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Relation	

Assessing Cyclone Disturbances (1988–2016) in the Sundarbans Mangrove Forests Using Landsat and Google Earth Engine

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ABSTRACT

Cyclone disturbances can cause significant damage to forest vegetation. The Sundarbans spreading across Bangladesh and India, the world's largest mangrove forest, is frequently exposed to cyclones of various magnitudes. However, the extent and pattern of forest disturbances caused by cyclones in the Sundarbans (both parts) remain poorly understood, and a long-term dataset focused on cyclones and forest disturbances is required. In this study, Google Earth Engine (GEE) and Landsat images were used to evaluate changes in the normalized difference vegetation index (NDVI) before versus after 21 cyclones that occurred between 1988 and 2016. Supervised classification successfully classified the forest area with an overall accuracy of 86% and Kappa coefficient 0.80. The percentage of affected forest area (i.e., the area that exhibited negative changes in NDVI values following a cyclone) ranged from 0.5 to 24.1% of the total forest area. Of the 21 focal cyclones, 18 affected less than 10% of the forest area, while two cyclones, Sidr in 2007 (category H5) and a cyclone in 1988 (category H3), affected 24.1% and 20.4%, respectively. Among the cyclone parameters (i.e., maximum wind speed, distance from the Sundarbans, and river water level), wind speed was significantly and positively correlated with affected forest area. Wind speed and affected forest area were non-linearly related indicated by the piecewise linear regression and cubic regression. The piecewise model estimated a threshold point, suggesting that wind speed had little effects below a breakpoint of 101.9 km h^{-1}. Our analyses, based on a 29-year dataset, suggest that, although the region experienced cyclones almost every year, only the largest cyclones (i.e., in the H3 category or higher) affected 20% or more of the mangrove forest area, and these occurred around once per 7- to 12-year period. Trees with broken stems or uprooted canopies as a result of strong

winds are likely to contribute to the reduction in NDVI in the aftermath of a cyclone. From a long-term perspective, such rare yet intense cyclones may have a significant effect on regeneration and species composition in the Sundarbans mangrove forest. Since previous studies only focused on a few cyclones, our results based on 21 cyclones will certainly help better understanding of the effects of cyclones on mangrove forest disturbance.

Keywords: NDVI; GEE; wind damage; hurricane damage

1. Introduction

Tropical cyclones (hurricanes, typhoons, and southern hemisphere cyclones) are a frequent phenomenon; they can cause fatalities and major economic loss (Paul and Rashid, 2017), and are an important driver of forest ecosystems (Foster and Boose, 1992). Cyclones can affect forest structures (Everham and Brokaw, 1996) and can fragment forested landscapes (Foster and Boose, 1992). Besides the short-term effects, cyclones also have long-term implications with respect to forest succession (Vandermeer and Granzow De La Cerda, 2004), nutrient recycling (Van Bloem et al. 2005), site productivity (Wang and Hall, 2004), species composition (Xi et al., 2008), carbon cycle (Chambers et al., 2007), and drainage (Peierls et al., 2003). There are several factors associated with the disturbances caused by cyclones, including wind speed, distance from the cyclone's eye, and storm surges (Lugo, 2008). Moreover, intense cyclones with high wind speed and precipitation are likely to be more frequent due to global climate change (Solomon et al., 2007). Changes in the frequency and intensity of cyclones can have significant implications for ecosystems (Zeng et al., 2009). Therefore, a fuller appreciation of how tropical cyclones affect ecosystem dynamics is necessary, so that changes in ecosystems that occur in response to climate change may be anticipated (Solomon et al., 2007).

Mangrove ecosystems are diverse and dynamic, accommodating both terrestrial and marine organisms (Hogarth, 2007). Mangroves are more vulnerable than inland forests to tropical cyclones, due to their greater exposure to higher wind energies (Baldwin et al. 1995). Located on the active delta of the Ganges-Brahmaputra river system, the Sundarbans constitutes the world's largest single tract of mangrove forest, and has been exposed to frequent cyclonic storms and tidal bores (Giri et al., 2007). Between 1981 and 2018, 252 cyclonic storms, ranging in intensity from very low to severe, formed in the Bay of Bengal (IMD, 2019). Although the number of cyclonic storms has declined during the past decade, their intensity is increasing (Paul and Rashid, 2017). Moreover, based on projected climate change scenarios, it is predicted that the coastal areas of Bangladesh will be inundated due to rising sea levels; consequently, Sundarbans is classified as an endangered ecosystem (Paul and Rashid, 2017). In consideration of these climate change scenarios, to better understand the potential effects of future cyclonic storms on the Sundarbans mangrove forests, the effects of historical tropical cyclones on the Sundarbans forest vegetation should be investigated. However, few attempts have been made to assess the disturbances inflicted on the Sundarbans by tropical cyclones, and the studies that have been conducted have focused only on recent or major cyclones, including cyclone Sidr in particular (Table 1).

Satellite imagery and remote sensing techniques have been used to study forest phenology (Walker et al., 2012), land-cover change (Hansen et al., 2013), and flowering (Azmy et al., 2016). Multispectral remote sensing data facilitate satisfactory assessment of forest disturbances from the local to the regional scale (Chambers et al., 2007; Zeng et al., 2009; Zhang et al., 2016). Therefore, remote sensing has been used to identify forest disturbances caused by cyclones in various types of forest, including natural forests (Lee et al., 2008), mangroves (Parker et al., 2018), and coastal forests (Negrón-Juárez et al., 2010). Since the majority of the Sundarbans region is difficult to access, and detailed forest inventories are scarce (Giri et al., 2007), satellite imagery offers the optimum means of studying large-scale forest disturbances.

Landsat data products, which offer a high-resolution (30 m) and the largest historical archive of sensed data (around 40 years), are useful for long-term and large-scale ecological studies (Zhao et al., 2018). Google Earth Engine (GEE) is a cloud-based platform for planetary-scale environmental data analysis, with a vast store of data and satellite imagery that can be searched, analyzed, and extracted on the server (Gorelick et al., 2017). Google Earth Engine (GEE) is a relatively new tool that facilitates easier handling and analysis of remote sensing data.

The aim of the present study was to elucidate the pattern and extent of forest disturbances caused by tropical cyclones in the Sundarbans (Bangladesh and India) mangrove forests, using 29-years Landsat and GEE data. Specifically, we were guided by the following questions: (i) how often and to what extent were forest disturbances created by cyclones? and ii) which cyclone parameter had the greatest influence in the affected forest area?

2. Materials and methods

2.1 Study Area

We focused on both Bangladesh and Indian part of the Sundarbans mangrove forest region (Figure 1), bounded by 21°32´ – 22°40´N latitude and 88°05´–89°51´E longitude, for this study. It covers an area of around 10,000 km^2, of which approximately 60% lies in Bangladesh and 40% in India (Giri et al., 2007). The Harinbhanga river forms a natural demarcation, separating the Bangladeshi and Indian Sundarbans. The United Nations Education, Scientific and Cultural Organization (UNESCO) conferred World Heritage Site status on the Sundarbans in 1997.

The region is characterized by numerous complex, interconnected tidal creeks or channels, mudflats, and mangrove forests, making it a unique ecosystem that accommodates large numbers of flora and fauna. The mangrove forest is particularly rich in biodiversity, and hosts over 300 plant and 1,760 animal species (Ishtiaque et al., 2016). Among over 27 mangrove tree species, *Heritiera fomes, Excoecaria agallocha, Ceriops decandra* and *Sonneratia apetala* are the four predominant species; others include *Avicenia, Xylocarpus, Bruguiera, Rhizophora* trees and *Nypa* palm. The mangrove ecosystem is also characterized by monsoonal rains, flooding, delta formation, tidal influences, and mangrove colonization (Giri et al., 2007).

The land slope in this region is 0.03 m vertically per km of horizontal distance from north to south. The elevation of the forest area varies between 0.9 m and 2.1 m above mean sea level (Rahman, 2000). The average monthly temperature ranges from 12 to 35 °C, and 80% of the total rainfall in the region occurs during the monsoon season from June to October. Relative humidity varies between 70 and 80% (Rahman et al., 2010). It is also during monsoon season that the region is most frequently affected by severe cyclonic storms, which inflict severe damage on the region, owing to the effects of strong winds and saline water ingression.

2.2 Cyclone Data

Meteorological data on major cyclones that formed over the Northern India (NI) basin and made landfall within a range of 370.4 km was collected from the International Best Track Archive for Climate Stewardship (IBTrACS) database (Knapp et al., 2010) and the Bangladesh Meteorological Department (BMD). A total of 21 cyclones that occurred over the period between 1988 and 2016 were selected (Figure 1). Very weak Tropical Depression (TD) (61 km hr^{-1} or lower), and slightly stronger Tropical Storm (TS) (63-117 km hr^{-1}) and Saffir-Simpson Hurricane Wind Scale from Category 1-5 (H1 = 119-153 km hr^{-1}; H2 = 154-177 km hr^{-1}, H3 = 178-208 km hr^{-1}, H4 = 209-251 km

hr^{-1}, H5 = 252 km hr^{-1} or higher) as described in Paul and Rashid (2017) were used in this study. Due to the unavailability of images from 2013, the cyclone that occurred that year was excluded from this study. No more than one cyclone was selected for each year; when multiple cyclones had occurred within a single year in the vicinity of Sundarbans, we selected the largest. For each cyclone, the maximum sustained wind speed (km h^{-1}; hereafter, wind speed), the minimum distance (km; hereafter, distance) from the center of Sundarbans (i.e., a centroid point: 21°56'21.31" N, 89°10'56.01" E), and the average maximum water level (m; hereafter, water level) of the rivers in the Sundarbans, on the day when and 1 day after the cyclone had made landfall, were calculated. Although storm surge may be a key factor affecting the mangrove forests, data on storm surges from the study period were unavailable. As an alternative, we used data on water levels at the four major rivers within the Sundarbans collected by the Bangladesh Water Development Board (BWDB), and calculated the average maximum water level at the time of cyclone occurrence; this should indicate any abnormal changes in the water levels in the Sundarbans region.

2.3 Supervised classification

To extract the forest area of the Sundarbans, we applied a supervised classification technique, Classification and Regression Tree (CART) analysis, to distinguish water, land, and other features from the vegetation classes. The work flow is presented in detail in Figure 2. We used Landsat 5 Surface Reflectance Tier 1 (LANDSAT/LT05/C01/T1_SR) data from 2011 for the entire year to construct the classification model. We filtered and masked cloud to make a quality mosaic, using the GEE algorithm. Clouds were masked using the CFMASK algorithm, which is incorporated into the product. The normalized difference vegetation index (NDVI) was calculated using the formula, NDVI = (NIR – Red)/ (NIR + Red), where NIR is Band 4 (B4) and Red is Band 3 (B3) for Landsat 5. An NDVI band was added to all selected images. A greenest pixel composite was created using GEE's *quality mosaic()* algorithm, which uses the NDVI band and computes the maximum NDVI value per pixel level, thus eliminating some of the basic problems associated with mosaicking, such as discontinuities between Landsat paths (GEE, https://developers.google.com/earth-engine/ic_composite_mosaic).

We randomly selected 30–100 points for four classes, vegetation, water, bare soil, and mudflats, as training data. After the classification, an accuracy assessment was performed within the GEE, using 40% of the training points and the Google Earth (CNES/Airbus DigitalGlobe 20 m) data for reference. Finally, maps of the vegetation class were exported for the following analyses of forest disturbances.

2.4 Assessment of forest disturbance

Landsat-5 TM, Landsat-7 and Landsat-8 32-Day NDVI (LT5_L1T_32DAY_NDVI, LE7_L1T_32DAY_NDVI, LC8_L1T_32DAY_NDVI image class ID, respectively) composites were used in the GEE to calculate changes in the NDVI from pre- to post-cyclonic events (Table 2). As the cyclones were dated from 1988 to 2016, Landsat 5 and 8 32-day NDVI products were selected based on their availability. As Landsat 7 has a scanline error from 2003 (Roy et al., 2014), it was only selected when other Landsat products were unavailable.

To detect forest disturbance, we computed pixel-based NDVI values for January to March in 2 consecutive years for each cyclone: the year of cyclone landfall and the subsequent year. Since all cyclones occurred between April and December, we regarded the NDVI values for the cyclone year and the subsequent year as pre- and post-cyclone, respectively. We then compared these values: any negative changes in post-cyclone NDVI values were considered to represent cyclone-induced forest disturbance, for the purpose of the present study. Disturbed area per pixel was converted into area in square kilometers, and finally converted into a percentage of the total forest area. The images captured between January and March were selected because that period falls within the dry season and therefore experiences less cloud; images captured immediately before and after cyclones were problematic, due to the extensive clouds, since cyclones usually occur during monsoon season (the Sundarbans area was almost entirely covered with clouds in many cases). Furthermore, using pre- and post-cyclone images from the same season minimizes the effect of seasonal changes in the NDVI, due to the seasonal leafing phenology of mangrove species.

2.5 Statistical analysis

To evaluate the importance of each cyclone parameter to predictions of the extent of the forest disturbance, we analyzed the relationships between cyclone parameters and affected forest area for each cyclone (N = 21) using a generalized linear model (GLM). We used the percentage of affected forest area to the total forest area as a response variable and three cyclone parameters (i.e., wind speed, distance and water level) as explanatory variables with Gaussian error distribution.

The relationship between cyclone parameter and forest disturbance may not be simply linear; instead, there might be a threshold up to which there is minimal disturbance, but after which the disturbance intensifies (Lugo, 2008, Imbert, 2018).

Since wind speed was the only significant parameter in the GLM, we also constructed a piecewise regression models to examine the possibility of a non-linear relationship between the cyclone wind speed and the affected forest area. If such a threshold were to exist, it would be indicated by a breakpoint in the piecewise model. Moreover, as the power of wind is cube of velocity, the cubic regression may improve our model. We compared the three models, i.e. a simple linear, piecewise, and cubic regression models, in the adjusted R-squared (R^2) value and the Akaike information criterion corrected for small sample size (AICc), to evaluate the models' performances. All statistical analyses were conducted in the R environment (R Core Team, 2014). We employed a piecewise regression using the *segmented* package in R (Muggeo, 2008).

3. Results

3.1 Supervised classification and accuracy assessment

Classification and Regression Tree (CART) analysis revealed mangrove forest vegetation as the dominant class among the four classes (vegetation, water bodies, bare soil, and mudflats). The estimated area covered by the mangrove forests was 5,352.31 km^2, that of water bodies was 3,457.30 km^2, while those of the bare soil and mudflats were around 500 km^2 each (Table 3, Figure 3). The overall accuracy of the land cover assessment was 86% and the Kappa coefficient was 0.80. Vegetation and water data indicated very high producer and consumer accuracy, while the mudflats data showed relatively lower accuracy (Table 3).

3.2 NDVI change

In total, 84.55% of the vegetation area in the Sundarbans experienced negative change in NDVI after at least one of the 21 cyclones; 45.59%, 34.00%, 4.57% and 0.39% of the area was affected by one, two – three, four – five, and six – 12 cyclones, respectively (Figure 4). Bangladeshi region of the Sundarbans, the eastern part in particular, was affected by cyclonic events more frequently during this study period than was the Indian region.

Of the 21 cyclones studied, 11 affected less than 5% of the forested area in the Sundarbans (Table 4). Seven cyclones had affected between 5 and 10% of the forested area, and three between 10 and 25%. The highest level of disturbance observed was associated with cyclone Sidr (C07, category H5), which affected 24.13% (1,291.39 km^2) of the forested area (Table 4). Cyclone Sidr was the strongest among the cyclones studied, with the highest maximum sustained wind speed of 259.28 km h^{-1}, and made landfall close to the Sundarbans. The second highest (20.41% or 1,092.51 km^2) disturbance was observed for a cyclone that occurred in 1988 (C88, category H3), which passed through the Sundarbans mangrove forest. That cyclone had a maximum sustained wind speed of 203.72 km h^{-1}. A cyclone in 1995 (C95, category H2) was the third strongest, affecting 12.32% (659.14 km^2) of forest area. The maximum sustained wind speed of this cyclone was 157.42 km h^{-1}, and it made landfall in Cox's Bazar, Bangladesh.

3.3 Relationships between cyclone characteristics and forest disturbance

The GLM revealed that wind speed was significantly and positively correlated with affected forest area, while the correlation between affected forest area and distance was nonsignificant (Table 5). Water level was not significantly correlated with affected forest area.

Since wind speed was the only significant parameter, we constructed a piecewise linear and a cubic regression model using affected forest area as a response variable and wind speed as an explanatory variable then compared with a linear model. The piecewise model estimated wind speed of 101.86 km h^{-1} as a breakpoint (Figure 5). The estimated coefficients of wind speed were close to zero before the breakpoint (mean ± SE: -0.05 ± 0.12), increasing significantly thereafter (0.16 ± 0.12). Adjusted R^2 value of piecewise ($R^2 = 0.58$) and cubic model ($R^2 = 0.58$) were slightly higher than that of the simple linear model ($R^2 = 0.51$). AICc of the cubic model (124.22) was lower than that of the piecewise model (AICc = 128.55) and the linear model (AICc = 127.38). Therefore, cubic model was the most parsimonious model, but model fitness was similar between piecewise and cubic model.

4. Discussion

4.1 Classification

Our classification estimation of the forest area in the Sundarbans was reasonable as reported in the literature (Giri et al., 2007 and Islam, 2014) with satisfactory accuracy. However, producer's accuracy for mudflats was lower than that for the other classes possibly due to periodical flooding precipitated by the ingression of tidal sea water into the forest, which contributed to confusion between the bare soil and mudflat classes (Giri et al., 2007).

4.2 Forest disturbances

Based on our 29-year period data analyses, the extent of the disturbances varied by cyclone (Figure 6). Strong effects on mangrove tree canopies was reported as a result of strong winds in association with the cyclones of 1988, 1991, 1995, 2007 (Sidr), and 2009 (Aila) (Paul and Rashid, 2017). However, the extent of the structural changes due to cyclones was not previously estimated, although it is critical for understanding forest regeneration and management. In this study, we estimated the NDVI changes caused by cyclones over a 29-year period, and found that the cyclones of 1988, 1995, and 2007 affected more than 10% of vegetated areas, while the others affected less than 10%. As indicated by our findings, the Sundarbans suffers from major cyclone disturbances every 7 to 12 years, with smaller disturbances occurring more frequently. During the cyclone of 1988 (C88), a total of 3.71 million *Sundari* trees (*Heritiera fomes*) and 4.71 million *Keora* trees (*Sonneretia apetala*) were affected through stem breaking, uprooting and at places increasing salinity (Aziz and Paul, 2015). Hossain and Begum

(2011) conducted a field observation in the aftermath of cyclone Sidr (C07), and reported that the cyclone uprooted at least one tree per 100 m^2. Cyclone Aila (C09) caused uprooting and branch snapping affected *Gewa* trees (*Excoecaria agallocha*) in and around the Sundarbans area (Rahman et al., 2017). Cyclones Sidr (2007) and Aila (2009) resulted in reduced numbers of individuals tress (poles and saplings) in the eastern part of Bangladesh Sundarbans (GOB, 2008; Islam et al., 2014; Paul et al., 2017). The frequency of the disturbances also has a profound effect on forest vegetation, since re-establishment of the original stand takes 10 to 15 years (Lugo 2008). In our study we found that only 15.45 % forest area escape cyclone effect meaning multiple cyclone affecting the same area. Therefore, frequent and intensive cyclone disturbances may be among the major factors that drive forest regeneration and species assembly in the Sundarbans.

This study found that cyclone Sidr affected the Sundarbans forest most severely (24.13%). Previous studies on cyclone Sidr reported similar levels of forested area were disturbed by the cyclone, ranging from 19 to 31% (Akhter et al., 2008; GOB, 2008; Cornforth et al., 2013; Rahman et al., 2010), suggesting that our estimation was reasonable. Field observation after cyclone Sidr showed evidence of damage (e.g., trunk bending or breakage, uprooting, loss of the substrate and local scour around the trees) to the major mangrove species, including *Sundari*, *Gewa*, *Passur* (*Xylocarpus molluccencis*) and *Keora* (GOB, 2008). The flooding that followed increased the salinity caused by the cyclone, resulting in increased mortality of *Sundari* trees (Uddin et al., 2013). Therefore, strong cyclonic disturbances, as in the cases of cyclone Sidr (C07), the cyclone in 1995, and that in 1988 (C88), can result in long-term changes to forest structure and species composition, which may in turn contribute to the maintenance of species diversity in mangrove ecosystems (Lugo 2008).

Among the cyclone parameters, wind speed exerted the greatest influence on the affected forest area. Mangrove forests experience greater mortality and structural change as a result of direct exposure to wind energy than do inland forests (Lugo, 2008). Strong cyclonic wind often results in defoliation, instantaneous litterfall, and the uprooting of trees (GOB, 2008; Hossain and Begum, 2011), and is therefore likely to contribute to negative changes in the NDVI. Better performance of cubic and piecewise model rather than linear model suggested non-linear relationship between cyclone wind speed and affected forest area. Affected forest area drastically increased when wind speed exceeds a certain level (Figure 6). The piecewise model estimated a wind speed threshold of 101.86 km h^{-1}, below which forest disturbances were minimal and unrelated to wind speed. Tanaka et al. (2008), based on their field survey, also reported that trees of larger diameter were subjected to more wind drag force than storm surge, and were affected most by wind speeds of over 96.56 km h^{-1}. Francis and Gillespie (1993) reported that, beyond a certain wind speed, forests are affected regardless of their species composition. Cyclones with maximum sustained wind speeds of approximately 100 km h^{-1} or more can cause large-scale forest disturbance in the Sundarbans.

By contrast, the distance between the cyclone's path and the center of the Sundarbans was less influential in terms of the affected forest area in the Sundarbans. However, major cyclones making landfall at the Sundarbans caused considerable disturbances (Dutta et al., 2015). Our data also suggested that cyclones of higher magnitudes (i.e., H3 and stronger) that made landfall at the Sundarbans (C88 and C07) affected large areas (20.4 and 24.1%, respectively), while those that were distant from the Sundarbans (C91 and C95) affected much smaller areas (8.1 and 7.8%, respectively) (Table 4). Therefore, distance is only an influential parameter for the cyclones with higher magnitudes.

Water level, as an index for storm surge in this study, was not influential in the affected forest area. Although the average river water level on the day of the cyclone's landfall, and on the day after, may not be a relevant measure of each cyclone's storm surge, earlier studies have also suggested that storm surges may not always precipitate major effects on mangrove forests (Lugo, 2008; Paul and Rashid, 2017).

4.3 Limitations

Our study compared the pre- and post-cyclone NDVI values of the Sundarbans mangrove forests and assumed that any negative changes in NDVI values after the cyclone could be attributed to the event. However, there might be other factors that affect forests' NDVI values: anthropogenic disturbances, such as timber logging, may create canopy gaps, thus lowering forests' NDVI values. However, clearcutting and forest encroachment have been prohibited under strict forest management guidelines since 1982 in the Sundarbans region (Giri et al., 2007, Kamruzzaman et al., 2017). Consequently, the annual deforestation rate was almost zero throughout the study period (Reddy et al., 2016).

We focused exclusively on the short-term (< 1 year) responses of mangrove forests to cyclones. However, the effects of cyclones sometimes become evident only in the long-term (Lugo, 2008). Negrón-Juárez et al., (2014) reported that cyclone-induced forest disturbances can be detected even up to 1 year after the cyclone's occurrence.

Therefore, although we examined the correlation between a cyclone and an NDVI change within a given year, it should be noted that the NDVI change may result from multiple previous cyclones.

5. Conclusion

Our analyses, based on a 29-year dataset, suggest that, although the region experienced cyclones on an almost annual basis, only the largest cyclones (H3 or higher category) could affect 20% or more of the mangrove forest areas, where these occurred around once every 7 to 12 years. Trees with broken stems or uprooted canopies as a result of strong winds can contribute to reductions in the NDVI after cyclones. From a long-term perspective, such rare yet catastrophic cyclones may have a significant effect on regeneration and species composition in the Sundarbans mangrove forest.

Since the disturbance caused by cyclones can also promote forest regeneration, it remains challenging to predict how cyclones affect mangrove forests in the context of future climate change. With the current pace of climate change, a vast section of Bangladesh's coastal area is set to become submerged over the next 100 years. Recent reports predict that, while the frequency of cyclonic storms in the Bay of Bengal will decrease, their intensity may increase considerably (Paul and Rashid, 2017). As our results suggest, weaker cyclonic storms tend to inflict little effects on this forest; however, an extremely severe cyclone affects more than 20% of the forest area.

Although previous studies in other part of the world also reported the linear (Han et al., 2018) or non-linear relationship (Negrón-Juárez et al., 2014; Imbert, 2018) between cyclone wind speed and mangrove forest disturbance, these studies are based on the observation of only 3-5 cyclones. Therefore, our results based on 21 cyclones will certainly help better understanding of the relationship in general. In combination with decreased freshwater, increased salinity, rising sea levels, water contamination, diseases, and human interference, intense cyclones may cause irreversible changes to this already endangered ecosystem (Giri et al., 2007, Kamruzzaman et al., 2018, Imbert, 2018). The findings of this study will help long-term studies in understanding the complex phenomenon involving tropical cyclones and mangrove forests.

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Conflict of interest

The authors declare no conflicts of interest.

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Table 1 Overview of previous research on forest disturbances caused by cyclones in the Sundarbans using remote sensing

No	Studied parameters	Data used	Location	Study period	Cyclones	Key findings	References
1	Ecological disturbances	MODIS	Sundarbans	2001-2011	SIDR (2007), Rashmi (2008), Aila (2009)	Disturbances detection from three major cyclones	Dutta et al. (2015)
2	Sundarbans Floristic Diversity	Landsat 7	Sundarbans, Bangladesh	2007-2010	Sidr (2007)	45% Bangladesh Sundarbans was affected	Bhowmik, A. K., & Cabral, P. (2013).
3	Tropical cyclone impacts	SPOT 5	Sarankhola, Bangladesh	2007-2008	Sidr (2007)	63.15% study area was affected	Hoque et al. (2016)
4	Conservation of mangroves	ALOS - PALSAR	Sundarbans	2007-2009	Sidr (2007)	Mapping of changes	Cornforth et al., (2013)
5	Damage estimation by cyclone	ASTER	Sundarbans	2007	Sidr (2007)	22.2% damage due to cyclone	Akhter et al., (2008)
6	Impact assessment	MODIS	Sundarbans	2007	Sidr (2007)	31% of the Sundarbans was affected	GOB (2008)

Table 2 List of cyclones included in this study and the Landsat images used

No	Code	Name	Date	Category	Place of Landfall	Landsat
1	C88	Tropical Cyclone 04B	28-29 November, 1988	H3	Khulna, Bangladesh	
2	C89	Unnamed	23-26 May, 1989	TS	Sundarban coast, Bangladesh	
3	C90	BOB 09/04B	17-18 December, 1990	TS	Cox's Bazar, Bangladesh	
4	C91	Gorky	29-30 April, 1991	H4	Chattogram, Bangladesh	Landsat 5 TM
5	C92	Unnamed	22-24 September, 1992	TD	Sundarban coast, Bangladesh	
6	C94	Unnamed	02 May, 1994	H3	Cox's Bazar, Bangladesh	
7	C95	Unnamed	24-25 November, 1995	H2	Cox's Bazar, Bangladesh	
8	C96	Unnamed	28 October, 1996	TD	Sundarban coast, Bangladesh	
9	C97	Unnamed	18-19 May, 1997	H1	Sitakundu, Bangladesh	
10	C98	Unnamed	18-20 May, 1998	H1	Sitakundu, Bangladesh	
11	C99	Unnamed	08-11 June, 1999	TS	Cox's Bazar, Bangladesh	
12	C00	Unnamed	27-28 October, 2000	TS	Sundarban coast, Bangladesh	
13	C02	Unnamed	12 November, 2002	TS	Sundarban coast, Bangladesh	Landsat 7
14	C04	Unnamed	15-18 May, 2004	H1	Teknaf, Bangladesh	Landsat 5 TM
15	C05	Unnamed	01-03 October, 2005	TS	West Bengal, India	
16	C06	Unnamed	30 June -5 July, 2006	TS	West Bengal, India	
17	C07	Sidr	15-16 November, 2007	H5	Khulna-Barisal coast, Bangladesh	
18	C08	Rashmi	25-26 October, 2008	TS	Khulna-Barisal coast, Bangladesh	
19	C09	Aila	25-26 May, 2009	H2	West Bengal, India	
20	C15	Komen	26 June – 02 August, 2015	TS	Chattogram, Bangladesh	Landsat 8
21	C16	Roanu	20-21 May, 2016	TS	Chattogram, Bangladesh	

(TD = Tropical Depression, TS = Tropical Storm, H1-H5 = Hurricanes of category 1-5 on the Saffir-Simpson scale)

Table 3 Area classified for each class after Classification and Regression Tree (CART) analysis; and summary of accuracy assessment

NO	**Classes**	**Description**	**Area (km^2)**	**Producer's Accuracy (%)**	**Consumer's Accuracy (%)**
1	Vegetation	Mangrove forest vegetation	5352.31	95	90
2	Water	Water body	3457.30	97	97
3	Bare soil	Bare earth/sand beach	551.08	79	65
4	Mud flat	Flooded area/Mud flat	536.37	53	71
	Total area		9897.06 km^2		
	Overall Accuracy			86 %	
	Kappa coefficient			0.80	

Table 4 The minimum distance from the center of the Sundarbans, the maximum sustained wind speed, average maximum water levels of the rivers in the Sundarbans on the day of and 1 day after landfall, and affected forest area for each cyclone

No	Code	Distance (km)	Wind speed (km hr^{-1})	Water level (m)	Affected vegetation (km^2)	Affected forest area (%)
1	C88	24.34	203.72	2.61	1092.51	**20.41**
2	C89	199.63	101.86	3.25	25.37	0.47
3	C90	210.02	83.34	2.05	23.83	0.45
4	C91	160.47	240.76	2.85	431.88	8.07
5	C92	32.51	55.56	2.75	93.05	1.74
6	C94	327.87	203.72	2.05	417.64	7.80
7	C95	254.71	157.42	2.80	659.14	**12.32**
8	C96	33.50	74.08	2.69	61.26	1.14
9	C97	242.65	120.38	2.53	281.12	5.25
10	C98	210.02	129.64	2.35	166.15	3.10
11	C99	123.30	64.82	2.45	335.50	6.27
12	C00	52.16	64.82	2.86	78.33	1.46
13	C02	93.82	101.86	2.91	29.42	0.55
14	C04	302.93	120.38	3.81	300.03	5.61
15	C05	115.37	74.08	3.16	278.54	5.20
16	C06	160.47	64.82	2.86	441.03	8.24
17	C07	58.71	259.28	2.66	1291.39	**24.13**
18	C08	58.71	83.34	2.84	257.58	4.81
19	C09	122.29	120.38	4.20	53.16	0.99
20	C15	115.99	46.30	2.10	137.32	2.57
21	C16	105.70	115.83	3.20	152.42	2.85

(TD = Tropical Depression, TS = Tropical Storm, H1-H5 = Hurricanes of category 1-5 on the Saffir-Simpson scale)

Table 5 Results of the generalized linear model on the relationship between cyclone parameters (wind speed, distance, and water level) and affected forest area.

	Estimate	Std. Error	t value	Pr(>|t|)
(Intercept)	3.40	5.74	0.59	0.56
Wind speed (km hr^{-1})	0.08	0.02	5.02	0.0001
Distance (km)	-0.02	0.01	-1.62	0.12
Water level (m)	-1.58	1.82	-0.87	0.40

Figure 1 The Sundarbans mangrove forests with the international boundary between Bangladesh and India. Approximate landfall sites of 20 cyclones can be confirmed of the 21 studied cyclones that occurred between 1988 and 2016; One cyclone path was close to the Cox's bazar Bangladesh but did not show the landfall in the original data. And the center of Sundarbans, a centroid point used to calculate the distance between the cyclonic paths and the Sundarbans.

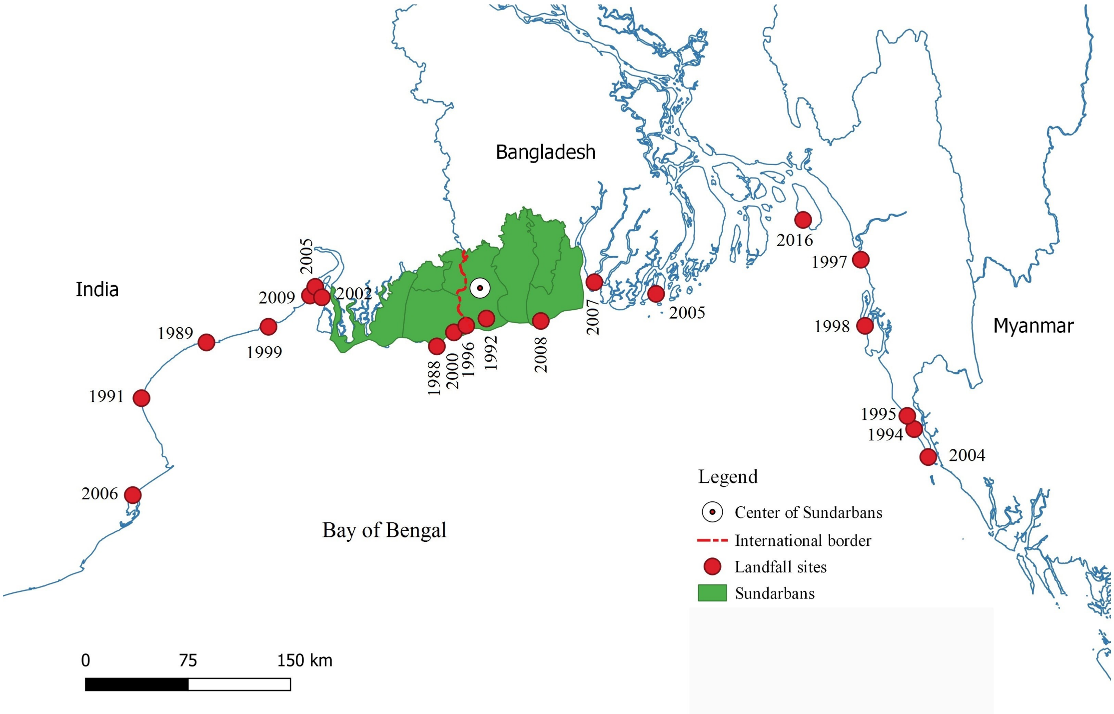

Figure 2 Flowchart of this study's working procedures.

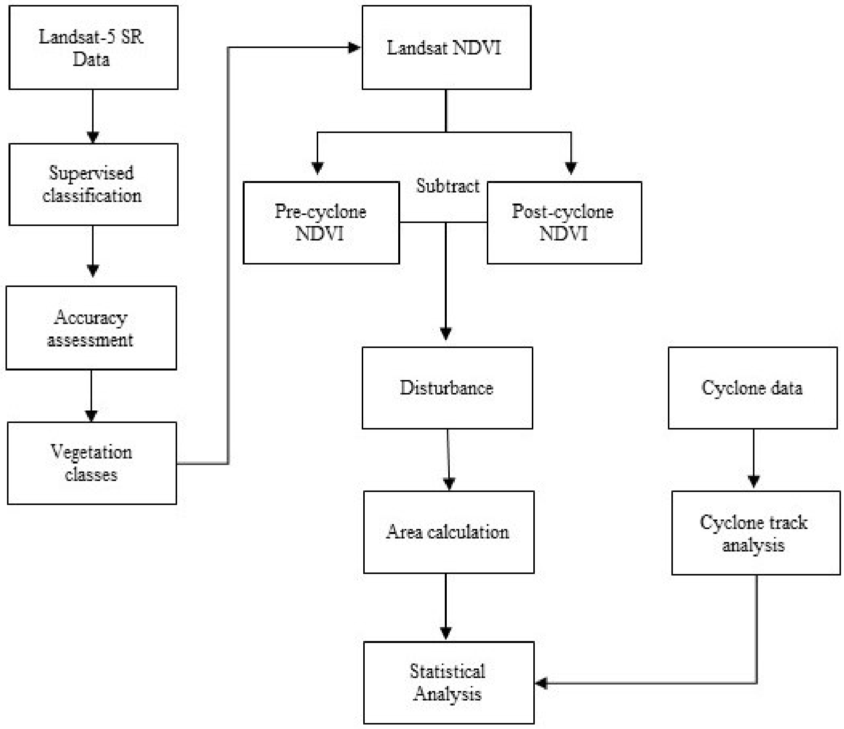

Figure 3 The forest class map yielded by Classification and Regression Tree (CART) analysis.

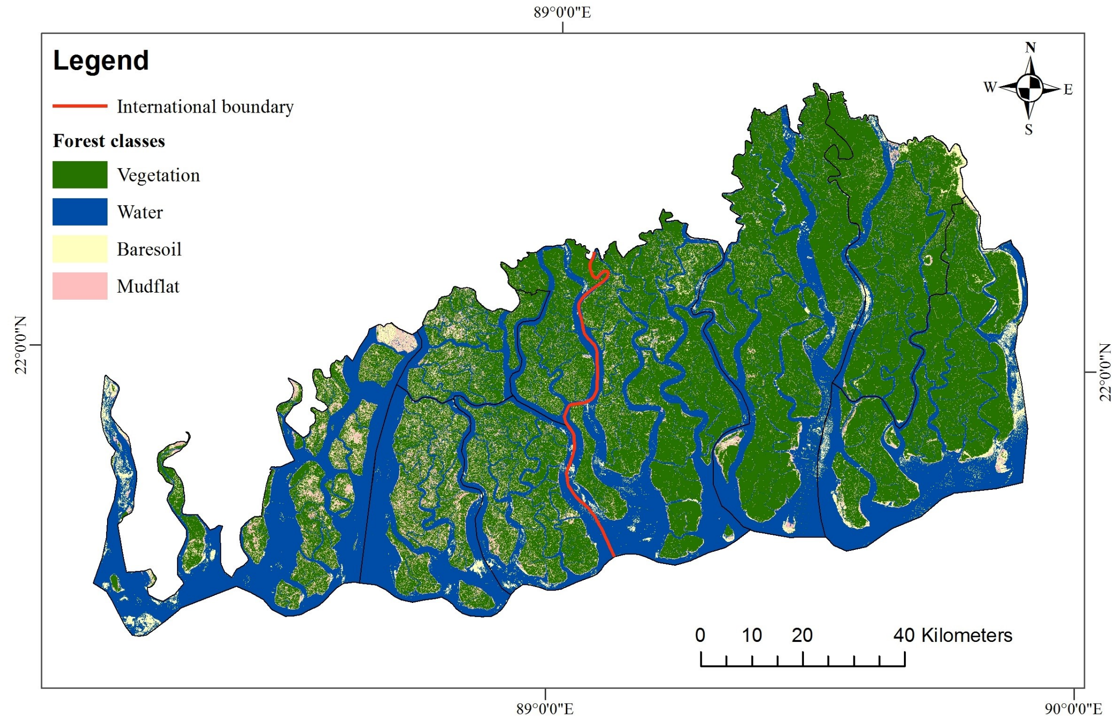

Figure 4 A map showing cumulative number of cyclones affected per pixels in the Sundarbans

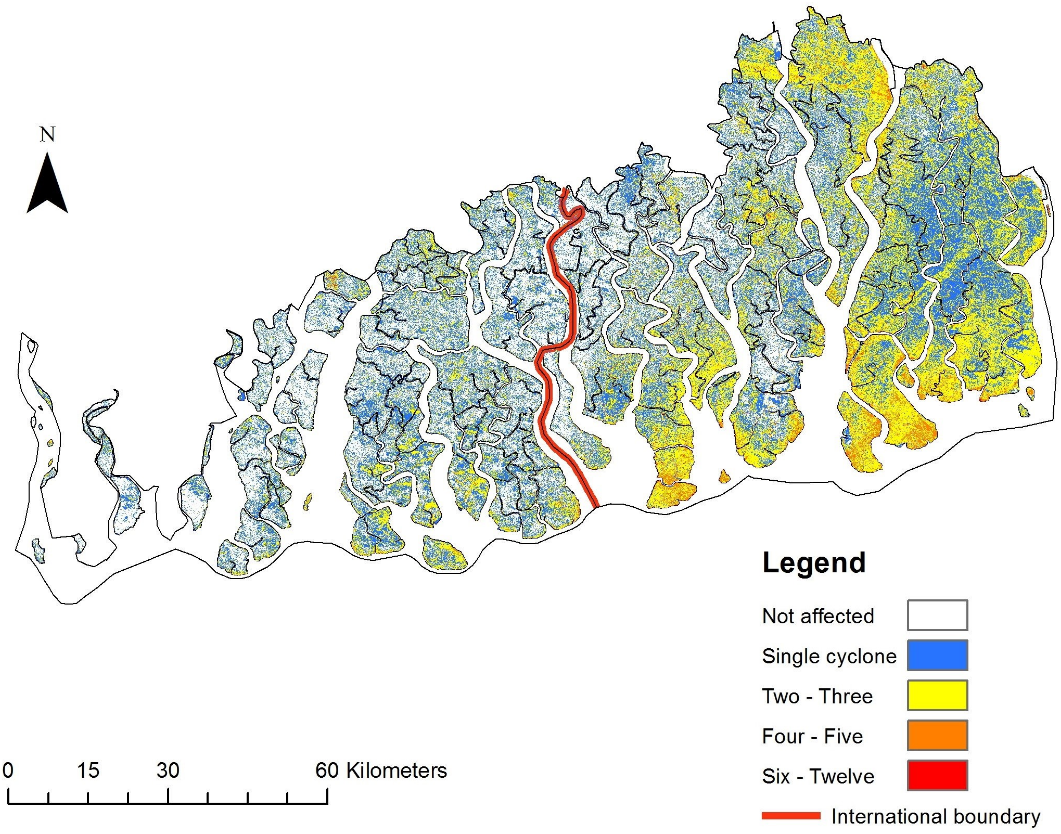

Figure 5 Scatter plot showing the relationship between wind speed (km h^{-1}) and affected forest area (%) for each cyclone, and three regression lines: (a) linear (b) piecewise and (c) cubic regression.

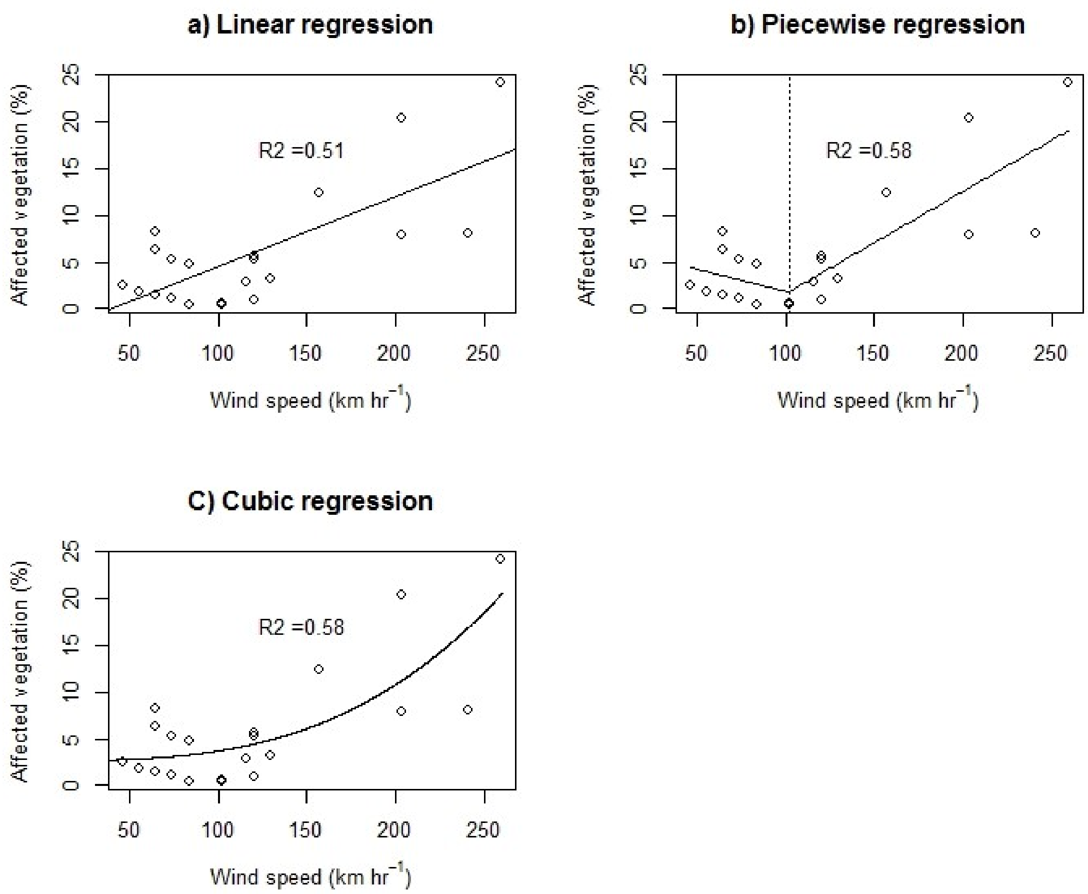

Figure 6 A map of the forest areas affected by each cyclone. Red indicates affected forests. The cyclone track (indicated by a solid black line) is included only for cyclones that made landfall within or close to the Sundarbans.

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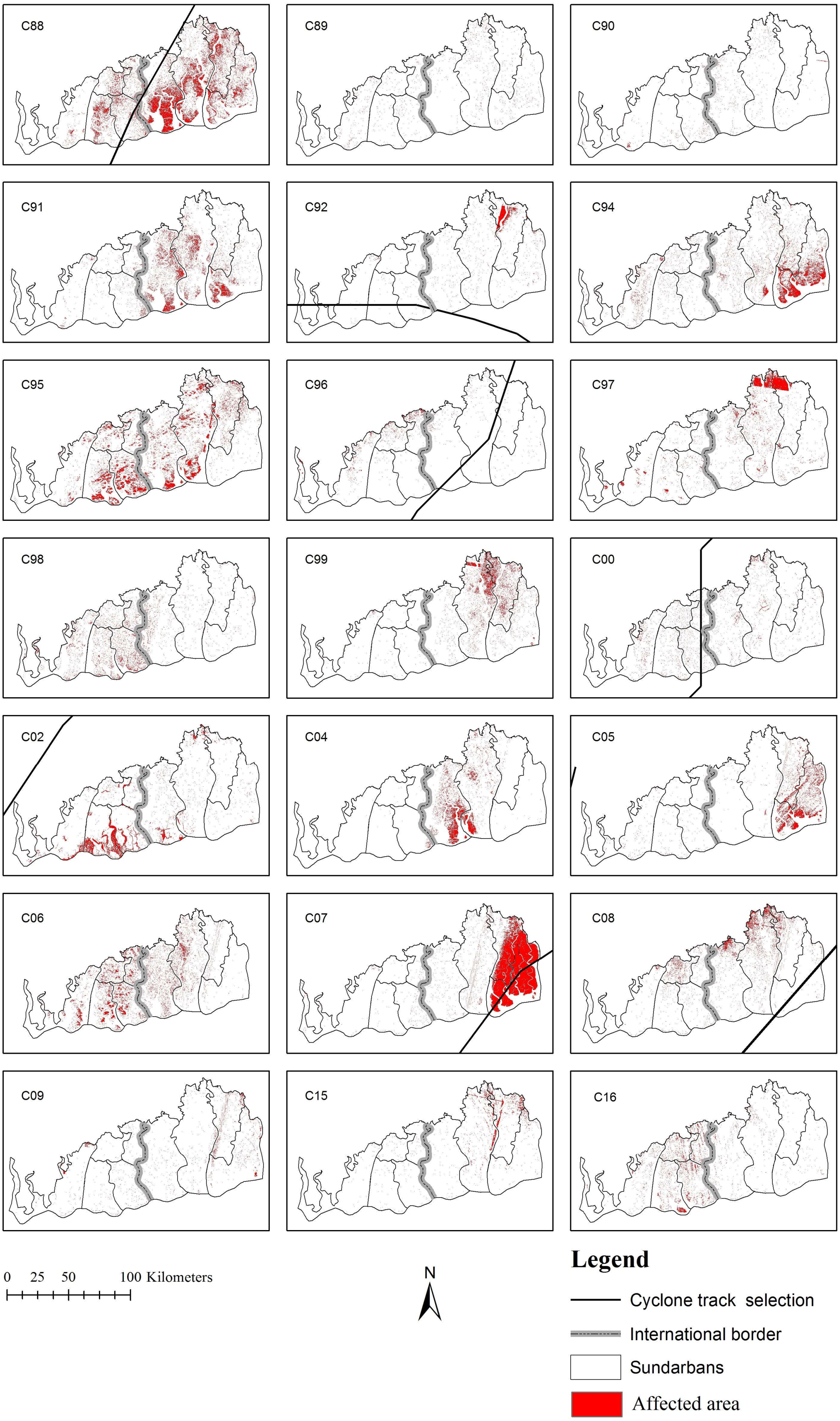
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