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ASSESSING THE IMPACT OF CYCLONE *SIDR*AND *AILA* ON THE BANGLADESH *SUNDARBANS* AND ITS RECOVERY USING REMOTELY SENSED IMAGERY

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Abstract: The *Sundarbans* - largest tract of mangrove forest in the world - acts as a shield against natural disasters. *SIDR* and *AILA* are the two recent cyclones that severely disrupted the vegetation of the *Sundarbans* in the past decade. This study is to identify the impact of these cyclones on different vegetation density coverage of the Bangladesh *Sundarbans* and their recovery status using remotely sensed imagery. Landsat (TM) satellite imageries (2006 to 2017) are used for analyzing the vegetation structure of the *Sundarbans*. Forest Canopy Density (FCD) map that combines three biophysical indices, namely Advanced Vegetation Index (AVI), Bare Soil Index (BI), and Canopy Shadow Index (SI) is used to generate vegetation density map. The FCD map divulges that very high-density vegetation coverage has increased from 33.32% to 35.73% between 2006 and 2017. High-density coverage increased from 35% to 42.52% between these years. Evidently, the Bangladesh *Sundarbans* has a high recovery rate and it has already recovered itself from the destructions caused by *SIDR* and *AILA*.

Keywords: Vegetation density, *Sundarbans*, Landsat, Forest Canopy Density (FCD).

Introduction

The *Sundarbans* is the largest single tract of mangrove forest in the world. Total area of Bangladesh *Sundarbans* is 6,017 sq. km.(Forest Department, 2010; p. 08). Because of its location on the edge of the Bay of Bengal (Fig.01), it is highly vulnerable to different natural calamities.

SIDR is one of the most devastating cyclones that made landfall on 15 November 2007 with an average wind speed of 240 kilometers per hour, causing more than 3400 deaths (GoB, 2008a). It caused disruption to the *Sundarbans*; trees were uprooted and hundreds of animals died (Forest Department, 2010; p. 28). About 30,000 hector forest land was heavily damaged and an additional 80,000 hector area was partially damaged (ibid. p. 29). FAO (2007) reported that 4-5 % (20000-25000 hector) of the forest area was severely damaged and nearly 15% (60000 hectors) was partially damaged. The eastern part of the forest was affected largely because of its proximity to the cyclone trajectory (Bhowmik and Cabral, 2013). Another cyclone, *AIL A* slammed the forest on 25 May 2009 with an average speed of 120 kilometers per hour (Khatun et al., 2018). Notably, the damage caused by *AILA* compared to *SIDR* was insignificant (Forest Department, 2010).

Recovery of mangrove forest is an inherently complex process. A number of variables contribute towards the rate of natural recovery of a mangrove forest; e.g. tree stand structure, tree

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abundance, species richness and diversity, primary production (biomass and litter), nutrient availability, and hydrological pattern (Ellison, 2000). Brown (2006) suggested that place like mudflats, sand flats; coral reefs and sea grass beds are suitable for the natural recovery process. He also identified the *Sundarbans* as one of the most suitable places for natural recovery. Many studies found that the natural recovery process of the mangrove ecosystem is quite rapid if they remain undisturbed (Patanaponpaiboon and Poungparn, 2005). Lewis and Gilmore (2007) argued that mangrove forest around the world could be recovered successfully within a period of 15-30 years if the growth is not disrupted by further natural or anthropogenic hazard.

This paper attempts to see whether these arguments are correct for the *Sundarbans* using historical satellite imagery.

Materials and methods

To identify the impact of both *AILA* and *SIDR* on the *Sundarbans*, freely downloadable Landsat images of the years 2006, 2007, 2008, 2009 and 2017 have been used. These images inherit similar properties (for the required bands) but were captured by two sensors - Thematic Mapper (TM) and Enhanced Thematic Mapper Plus (ETM+). Downloaded images are processed (e.g. stacking, mosaicking) for further analysis. For further details of the imageries, please explore the USGS website (https://landsat.usgs.gov).

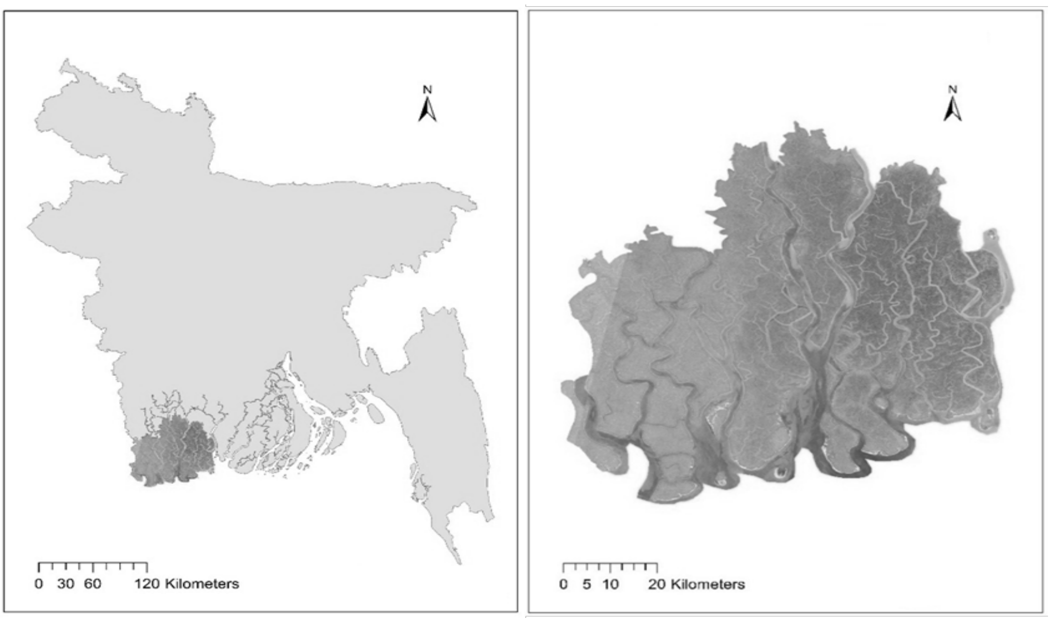

Fig. 01: Location of the *Sundarbans* in Bangladesh

FCD Mapping Procedure: Landsat TM based FCD map is produced to identify the impact of *SIDR* and *AILA* following Rikimaru et al. (2002). This paper utilized the same process to identify the impact of Cyclone *AILA* and *SIDR*. Growth phenomenon of forest and the biophysical spectral response of the area are the core components for FCD mapping. FCD map is developed based on three biophysical indices, namely (i) Advanced Vegetation Index (AVI), (ii) Bare Soil Index (BI) and (iii) Canopy Shadow Index (SI). These index values are calculated for every pixel. The total procedure of FCD mapping is stated in the following sections. Table 01elucidates the relationship among these three biophysical indices (AVI, BI and SI).

Table 01: Relationship between Different Indices and Vegetation Density

FCD Indices	Very High Density	High Density	Moderate Density	Low Density	No Forest
AVI	High	High	Medium	High	Low
BI	Low	Low	Low	Medium	High
SI	High	High	Medium	Low	Low

Above-mentioned vegetation density classes are extracted for different years (2006, 2007, 2008, and 2009); using Jenks (1967) natural break classification method. This classification procedure concludes through minimizing each class's average deviation from the class mean while maximizing each class's deviation from the means of the other groups. Thus, this classification is dependent on the cell values of the image of a particular year. For the FCD map of 2017, the range of the cell values is shown in the following table (02).

Table 02: Classification of Vegetation Density for the FCD map of 2017 using Jenks natural break classification method

Vegetation Density categories	Cell values of the FCD map
No Forest	0-56.7563
Low Density	56.7563-88.6093
Moderate Density	88.6093-107.7211
High Density	107.7211-116.9875
Very High Density	116.9875-147.6822

Advanced vegetation index (AVI): Advanced vegetation index (AVI) uses the red and near-infrared spectral bands in vegetation monitoring. As stated earlier, this index is more sensitive to forest density and physiognomic vegetation classes. The biophysical index does not incorporate the reflection of the water body. Thus, it provides better result of vegetation coverage compared to NDVI (Normalized Difference Vegetation Index). Eq. 01 shows the process of identifying AVI, where B3 and B4 denote the corresponding spectral bands of Landsat image.

$$AVI = \{(B4+1)*(256-B3)*(B4-B3)\}^{1/3} \quad \text{(Eq. 01)}$$

Bare soil index (BI): The bare soil areas are enhanced using the Bare Soil Index (BI). It is a combination of blue, red, near infrared and short wave infrared (SWIR) spectral bands to capture soil variations where the SWIR and the red spectral bands detect the soil composition while the blue and near-infrared spectral bands reveal vegetation character. Equation 02 shows the process of identifying BI, where B1, B3, B4 and B5 denote the corresponding spectral bands of Landsat image. BSI is used in numerous remote sensing applications, like soil mapping, crop identification in combination with AVI.

$$BI = \{(B5 + B3) - (B4 + B1)\}/\{(B5 + B3) + (B4 + B1)\} \quad \text{(Eq. 02)}$$

Shadow index (SI): For Shadow Index (SI) green and red spectral bands are used. Eq. 03 shows the process of identifying SI, where B2 and B3 denote the corresponding spectral bands of Landsat image. The young canopy stands have low canopy shadow index (SI) compared to the mature stands. The shadow index is articulated through the action of the low radiance of visible bands. In a combination of AVI and BI, SI is used to understand the status of vegetation.

$$\mathbf{SI} = \{(\mathbf{256} - \mathbf{B2}) * (\mathbf{256} - \mathbf{B3})\}^{1/2} \quad \text{(Eq. 03)}$$

Vegetation density (VD): VD is synthesized using AVI and BI as shown in Eq. 04.

$$VD = AVI * BI \quad \text{(Eq. 04)}$$

Forest canopy map (FCD) map preparation: Finally, FCD map has been produced by integrating VD and SI using Eq. 05 (Rikimaru, 2002).

$$FCD = \sqrt{(VD * SI) + 1} - 1 \quad \text{(Eq. 05)}$$

Results and Discussion

Impact of the extremely severe cyclonic storm, *SIDR* is clearly visible from the AVI image of 2007.For *AILA*, vegetation disturbance is mainly concentrated at the central part along the *Poshur* and *Shibsha* River. As the magnitude of *AILA* was not high compared to that of *SIDR*, the impact zone of *AILA* is rather dispersed and relatively less prominent. Due to both the cyclones, along the trajectory, the vegetation was disturbed and soil became exposed as can be seen from the BI image of 2007 and 2009. Fig. 02 and 03 show the AVI and BI images revealing this situation.

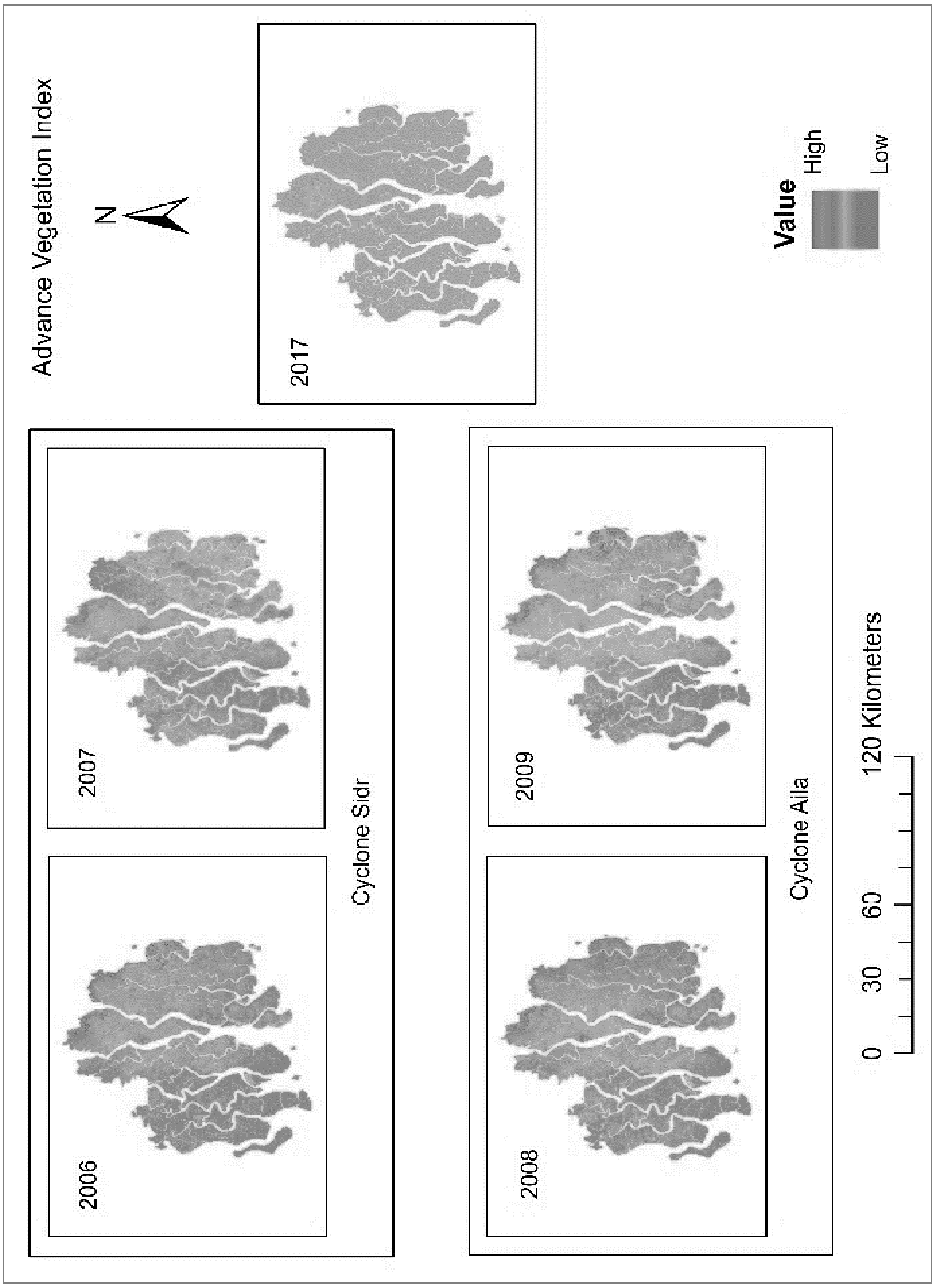

Fig. 02: Advanced Vegetation Index (AVI) map of different years

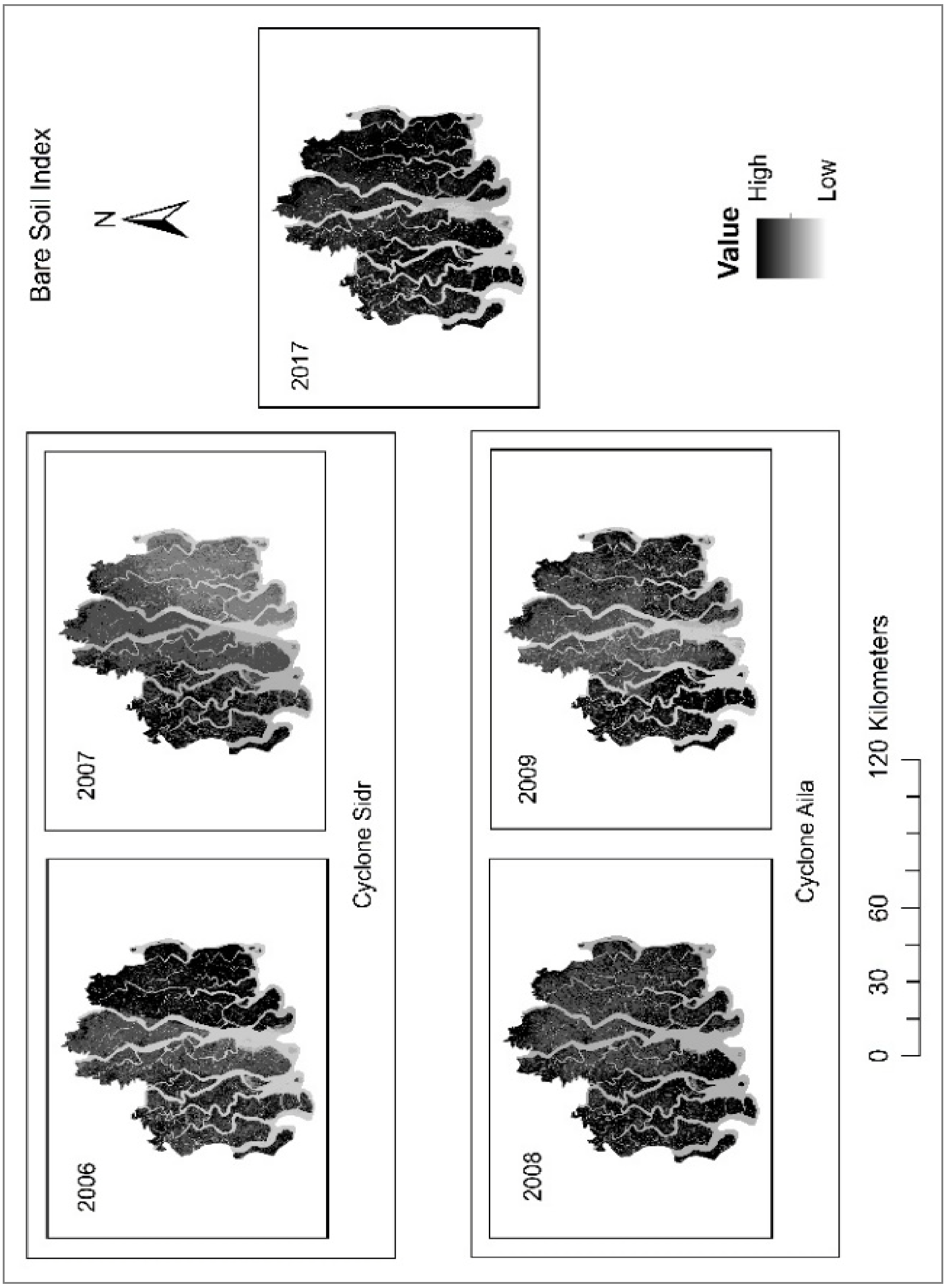

Fig. 03: Bare Soil Index (BI) map of different years

SI image also divulges that due to *SIDR* canopy shadow decreased significantly at the eastern part of the *Sundarbans*. However, for *AILA* this impact is observed in the central part (Fig. 04). Evidently, VD image (Fig. 05) also confirms the outcome of the AVI, BI and SI images. Meaning vegetation density decreased along the cyclone trajectories of both *SIDR* and *AILA*. Effect of *SIDR* is observed at the eastern part of the forest and *AILA* affected the central part. Using Eq. 05, FCD map of different years (Fig. 06) is generated.

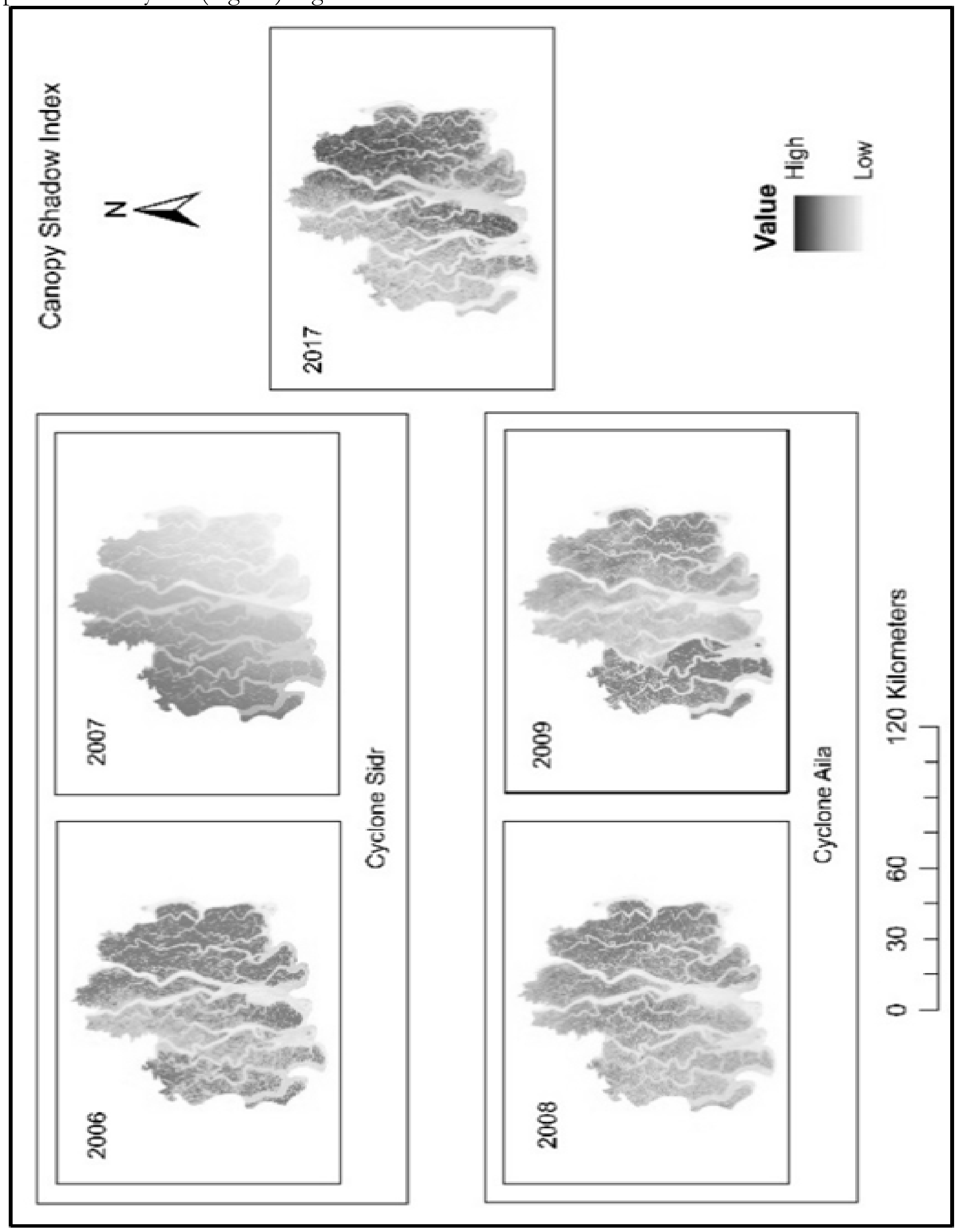

Fig. 04: Canopy Shadow Index (SI) map of different years

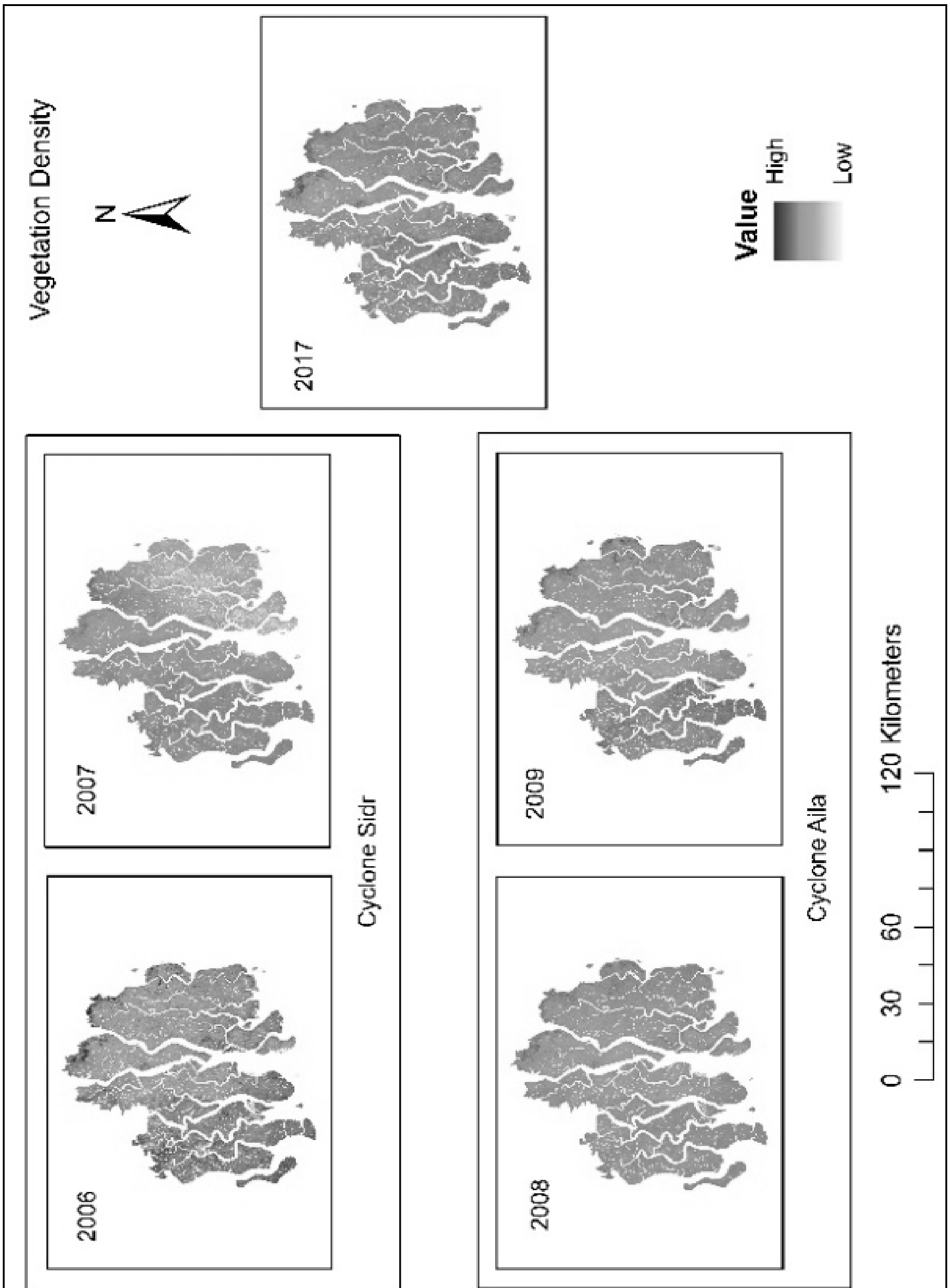

Fig. 05: Vegetation Density (VD) map of different years

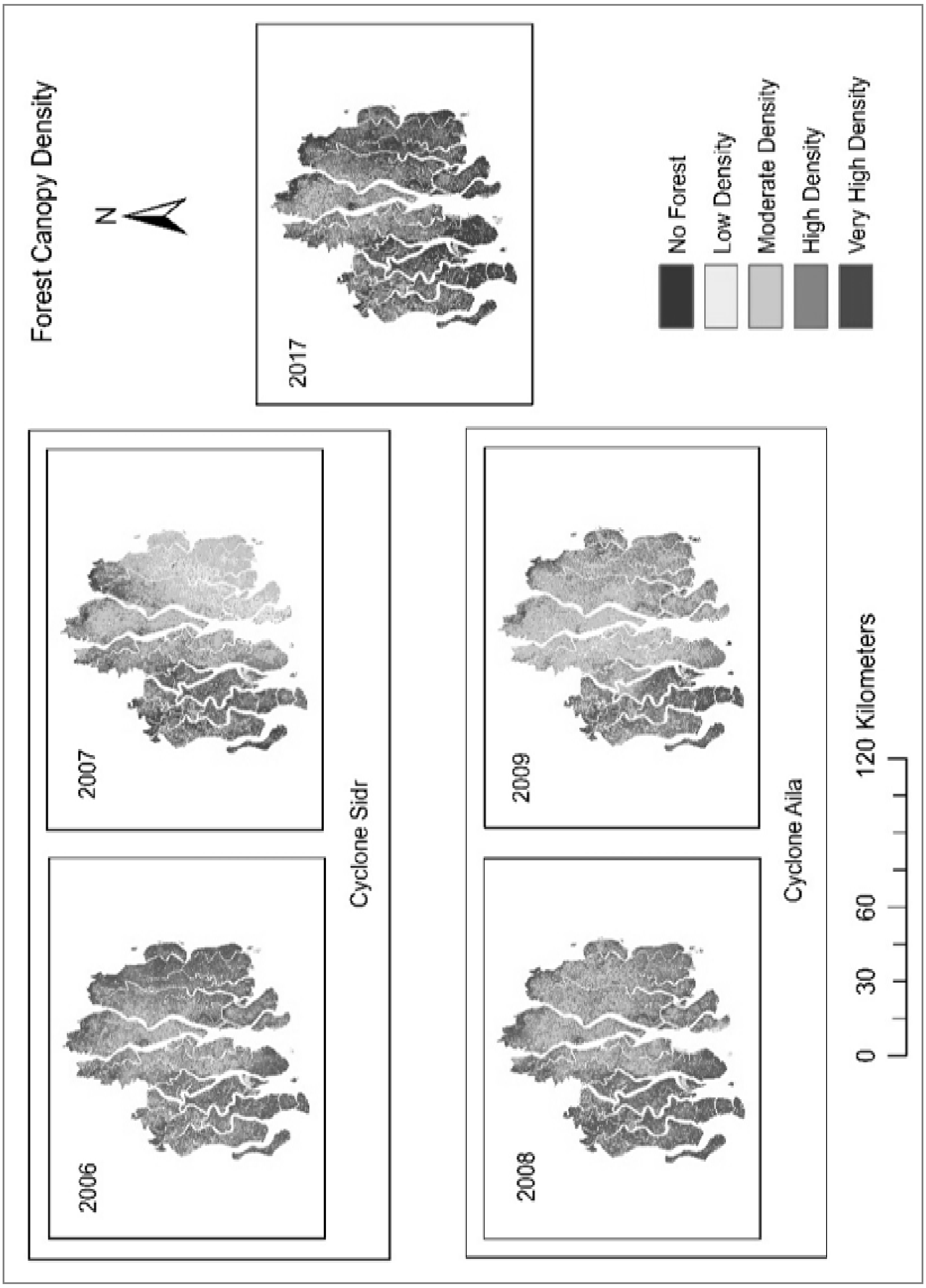

Fig. 06: Forest Canopy Density (FCD) map of different years

Fig. 07 demonstrates the effect of Cyclone *SIDR* as it has been revealed by FCD map of 2007 (after *SIDR*). This map divulges that the *SIDR* devastated eastern part of the *Sundarbans*. FCD map of 2006 (before *SIDR*) (Fig. 06) discloses that the eastern part of the forest was dominated by the high-density vegetation coverage. The reason for such vegetation density structure is beyond the scope of this paper. Nevertheless, as *SIDR* affected the most densely vegetated part of the *Sundarbans*, the impact revealed by the FCD map is also higher. Magnitude of the cyclone is mainly responsible for such pattern of disturbances.

Table 03 shows the overall change in area and percentage of different types of vegetation density coverage of the *Sundarbans* from 2006 (before *SIDR* and *AILA*) to 2017 to understand the impact of the cyclones and recovery condition of different vegetation density coverage in the last 8 years. This study found that the very high-density vegetation dropped from 1372.65 sq. km.(33.32%) to 460.01 sq. km. (12.06%) whereas the high-density vegetation coverage reduced from 1441.79 sq. km. (35%) to 1341.47 sq.km. (32.60%) in 2007 due to *SIDR*. Conversely, the moderate-density vegetation coverage increased from 1102.20 sq. km (26.75%) to 1774.74 sq. km. (43.12%) in 2007 (Table 03) as the high-density and very-high density vegetation coverage converted to moderate-density coverage.

Shortly after Cyclone *SIDR*, another devastating cyclone called as *AILA* smashedon to the *Sundarbans* on 25 May 2009. *AILA* mainly affected the middle-part of the *Sundarbans* (Fig. 08). Once again the very high-density vegetation lost its coverage from 670.83 sq. km. (16.29%) in 2008 to 418 sq. km. (10.15%) in 2009. Noticeably *Sundarbans* was able to recover (670.83 sq. km. - 460.01 sq. km)= 210.82 sq.km. of high-density vegetation coverage between *SIDR* and *AILA* which is about 23% of the area that it lost due to *SIDR*. Remarkably, within this period, the high-density vegetation coverage completely regained its area (about 106%).

Low-density vegetation coverage increased from 170.74 sq. km. (4.14%) to 496.15 sq.km. (11.18%) due to *SIDR*. Destruction of high and very high-density has contributed towards such change. Right after *SIDR*, *Sundarbans* started recovering its high-density vegetation coverage lowering the proportion of low-density coverage to 217.91 sq. km. (5.29%). Meaning it recovered about 86% of its total lost area (Table 03). The process was interrupted by *AILA* as shown in Fig. 08.

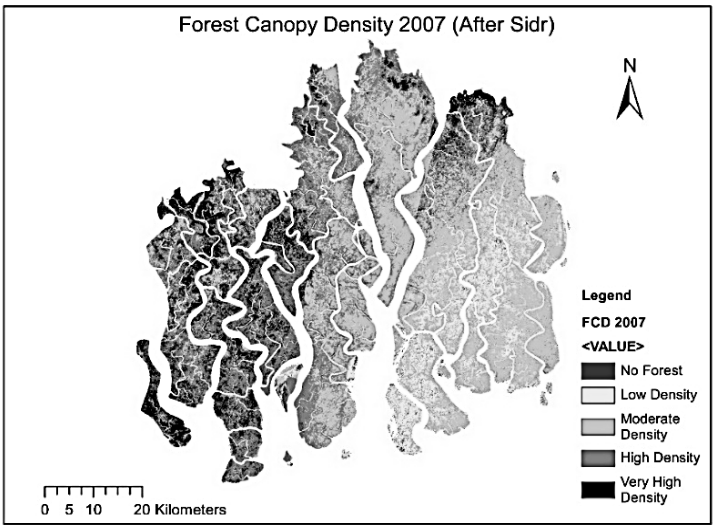

Fig. 07: FCD Map of 2007 (After Cyclone *SIDR*)

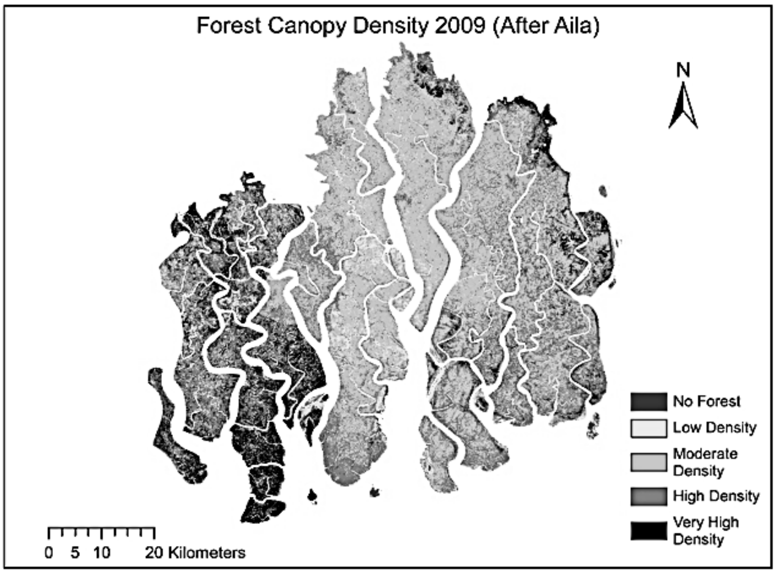

Fig. 08: FCD Map of 2009 (After Cyclone *AILA*)

Table 03: Change of vegetation density structure due to *SIDR* and *AILA* and its recovery status

Vegetation density classes	Area (sq. km.)						
	Pre-*SIDR* (2006)	Post-*SIDR* (2007)	Pre-*AILA* (2008)	Recovery (2007-08) (% of lost area)	Post-*AILA* (2009)	Situation at 2017	Recovery (2009-17) (% of lost area)
No Forest	32.56	43.14	35.08	76.13	52.64	49.94	15.39
Low Density	170.74	496.15	217.91	85.50	342.63	168.38	(-)139.71
Moderate Density	1102.20	1774.74	1746.43	4.21	1885.10	677.88	(-)870.55
High Density	1441.79	1341.47	1448.16	106.35	1421.66	1752.57	1248.97
Very High Density	1372.65	460.01	670.83	23.10	418.04	1472.58	417.17
Total Area	4119.93	4115.51	4118.41		4120.08	4121.35	

After *AILA*, high-density vegetation exhibited significant increase by 2017. Coverage of the same expanded from 1441.79 sq. km. in 2006 to 1752.57 sq. km. in 2017, which is nearly 310 sq.km. more compared to 2006. Meaning it regained about 12.49 times more area that it lost due to *AILA*. Very high-density coverage followed similar but slower trend. It increased from 35% to 42.52% between the year 2006 and 2017 (table 03). Likewise, Moderate-density vegetation coverage has reduced from 1885.10 sq. km. in 2009 to 677.88 sq. km. in 2017. Contrary to this, almost 25.58% area of very high-density coverage has recovered during same period.

Current Status of Vegetation Coverage **:** It has been observed from the table 02 that, very high-density vegetation coverage has recovered by gaining its area from 418.04 sq. km (2009) to 1472.58 sq. km. (2017), which is close to the very high density coverage of 2006 (1372.65 sq. km).

By 2017, high-density vegetation coverage increased from 1421.66 sq. km. at 2009 to 1752.57 sq. km in 2017 which is about 338 sq. km. more than its coverage in 2006 (1414.79 sq. km.). Contrarily, moderate-density vegetation coverage decreased from 1885.10 sq. km. to 677.88 sq. km., which is about 424 sq. km. lesser than the coverage of 2006 (1102.20 sq. km.) as about 1207.22 sq. km. of moderate-density coverage has been converted to very high density and high-density coverage. Likewise, the situation of low-density vegetation coverage has reduced from 342.63 sq. km. to 168.38 sq. km., which is nearly same as the *Figure* of 2006.

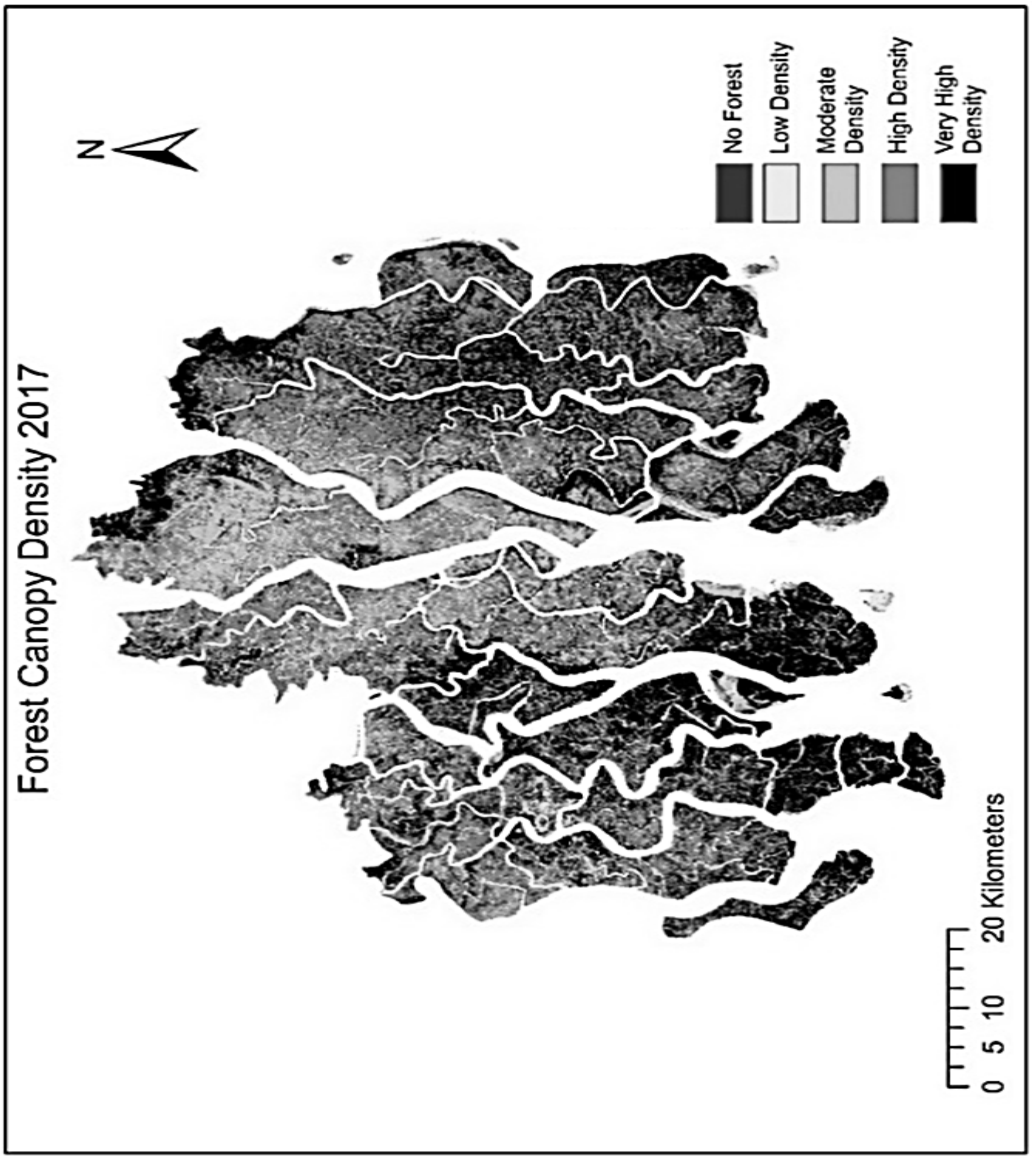

Fig. 11: FCD map of 2017

After the cyclones, the Government of Bangladesh (GoB) and its development partners took necessary measures to aid in the regeneration process of the *Sundarbans*. The Ministry of Environment, Forest, and Climate Change (MOEF) (the then "Ministry of Environment and Forests") accentuated on the natural recovery process as the most important strategy for the *Sundarbans* (GoB, 2008b; UN, 2010). To help the natural recovery of the *Sundarbans*, GoB emphasized on livelihood rehabilitation and compensation for the forest resource extractors who were dependent on the *Sundarbans* (*mawali*, *bawali*, fishers, fry collectors, boatmen, etc.). Additionally, some initiatives such as collaborative forest station-based monitoring, smart patrolling, and afforestation in government khas land outside *Sundarbans* by the MOEF in collaboration with Forest Department helped *Sundarbans* to recover itself (GoB, 2008b). These efforts reduced the disturbances in the *Sundarbans* caused by the resource extractors and let it to recover by itself. It is to be noted here that several scholarly literatures identified the *Sundarbans* as one of the most suitable places for natural recovery (Ellison, 2000).

Conclusion

Unlike the conventional remote sensing method, the Forest Canopy Density (FCD) model specifies the growth phenomena of forests by means of qualitative analysis through three biophysical indices- Advanced Vegetation Index (AVI), Bare Soil Index (BI) and Shadow Index (SI).The result shows that *Sundarbans* suffered catastrophic impact due to *SIDR* and *AILA*. For *SIDR*, along the trajectory, the impact is relatively higher. On the contrary, as wind speed of *AILA* was comparatively weaker than *SIDR*, distinct path of destruction cannot be identified. *AILA*'s impact was not so significant compared to *SIDR* and central part of the *Sundarbans* along the Poshur and Shibsha River was mainly affected.

Recovery of vegetation in the last 8 years was remarkable. It has recovered its losses of different vegetation density coverage. Study shows that the relatively higher density vegetation coverage gained relatively more areas compared to the pre-cyclone period (2006).

Nevertheless, a few issues yet deserve further investigation. The difference of vegetation diversity (species) before and after the cyclones, change of vegetation stems height and crown projection area, etc. need to be analyzed to understand the change of vegetation structure. Several of these properties (e.g. ground density and height) need to be combined together to correctly identify the tree species. However, this is beyond the scope of this research. Nevertheless, result of this study will provide valuable foundation and understanding for further studies.

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