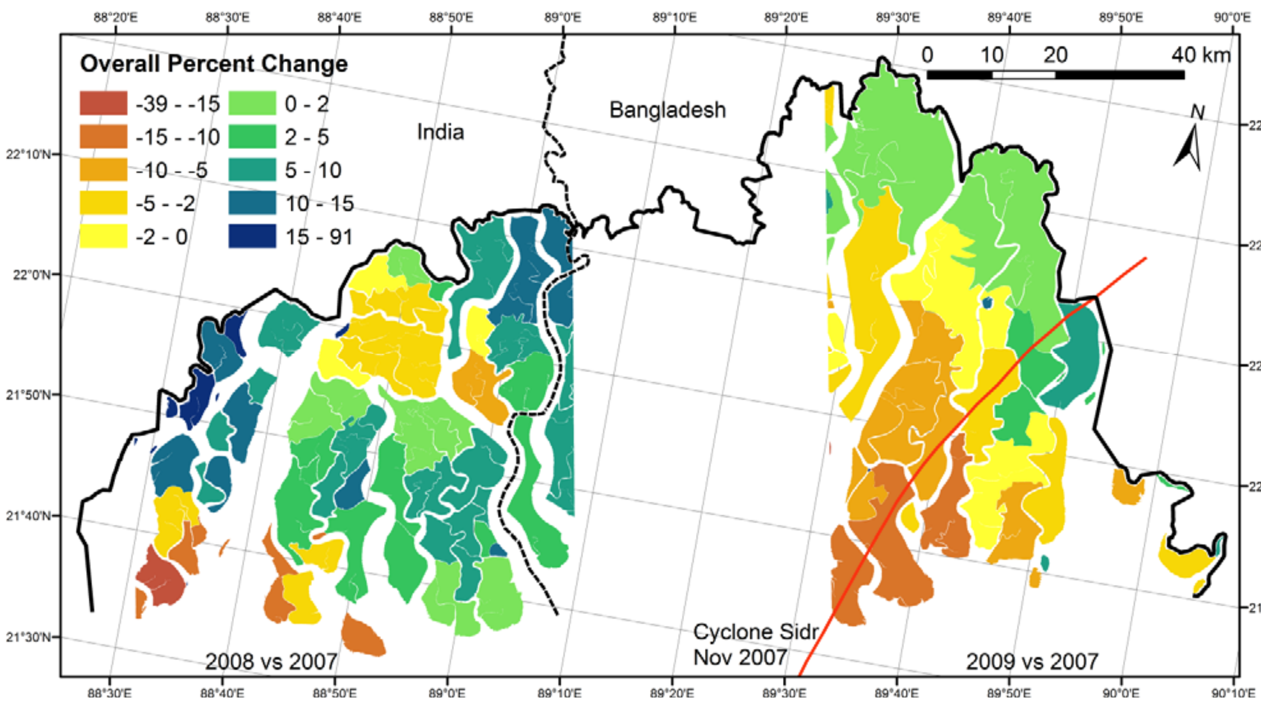
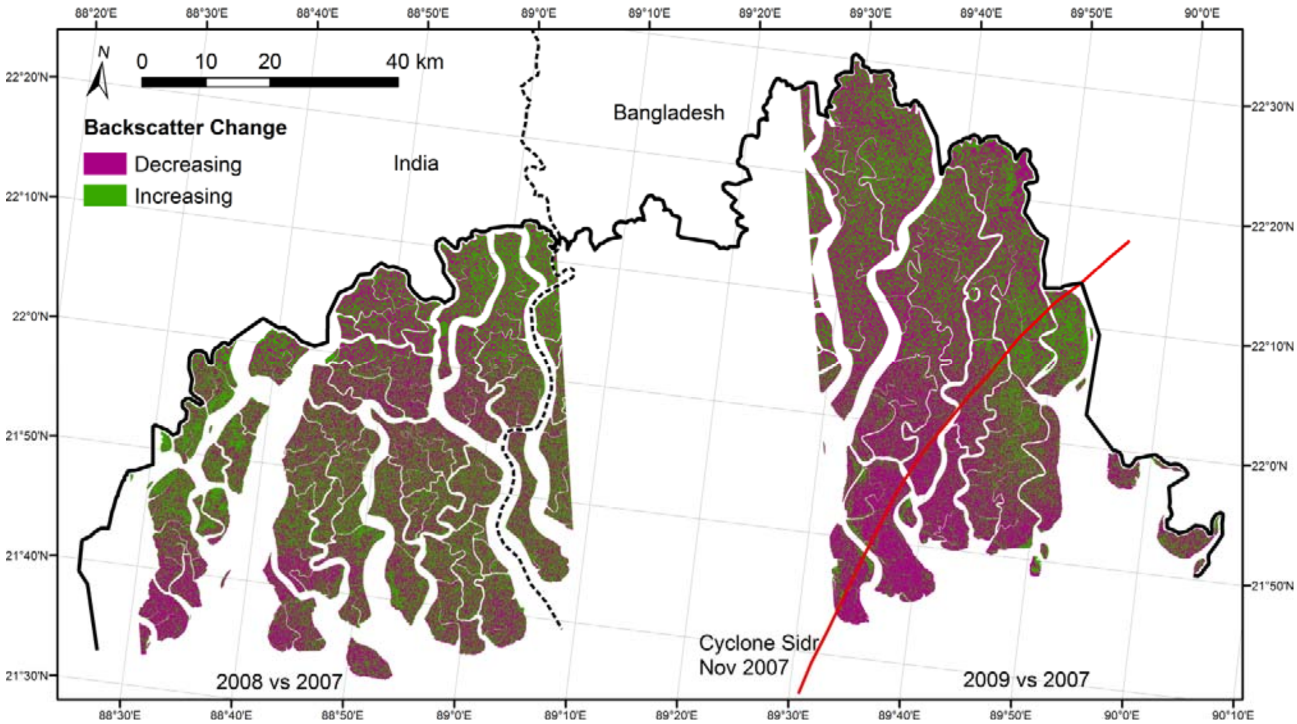


Figure 3. Recent habitat degradation in the Sundarbans. Purple areas correspond to areas of or closest to decreased backscatter (of at least 10%) for the periods 2007–2008 (for the west side of the Sundarbans) and 2007–2009 (for the east side of the Sundarbans). Green areas correspond to areas of or closest to increased backscatter over the same periods.



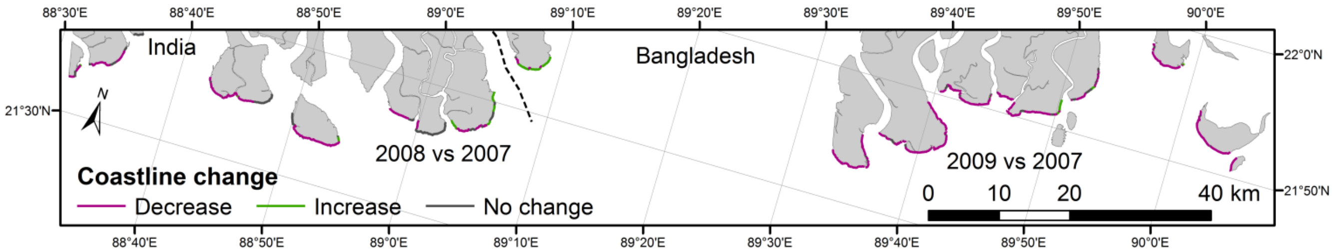
3. Results and Discussion

Because we assessed recent changes in mangrove health over a very short period of time, and because cyclone Sidr was the main known source of disturbance expected to impact the Sundarbans over this period, we expected our analyses to detect degradation mainly in Bangladesh (H1). Our results partially supported this expectation: in Bangladesh, 10.24% of the pixels assessed showed a decrease of at least 10% in backscatter, while only 8.07% showed an increase of at least 10% in backscatter (overall decrease of 2.17% in backscatter). In India, on the other hand, 13.17% of the pixels assessed showed a decrease of at least 10% in backscatter, while 15.88% showed an increase of at least 10% in backscatter (overall increase of 2.71% in backscatter). On both sides of the Sundarbans, presence of fragmented degradation was apparent, suggesting that Sidr is far from being the only cause of degradation in the Sundarbans over the time period considered. Causes behind the reported patterns in degradation cannot be identified from our analysis, however a variety of reasons including changing salinity, top-dying disease, storm surges, effects of climate change such as increased melt-water and changes in sea-level, and direct anthropogenic impacts such as redirection of freshwater (e.g., the Farraka Barrage), deforestation and oil-spills, have been previously associated with mangrove degradation in this region [8,37,45].

An assessment by Akhter and colleagues [32] based on a Principal Component Analysis of an ASTER image collected a few days after the cyclone struck suggested that approximately 22% of the Sundarbans was affected by cyclone Sidr, 11% of which was ‘highly affected’, whilst other studies estimated that between 19% and 31% of the Sundarbans’ mangroves was impacted by this extreme natural event [42,46,47]. For the first two islands struck by cyclone Sidr, which were the areas suffering the most damage, our analysis highlighted a decrease (of at least 10%) in backscatter for 19% and 17.6% of the pixels. Our results therefore show a lesser extent of damage than calculated from optical data. These differences are likely to stem from (a) differences in the areas evaluated; (b) the existence of a two year gap between the two images we used to assess degradation in Bangladesh, with over one and a half of those years allowing for recovery of mangroves (which can happen at a relatively fast pace). But such differences can also be explained by the difference in the methodology used to assess degradation. Previous assessments indeed did not make a comparison to data collected before the cyclone's impact (impact was evaluated based on the classification of optical imagery collected shortly after the event), and this can lead to bias in reported damages. For example, some coastal areas at least 25 km from the cyclone's path were classified as 'highly affected', whilst large areas of mangroves, some on the coastline, classified as 'slightly to not affected' were within 10 km of the same part of the cyclone's path. Without a point of reference pre-event, damages are likely to be both over and under-estimated, since forest degradation cannot be inferred without knowledge of prior condition [48]. Moreover, these attempts aimed at simply outlining the potential area where damages might have occurred, without providing a clear assessment of the impact of Sidr. Akhter and colleagues [32] for example assumed that the entire area considered for their analysis was at least slightly affected, producing a likely inflated result of 22% of the Sundarbans being affected by the cyclone. The use of the Normalized Difference Vegetation Index (NDVI) from MODIS scenes, a week before and after the cyclone showed a good overview of the spread of damage, albeit at a very low spatial resolution [49]. The NDVI is a widely used index, suitable for a vast array of ecosystems and shown to be a robust measurement of environmental change [50]. Yet, for the Sundarbans, which is covered by cloud almost the entire year, optical indices are not a reliable determinant of vegetation health. Additionally, atmospheric effects, illumination variation and poor radiometric calibration make optical imagery generally unsuitable for change detection [51].

Although average trends indicate higher degradation levels in Bangladesh and increased health status in India (Figure 3), our results also illustrate (a) a high degree of spatial variation in degradation, (b) the existence of several degraded areas outside the path of Sidr. For example, a noticeable impact from cyclone Sidr is apparent, yet not along its entire path. About 50 km after the cyclone struck land, there is then an unexpected increase in the backscatter (Figure 3). Possible causes include the growing back of a different mangrove species with a different structure. Changes in the backscatter coefficient can also be the result of changes in rugosity and soil moisture [40], which would have been severely disrupted by the cyclone. In areas which have not undergone significant disturbance (e.g., deforestation) we expect most of the changes in backscatter to be due to changes in physical parameters of the tree such as canopy dieback or top-dying, which is a widely reported problem in the Sundarbans, with 70% of some dominant species having some level of impact [45]. North of the cyclone path on the easternmost side there appears to be a large area suffering degradation, which is likely a result of anthropogenic disturbance. We then report a consistently decreasing backscatter for the south and south-west areas of the Sundarbans along the coast of India, whereas the regions north of this show a contrasting increase in backscatter (Figure 3). Such a widespread decrease in backscatter over the period of one year is congruous with reports of top-dying across the Sundarbans as a result of undetermined stressors [8]. The central-north area of the Indian Sundarbans also appears to be degrading. This is interspersed with small areas of increasing backscatter indicating a less severe level of degradation is occurring. As this area is closer to the communities that line the edge of the Sundarbans, the result of this degradation is most likely directly anthropogenic. Surrounding areas on the Indian side have increasing backscatter, which may be recovery from previous degradation, which has been far worse on the Indian side [8].

Figure 4. Coastline retreat assessment showing the change for the periods 2007–2008 (for the west side of the Sundarbans) and 2007–2009 (for the east side of the Sundarbans). The purple lines show retreating coastline; the grey line corresponds to areas of the coastline with no change; the green line corresponds to areas of the coastline where expanding coastline is reported.



Based on previous reports, we also expected coastline retreat to be continuing along the entire coastline of the Sundarbans (H2). The reasons for coastline retreat or increased coastal erosion in the Sundarbans have not been fully determined; however, it is likely due to increased areas of immersed forests [45]. Our analyses strongly supported such expectation, showing that 71.1% of the coastline captured by the considered scenes is receding (Figure 4). This is based on the tree line which is visible in the PALSAR scene, which formed the edge of the coast along almost the entire coastline. Coastline retreat is evident everywhere: in Bangladesh, the easternmost part of the coast, which would have been largely unaffected by the cyclone was observed to recede by an average of about 100 m between 2007 and 2009, with a maximum of 170 m (50 and 85 $m \cdot yr^{-1}$ respectively). This is particularly worrying for the local fauna of some of the mangroves located in this area, which are separated from the remainder of the mangrove forest by over 7 km of water. A continuing rate of retreat would see these parts of the mangrove disappear within 50 years. On the Indian side of the Sundarbans, the island which extends most into the Bay of Bengal has receded by an average of 150 m in the one year period, with a maximum of just over 200 m; this would see the disappearance of the island in about 20 years. As described above, the Sundarbans naturally has a dynamic coastline, often with islands appearing, migrating and disappearing. However, our results indicate a systematic coastline retreat that cannot be accounted for by the regular dynamics. Rahman and colleagues [33] reported an average annual rate no greater than 65 $m \cdot yr^{-1}$ between 1973 and 2010. The causes for increasing coastline retreat, other than direct anthropogenic ones, include increased frequency of storm surges and other extreme natural events, rises in sea-level and increased salinity, which increases the vulnerability of mangroves [52–54].

However, our results are to be taken with caution. Firstly, due to limitations with available satellite data, we were unable to obtain at least two PALSAR scenes for the central Sundarbans regions covering the area immediately east of the political boundary between India and Bangladesh. The possibility to compare our results with previous degradation assessments carried out in the region is thus limited. The differences in scene acquisition dates create an inconsistency in temporal resolution used for analysis. Scenes used for Bangladeshi Sundarbans (2007 & 2009) span two years, compared to India of only one year (2007 & 2008). The technique of change detection on SAR imagery is also relatively new and untested. Although the response of mangrove biomass to HV backscatter is highly correlated, there is saturation above 120–150 $Mg \cdot ha^{-1}$ [9,39] and in some cases, a dense canopy with very high (>200 $Mg \cdot ha^{-1}$) biomass can in fact decrease backscatter [23]. However, with average biomass at 93.7 ± 33.0 $Mg \cdot ha^{-1}$ [55], it can be assumed most of the Sundarbans will not exceed saturation for sensitivity to biomass. Uncertainty in the results can arise from variations in the gain and response sensitivity of the instrument, however, the radiometric calibration for backscatter makes any difference negligible [56]. Soil moisture and differences in tides can moreover influence the outcome of like-for-like comparisons aimed at inferring mangrove degradation and coastline retreat. The dates of acquisition of data for the years considered corresponded with the beginning on the annual monsoon season in the Sundarbans, occurring in early June; as a result it is expected that the underlying soil would have reached high saturation. The tide dropped by 13 cm for the western scene, and rose by 69 cm for the eastern scene. Coastline retreat may have therefore been over-estimated for the eastern scene, while a higher tide may have induced elevated soil moisture, which could lead to an enhanced backscatter and would therefore reduce the ability to detect vegetation degradation [9]. Despite these potential limitations, we believe our results clearly demonstrate rapid changes in mangrove health following cyclone Sidr across the whole Sundarbans ecosystem. We therefore encourage future analyses based on SAR remote sensing to take advantage of any ground surveys and high resolution optical remote sensing data where possible to determine to what extent that the changes in backscatter correspond to changes in tree vigour.

4. Conclusions

As global environmental change takes its toll in this part of the world, more detailed, regular information on mangroves distribution and health is required, and our results illustrate how different threats experienced by mangroves can be detected and mapped using satellite-based information, to guide management action. This, alongside the need to assign sufficient legislative protection for ecosystems with high bio-ecological and socio-economic importance can help slow the rate of ecosystem decline, and move towards a state of recovery. Our study demonstrates the capabilities of radar-based remote sensing approach for monitoring and quantifying changes in ecosystem health and distribution for mangroves. With increases in temporal resolution and reduction of costs for SAR data, the approaches discussed here could be repeated, allowing a more informative monitoring approach for mangrove conservation.

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