Forest Ecology and Management 490 (2021) 119117

Contents lists available at ScienceDirect

Forest Ecology and Management

journal homepage: www.elsevier.com/locate/foreco

Why some trees are more vulnerable during catastrophic cyclone events in the Sundarbans mangrove forest of Bangladesh?

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ARTICLE INFO

Keywords:
Basal area
Climate change
Cyclone damage
Forest stand
Height/dbh ratio
Mangrove species
Sundarbans

ABSTRACT

Mangroves are recognised for their diverse set of ecosystem services, including protection from tropical cyclones and tidal surges. Mangroves are also adapted to withstand disturbances across a range of climatic conditions, and the frequency and severity of disturbances are projected to increase in the coming years due to climate change and sea-level rise. The Sundarbans of Bangladesh and India is one of the most frequently affected mangrove forests in South Asia. We investigated the effect of cyclone disturbance and stand characteristics on the survival of two dominant mangrove tree species – *Heritiera fomes* and *Excoecaria agallocha*. Data was collected through field surveys after cyclone Sidr, a category 5 cyclone that struck in the area in 2007, creating substantial forest damage. We used a Generalized Additive Mixed Model to analyse the effect of tree species, stem diameter at breast height (dbh), and tree spatial position in the forest stand on the degree of cyclonic damage. We find that cyclonic damage in the Sundarbans forest is sensitive to species and dbh. At similar tree size, *Heritiera fomes* was more vulnerable to cyclonic damage than *Excoecaria agallocha*. In *Heritiera fomes* the intensity of wind damage during cyclone increase with increasing dbh. In Sundarbans, cyclonic damage also depended on stand factors such as proximity to the riverbank or forest edges. We suggest silvicultural treatments, such as increasing the tapering of crown or decreasing height/dbh ratios of valuable species, could minimise future cyclonic damage in the area. Further investigations are necessary to improve the management of mangroves in the Sundarbans in the face of climate change, sea-level rise, and novel anthropogenic pressures.

1. Introduction

Mangroves are amongst the most productive ecosystem on Earth (Friess et al., 2019), and geographically located mainly in the tropics and sub-tropics (Thomas et al., 2017). Mangroves are also critical in providing a large number of ecosystem services and benefits, including protection from flooding, cyclones, and cyclone related storm surges (Menéndez et al., 2020; Sun and Carson, 2020), carbon storage and sequestration (Mukul et al., 2021; Donato et al., 2011), support for local livelihoods through the provision of food, fuel, timber, and construction materials (Abdullah et al., 2016; Uddin et al., 2013; Biswas et al., 2009). Mangroves also host a large variety of biodiversity, providing habitats for both terrestrial and aquatic fauna (Biswas et al., 2021; Spalding et al., 2010; Valiela et al., 2001). A recent estimate suggests that global flood protection benefits of mangrove worth nearly US$ 65 billion per year (Menéndez et al., 2020), while the cyclone protection value of mangroves worth about US$ 1.8 million/km^2 per year (Sun and Carson, 2020). Mangroves are also more likely to be affected by tropical cyclones than inland forests due to their location on the coast and exposed to higher wind energies during cyclones (Alongi, 2002; Baldwin et al., 1995).

Located on the active delta of the Ganges–Brahmaputra River

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https://doi.org/10.1016/j.foreco.2021.119117
Received 17 December 2020; Received in revised form 3 February 2021; Accepted 26 February 2021

system, the Sundarbans constitute the world's largest single tract of mangrove forest, covering an area of about 10,000 km^2 (Mukul et al., 2019; Ishtiaque et al., 2016). This mangrove ecosystem of Bangladesh and India plays an important role by acting as a bio-shield against cyclone and tidal surges, mostly originating in the Bay of Bengal and thereby reducing the vulnerability to such extreme climatic events (Akber et al., 2018; Biswas et al., 2009; Paul, 2009). Historically, eight out of ten deadliest tropical cyclones in the world have originated over the Bay of Bengal where Sundarbans is located (Vivekanandan et al., 2016). The Sundarbans region has experienced more than 20 major cyclones over the past two decades (Fig. 1), and regularly protects inland from catastrophic cyclone damage (Mandal and Hosaka, 2020; Dutta et al., 2015). Due to changing climate and sea-level rise, the severity and frequency of cyclones have also amplified in the Sundarbans region in the past few decades (Mandal and Hosaka, 2020; Auerbach et al., 2015).

Among the recent major cyclones that struck the Sundarbans region, cyclone Sidr, a category 5 intensity cyclone (Saffir–Simpson scale), caused substantial losses in property and forest cover in Bangladesh (MoEF, 2010). Sidr hit the eastern part of the Sundarbans on November 15, 2007, with a wind speed of 220–240 km/h and produced tidal waves up to 6 m high (Ahmed et al., 2016). It caused approximately 4000 human deaths and an estimated property damage of nearly US$ 1.7 billion (GoB, 2008). The disturbance effect of cyclone Sidr varied from moderate to highly along its path through the forest, which is summarised in Akhter et al. (2008). Almost 30 percent of the Sundarbans mangroves were affected due to cyclone Sidr, and it was estimated that about 12,000 ha of forest area was severely affected, and another 32,000 ha partially affected (MoEF, 2010).

Several studies have investigated the contribution of Sundarbans mangrove forest in reducing the intensity of wind and the storm surges during the cyclone Sidr (Akber et al., 2018; Dutta et al., 2015). In their study, Harun-or-Rashid et al. (2009) compared the variation in the soil seed bank and the aboveground vegetation in three different habitats in Sundarbans forest, while Azad et al. (2019), assessed the floristic composition, abundance, and biodiversity in two different sites (i.e. disturbed and undisturbed) of Sundarbans eight years after cyclone Sidr. In our study, we investigated the effect of stem diameter and tree spatial location on tree damage during cyclone Sidr. We hypothesized that the extent of cyclone induced damage to mangrove trees depends on species, stem diameter (diameter at breast height, dbh), wood density, and location of the tree (i.e. proximity to the riverbank). For our study, we particularly focused on two dominant tree species of the Sundarbans, viz. *Heritiera fomes* Buch.-Ham (Sundri) and *Excoecaria agallocha* L. (Gewa). *H. fomes* is the principal tree species of Sundarbans, constituting about 73 percent of the total forest cover while *E. agallocha* covers nearly 16 percent of the total forest area and is the second prominent tree species (see – Ghosh et al., 2016; Rahman and Asaduzzaman, 2010; Ifthekar and Saenger, 2008). The species *H. fomes* belongs to the family Malvaceae and *E. agallocha* belongs to the family Euphorbiaceae, and they have wood densities of 0.89 g cm^{-3} and 0.43 g cm^{-3} respectively (World Agroforestry, 2020). Our study provides critical insight into the knowledge of tree species and their vulnerability during catastrophic

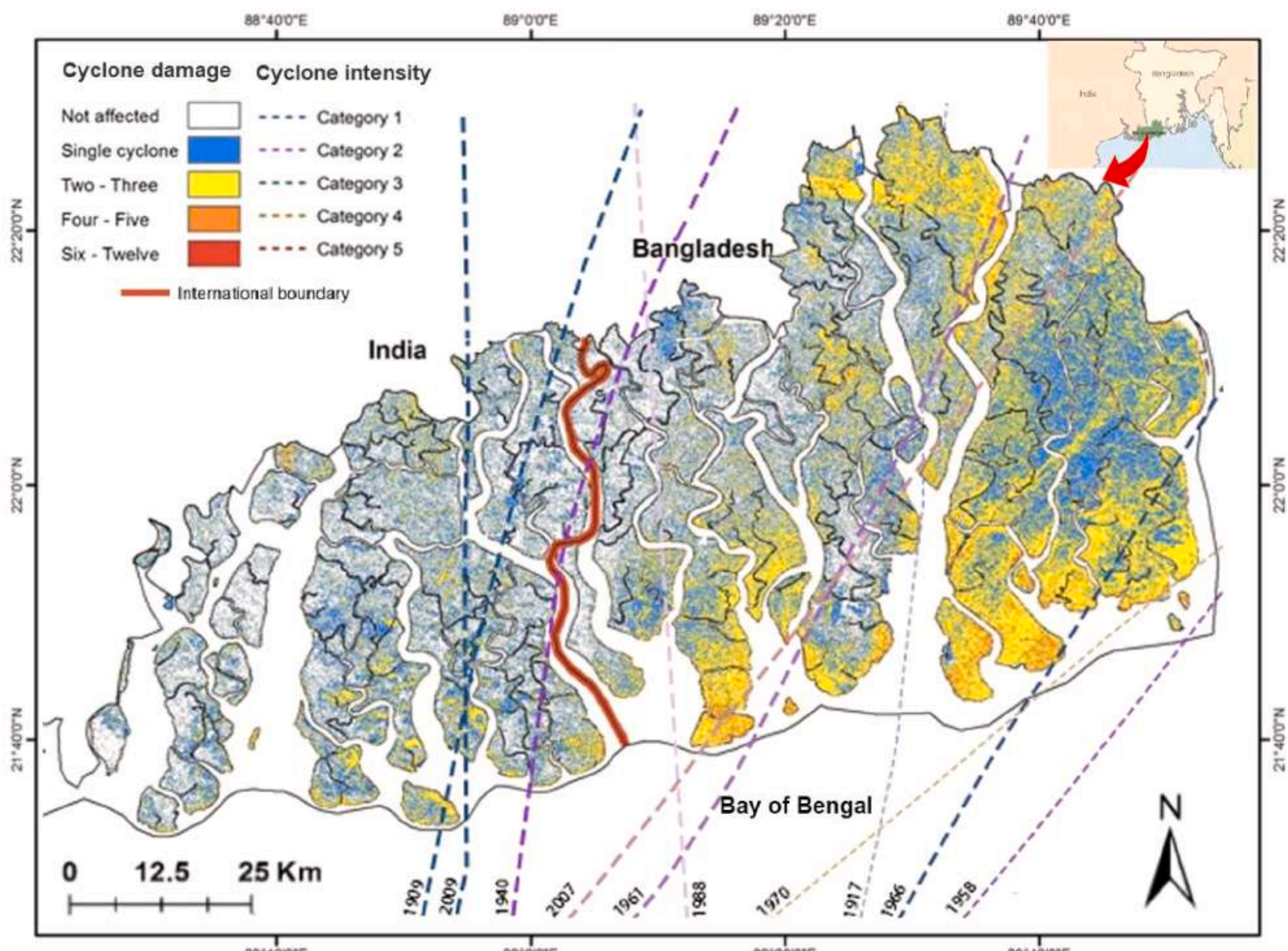

Fig. 1. Major cyclone routes with occurrence year, intensity, and damage in the Sundarbans mangrove forest.
Source: Mukul (2020).

cyclone events and could be useful for mangrove restoration planning after such disturbances.

2. Materials and method

2.1. Study area

Geographically, the Sundarbans are located in the south-west corner of Bangladesh, between 21°30′ and 22°30′ N and 89°00′ and 89°55′ E. Of the total area of the Sundarbans, nearly 60 percent is under the jurisdiction of Bangladesh and about 40 percent is under the jurisdiction of India. The Bangladesh Sundarbans (BSF) contains nearly 40 percent of the total forest area of Bangladesh (Mukul et al., 2014). Administratively, there are 4 ranges and 55 compartments (smaller operational blocks) in the Bangladesh part of Sundarbans which is also a UNESCO World Heritage site (Fig. 2a). The elevation of most of the Sundarbans varies from 0.5 m to 3.0 m above sea level (asl) with nearly 70 percent of the area having elevations less than 1 m asl (Siddiqi, 2001).

One-third of the area of the Sundarbans consists of rivers and streams, which act as a nursery for fish and other aquatic life, including Asia's last two remaining freshwater dolphin species – the Ganges river dolphin and Irrawaddy dolphin (Mukul et al., 2020; Khan, 2013). At least 528 species of vascular plants, 49 mammals (including the globally endangered Bengal tiger), 87 species of reptiles, 14 amphibians, 291 species of fish and 355 bird species have been recorded from the Sundarbans area (Aziz and Paul, 2015; Rahman et al., 2015; Gopal and Chauhan, 2006). The vegetation of Sundarbans is dominated by halophytic species and three mangrove species, i.e. *H. fomes*, *E. agallocha* and *Ceriops decandra*, which account for approximately 95 percent of the vegetation in the area (Fig. 2b; Ifthekar and Saenger, 2008; Biswas et al., 2007).

Among the 55 compartments in the Bangladesh Sundarbans, 17 were affected during cyclone Sidr (Akhter et al., 2008). We selected two compartments, 7 and 12B, as our study sites for the present study (Fig. 2c). They were chosen to reflect a gradient of different cyclonic damage on structural integrity of the Sundarbans forest during cyclone Sidr. Based on the assessment of Bangladesh Forest Department, compartment 7 was moderately affected, and compartment 12B was highly affected during cyclone Sidr (Akhter et al., 2008). These compartments are located in different spatial position relative to the Bay of Bengal. Compartment 7 is closer to the coast and is, therefore, offered us an ideal setting to investigate the effect of forest spatial position (i.e. proximity to the river bank/coast vs distance from the forest interior) on tree damage (Halder, 2011).

2.2. Sampling protocol and field survey

Fieldwork for this research was conducted in 2010. A systematic random sampling using the transect method was used to complete the tree inventories in our sample plots. Six transects of 15 m width were established in each of the compartments (7 and 12B) of the forest. In each of these transects, 5 square plots of each of size 15 m × 15 m, were laid out totalling 60 (5 plots × 6 transects × 2 compartments) sample plots. Some river channels and/or small creeks in both compartments 7 and 12B were selected purposively to represent the spatial variation in trees located in the forest stand. All transects were set perpendicular to the river direction guided by a hand-held compass.

In the field, we first established a transect, 10 m away from the nearest river channel. Five sample plots, at an interval of 50 m distance, were then established along each transect. After completion of one transect, we travelled further 1 km along the river channel using a hand-held Global Positioning System to establish the next transect. During the fieldwork, we also recorded site basic information such as canopy coverage, inundation type etc. We measured all *H. fomes* and *E. agallocha* individuals within the plots which have a diameter at breast height (dbh) ≥ 5 cm. In cases where trees were broken lower than at a height of dbh (i.e. 1.3 m), we measured stump diameter (sd) of trees. We also measured height of 10 trees per species following a snap sample method over a range of diameters. The degree of cyclone effect on all measured tree individual was also recorded during the time of inventory. The extent of the cyclone effect over the individual trees was assessed against the criteria set in Table 1. We used a Spherical Crown Densiometer (Manufacturer: Forestry Suppliers, USA) for the measurement of crown damage at individual tree level.

2.3. Statistical analysis

We established the following relationship to assess the functional dependency of the dbh of tree species with stump diameter (sd) of broken trees.

$$dbh = \alpha + \beta sd + \varepsilon \quad (1)$$

where sd is stump diameter, dbh is diameter at breast height, 'α' and 'β' are population constants and 'ε' is the error term.

Trees of a single plot cannot be treated as being independent repetitions. Thus, we aimed at aggregating the information regarding damage at the plot-level. The aggregation was performed in two steps. Firstly, the degree of the cyclone effect (see Table 1) was transformed to two categories, i.e. 'damaged' and 'undamaged' by binarizing the degree values of the damage. Trees with damage degree ≤ 2 were regarded as 'damaged' while trees with damage degree ≥ 3 were regarded as 'undamaged'. We performed a sensitivity analysis to adopt the most appropriate threshold level for the study (Supplementary material 1). As the proportion of degree of cyclone effect '3' is relatively small, neither the model outputs nor the graphs would change if a different threshold were used. Secondly, the mean diameter of all trees (damaged and undamaged) at breast height (dbh) and the proportion of the trees being damaged were computed species-wise on a plot-level. No weighting, e.g. by basal area, was completed in averaging the dbh and computing the damage proportion. After this procedure, 53 common plots were found with *H. fomes* and *E. agallocha*. However, each species occupied 3 plots exclusively, thus species were sharing 50 plots. As we were also interested in a species effect in damage sensitivity, a difference between the species was built in the damage proportions on the plot-level of those 50 plots where both species were present. A difference in the mean dbh of the two species on the plot-level (i.e. plot average) was also built. Both, the damage proportion difference and the dbh difference were established for *H. fomes* having positive values and for *E. agallocha* having negative values.

We used a Generalized Additive Mixed Model (GAMM) to analyse the data (Zuur et al., 2009) as estimation of regression and variance parameters, inferential test for covariates effects, confidence intervals for the mean function as well as optimal spatial predictions can be calculated within the well-founded framework of linear mixed model theory. We applied GAMM instead of GAM as our data were grouped in transects and compartments, making dependence probable. To allow for correlation between the observations and a nested data structure, GAMM is deemed appropriate. The model we applied consists of three parts, the first being the generalized linear model, the second being the additive smoother, and the third being random effects. The smoother was established to cover the effect of the distance to the riverbank which essentially is a covariate. The generalized linear part of the model included dbh on plot-average as a fixed covariate and the random factors were 'compartment' and 'transect'. The dependent variables in the model were the damage proportion for each species on plot-level and the difference in damage proportion between the two species on plot-level. The distributions of the dependent variables were observed carefully. In both species, the damage proportion on plot-level was best represented by a Poisson distribution with over dispersion. Thus, we applied the generalized approach and corrected the standard errors using a quasi-GAMM where the variance was computed by multiplying the mean

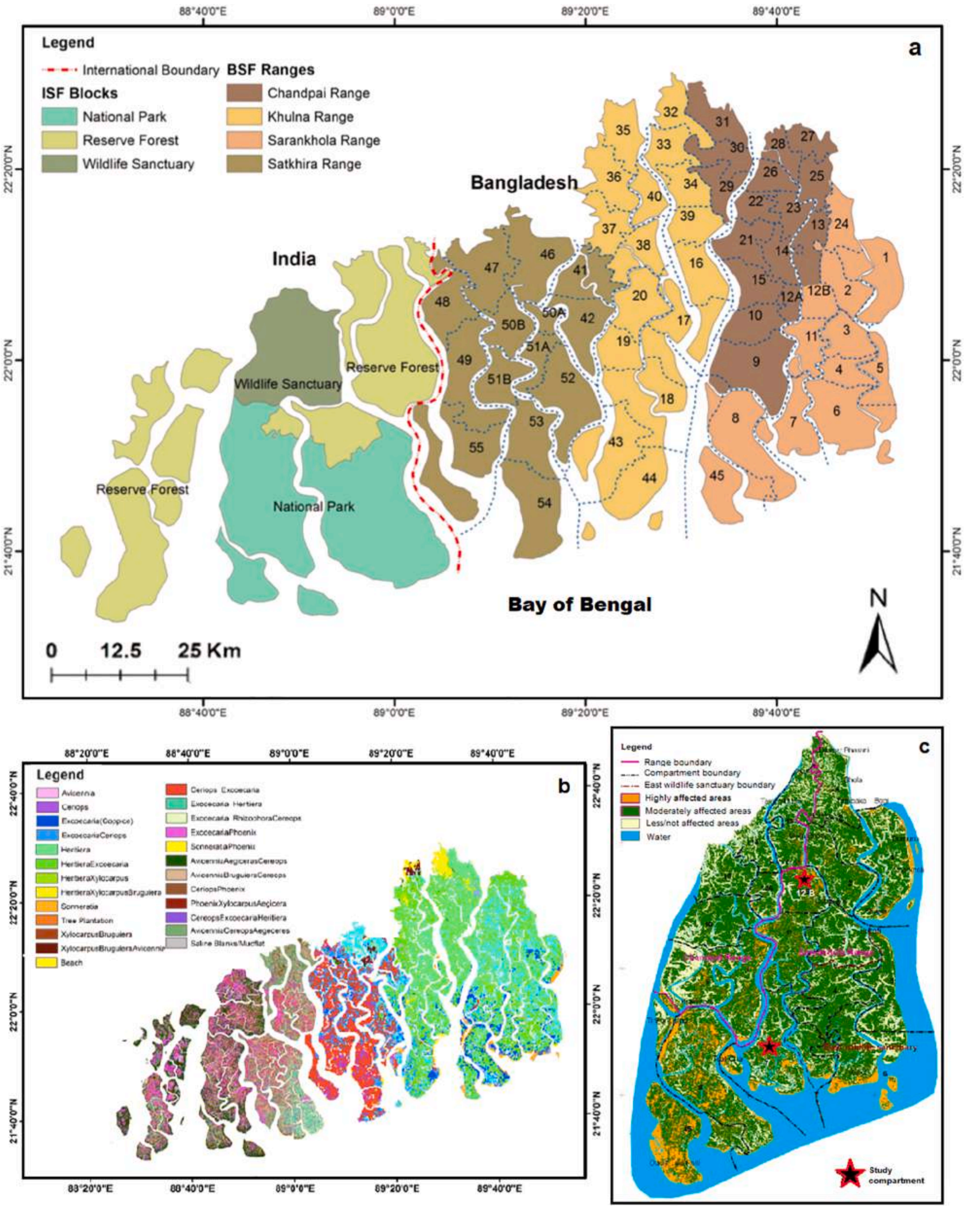

Fig. 2. Administrative (a), and vegetation (b) map of the Sundarbans, and the impact zone of cyclone Sidr in the Sundarbans with compartment 7 (moderately affected) and compartment 12B (highly affected) (c).

Table 1
Criteria used in scaling of degree of cyclone effect in our study in the Sundarbans.

Criteria	Degree of cyclone effect
Crown/stem fully broken	1
60–90% of crown damaged	2
30–60% crown damage	3
0–30% crown damage	4
0% crown damage	5

with the dispersion parameter (Zuur et al., 2009). The difference between damage proportions of the two species in a plot, however, was Gaussian distributed and thus the generalized approach was done with an identity link. Residuals of the models were checked for heteroscedasticity and spatial autocorrelation (Zuur et al., 2009). However, in no case, it was necessary to adjust the model to deviance from assumptions. From the random effects, i.e. compartment and transect, the only transect was of importance at all, being indicated by the value of standard deviation due to this random effect level.

The model formula for damage proportion as dependent variable and transect as random factor thus was:

$$\mathrm{DamProp_{ij}} = \alpha + \beta_1 \mathrm{dbh_{ij}} + f(\mathrm{X_{ij}}) + \mathrm{b_2 transect_{j+}}\varepsilon_{ij} \quad (2)$$

with 'DamProp' being the damage proportion of trees on the single plot, 'α' being the intercept, 'β_1' being the parameter of the fixed effect, i.e. dbh, '*f(X)*' being the smoother on distance to the river bank, 'b_2' being the parameter for the random effect, i.e. transect, and 'ε' being the error term.

3. Results

3.1. Damaged tree diameters differ in species and compartments

We measured dbh (and stump diameter, where applicable) for a total of 626 *H. fomes* and 499 *E. agallocha* stems within our study plots in the Sundarbans. Fig. 3 shows the dbh distributions of both species in our study plots in compartment 7 and 12B. The mean diameter was 8.68 cm and 7.01 cm respectively for *H. fomes* and *E. agallocha*. The maximum diameter for *H. fomes* and *E. agallocha* was 30 cm and 23 cm, respectively. The mean values of the coefficient of variation of dbh on the plot level were 39.1 percent for *H. fomes* and 31.9 percent for *E. agallocha*.

No common pattern in the dbh for both species (*H. fomes* and *E. agallocha*) were found in our study plots in compartment 7 and 12B in the Sundarbans. In Fig. 4, the dbh of both *H. fomes* and *E. agallocha* are plotted along a distant gradient in each compartment, where number 1 represents plot closest to the riverbank and number 5 represents the forest interior plot. In case of *H. fomes*, the diameter increased from river bank plots to the forest interior plots along the transect line. This was, however, more prevalent in compartment 12B, where the median diameter changed from about 8.2 cm to about 11 cm from the riverbank to forest interior plots. The median dbh of *E. agallocha* ranged from 7.0 to 8.0 cm in both of our compartments. In addition, *E. agallocha* always exhibits lower dbh values than that of *H. fomes* in our study plots.

3.2. Tree damage proportion of species is dbh sensitive

In the case of *H. fomes*, both the intercept and the effect of mean dbh on tree damage proportion were statistically significant at the plot level. The β estimate for the dbh (i.e. 0.160) leads to an increase of damage with increasing dbh. In case of *E. agallocha*, however, only the intercept was clearly significant while the effect of dbh was only marginally significant (p-value = 0.063). Table 2 shows the results of modelled tree damage at the plot level as a function of dbh of individual tree species.

The damage proportion in relation to mean dbh of in *H. fomes* ordered by transect number in our study plots is shown in Fig. 5. Only in transect 10, there was an anomaly detected. The relationship between the degree of cyclone damage and mean dbh for *E. agallocha* is shown in Fig. 6.

3.3. Damage proportion relative to proximity to the riverbank

The effect of the distance from the riverbank on damage proportion was significant in *H. fomes* but not significant in *E. agallocha*. The lowest damage proportion in *H. fomes* was expected to be closer to the riverbank and in more than 150 m apart from the riverbank while maximum in moderate distance from the riverbank (Fig. 7). This was, however, not the case in *E. agallocha* as there was no such pattern in damage along the transect line (Fig. 8).

The difference in the proportion of damage between *H. fomes* and *E. agallocha* at the plot level is taken as an indicator of species-level effect on damage proportion. The model leads to a significant intercept and a significant parameter of the dbh difference between the two species (Table 3). As the intercept is positive, it is clear that *H. fomes* has a larger damage proportion on plot level than in *E. agallocha* when the mean dbh of both species is same, i.e. the difference of the dbh is zero. When the dbh difference is not zero, the damage proportion difference changes proportionally between *H. fomes* and *E. agallocha* (Fig. 9).

4. Discussion

Tropical cyclones (synonymously used here for hurricanes and typhoons) are an important driver of ecosystem functioning, forest structure, diversity and functional composition (Hogan et al., 2020, 2018; Apan et al., 2017; Xi, 2015; Lin et al., 2011). In addition to the immediate disturbance effects, tropical cyclones also shape forest successional dynamics (Vandermeer and de la Cerda, 2004), species

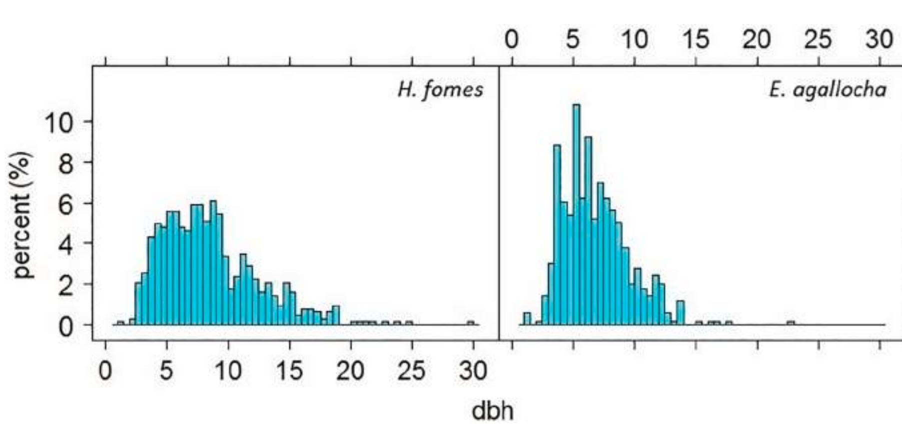

Fig. 3. Diameter at breast height (cm) of *H. fomes* and *E. agallocha* in compartment 7 and 12B in our study plots in the Sundarbans.

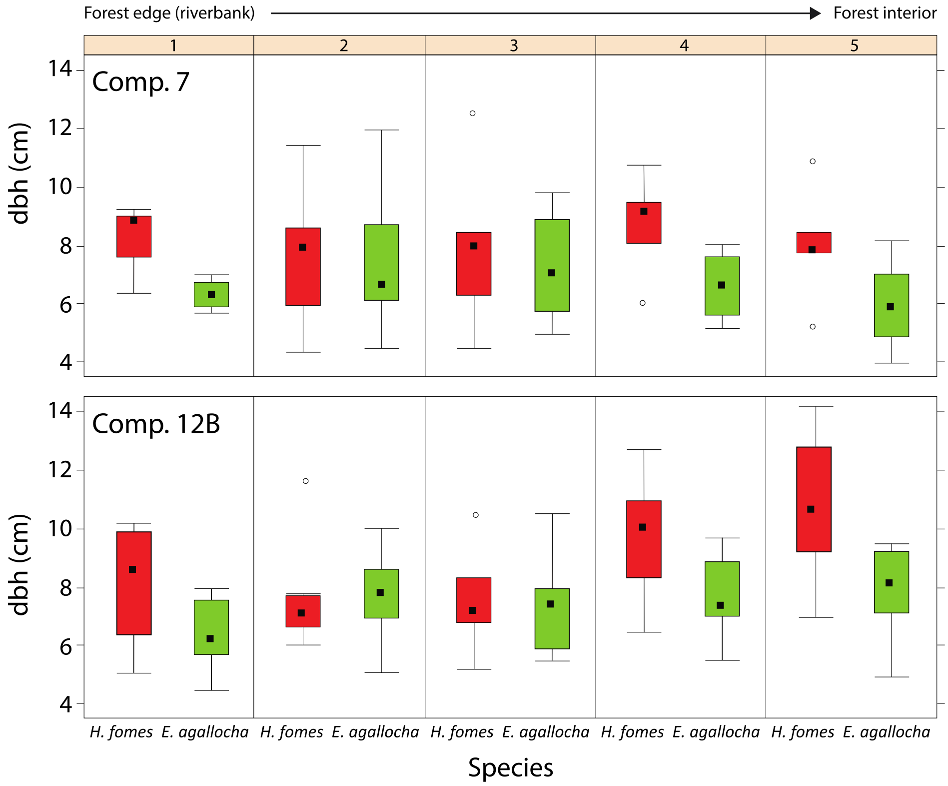

Fig. 4. Diameter at breast height (cm) of *H. fomes* and *E. agallocha* along a distant gradient in compartment 7 and 12B in our study plots in the Sundarbans. Increasing plot number represents increasing distance from the riverbank to the forest interior.

Table 2
Damage proportion in *H. fomes* and *E. agallocha* in our study plots in compartment 7 and 12B in the Sundarbans.

Species	Determinants	β estimate	Standard Error	*p* value fixed effects	*p* value of smooth terms	R^2 (adjusted)
H. fomes	Intercept	−2.969	0.373	2.19e-10	0.001	0.359
	dbh	0.161	0.038	9.39e-05		
E. agallocha	Intercept	−3.481	0.682	5.2e-06	0.118	0.057
	dbh	0.166	0.087	0.0626		

composition (Xi et al., 2008; Imbert et al., 1996), site productivity (Ross et al., 2006; Wang and Hall, 2004), carbon storage (Castillo et al., 2018, 2017; Chambers et al., 2007), functional trait dispersion (Lin et al., 2020, 2011), and nutrient recycling (Van Bloem et al., 2005) over long time scales (e.g. decades). There are several factors that influence damage during cyclones in tropical forests, such as wind speed, distance from cyclone's eye, and storm surge height (Doyle et al., 2009; Lugo, 2008; Milbrandt et al., 2006). Our understanding of the effect of cyclonic damage in tropical forest ecosystems, however, disproportionally comes from regions experiencing much lower cyclone frequency than forests that experience cyclones more frequently (Lin et al., 2011). As tropical cyclone increases in frequency and intensity with global climate change, it is also important to understand their effects on tropical tree communities which are in the frontline of such events (Hogan et al., 2018; Solomon et al., 2007.).

Our study shows how the degree of cyclonic damage varied between *H. fomes* and *E. agallocha* – the two dominant mangrove tree species in the Sundarbans. In case of *H. fomes*, a gradient of tree damage from the riverbank to forest interior was observed. There was, however, no such gradient of cyclonic damage for *E. agallocha*. The proximity to the coast as determined by compartment number in our study was not found to be important in determining damage proportion of the species studied. Our results consistent with the findings of Su et al. (2020), who observed that tree survival during cyclones is influenced by diameter and multi-stemming ability of trees in a subtropical forest in Taiwan. The phenomenon of a comparatively wind-stable forest edge combined with heavy damages within adjoining forest stand is well known (Otto, 1994). We found trees with diameters larger than 15 cm exceed the height of 30 m for both species. Thus, the height/dbh ratio of *H. fomes* and *E. agallocha* trees approximates the value of 200. The top height of trees with dbh no larger than 20 cm exceeds 35 m. Although we did not collect data on height/dbh ratios for each individual to make broad conclusions about the scale of cyclone damage in trees, it is expected that trees at the forest edge (i.e. close to riverbank) have lower height to dbh ratios than trees in the forest interior which can be responsible for differences in damage intensity of trees in plots in forest edge than in forest interior.

The species-specific susceptibility to wind damage of mangrove is a contentious issue. Ancelin et al. (2004) developed an individual tree-based mechanistic model where wind damage is predicted by sigmoidal function. Several authors (see – Baldwin et al., 2001; McCoy et al., 1996; Smith et al., 1994; Roth, 1992) have demonstrated that within a species, larger trees are more susceptible to stem breakage or blow down than smaller ones. Webb et al. (2014) found that wood density consistently and negatively affects the probability of tree species survival during catastrophic cyclone. In our study, *H fomes* has a wood density (0.89 g cm^{-3}) almost twice as high as *E. agallocha* (i.e. 0.43 g cm^{-3}). We also found significant variation in cyclonic damage between *H. fomes* and *E. agallocha* with respect to their mean dbh. In our model, damage intensity for *H. fomes* was found to be more sensitive than *E. agallocha* in both the compartment 7 and 12B when dbh of both

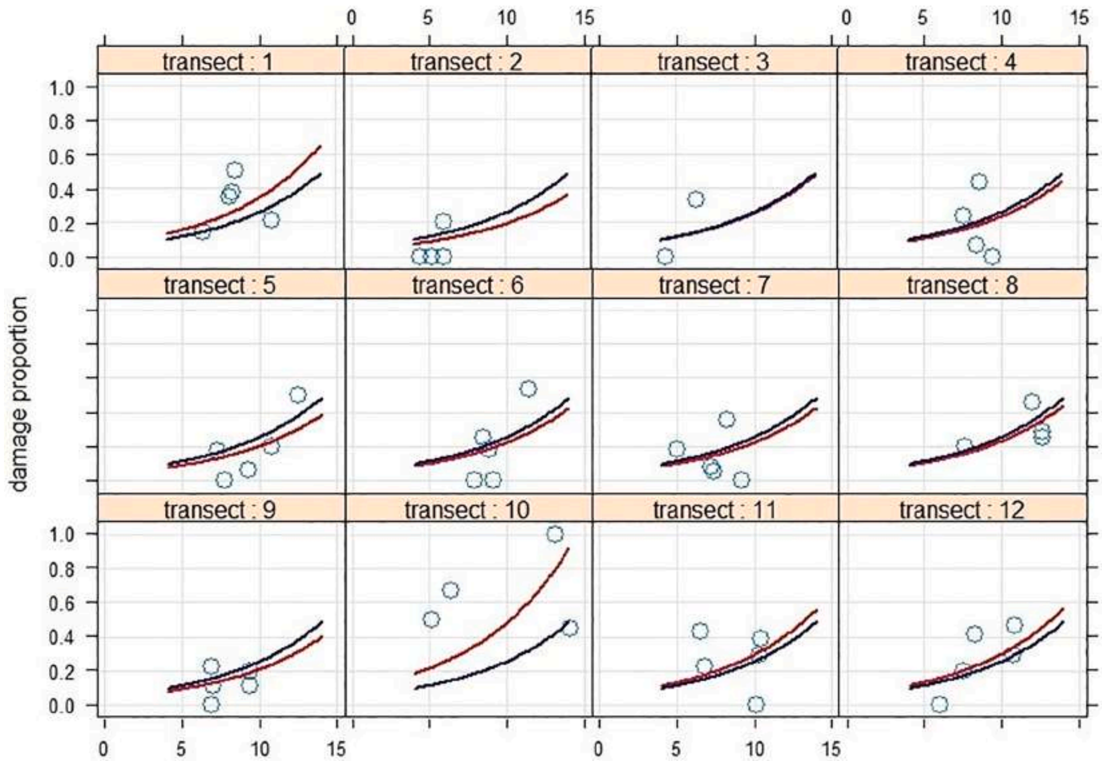

Fig. 5. Damage proportion in relation to mean dbh of the plot in *H. fomes*. The dark blue curve represents the overall model (without random effect and without the effect of distance to the riverbank) while the red curve represents the adjustment of the model in respective transects. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

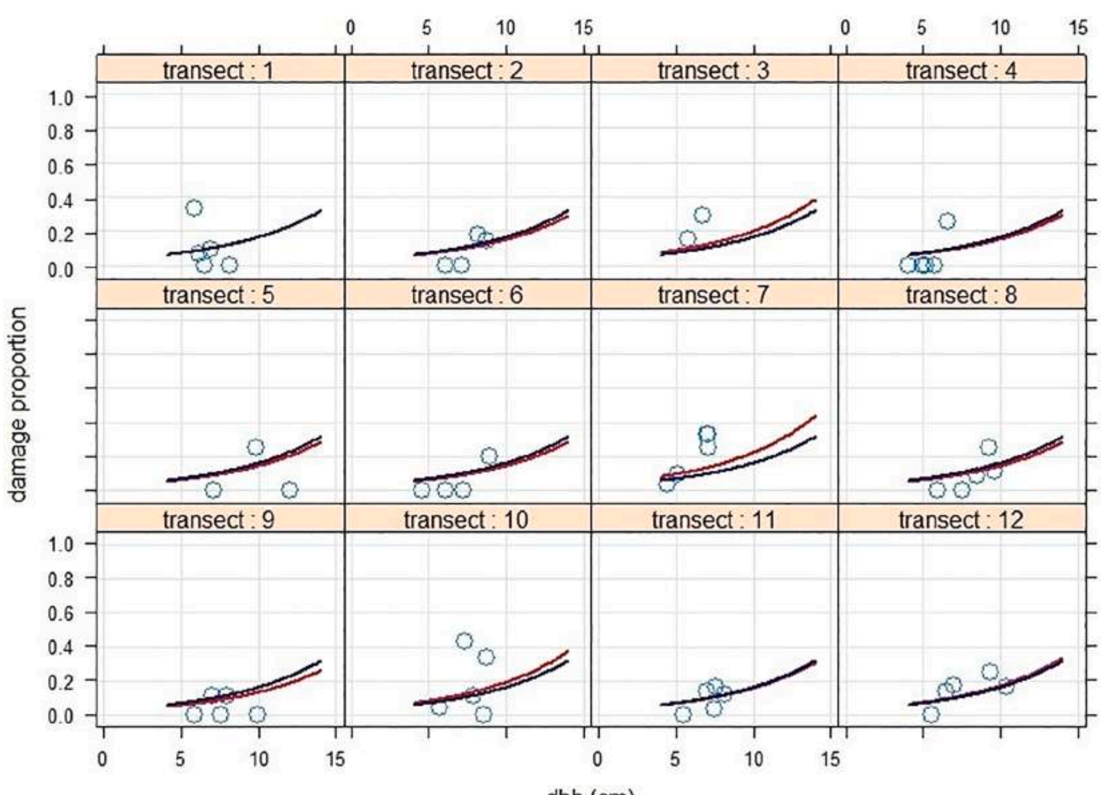

Fig. 6. Damage proportion in relation to mean dbh of the plot in *E. agallocha*. The dark blue curve represents the overall model (without random effect and without the effect of distance to the riverbank) while the red curve represents the adjustment of the model in respective transects. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

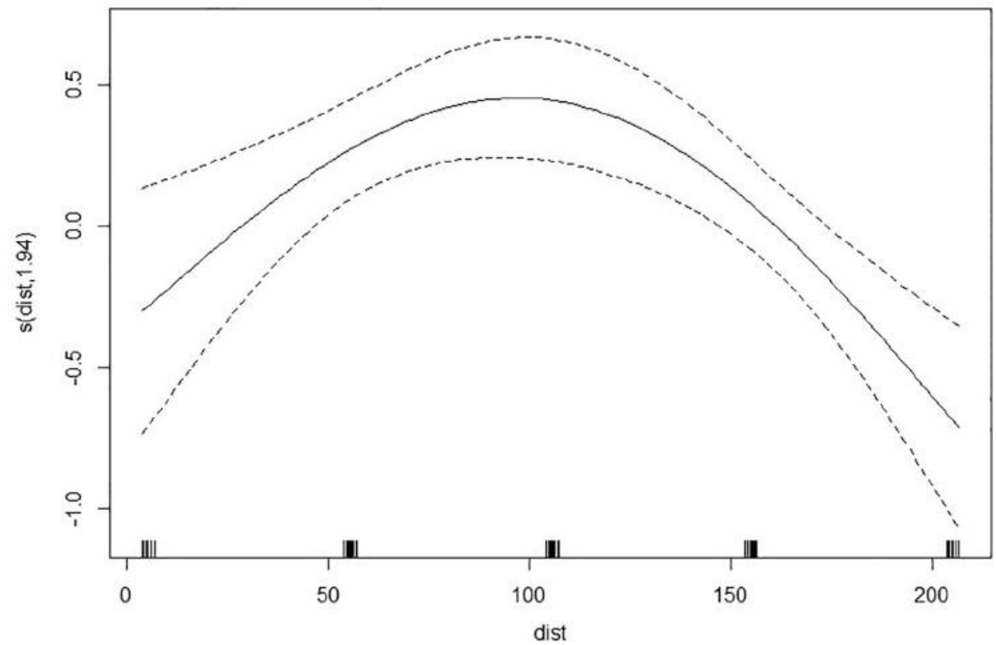

Fig. 7. Damage proportion in *H. fomes* in relation to distance from the riverbank. The dotted lines represent the estimated smoothing curve and point-wise 95% confidence bands. The horizontal axis represents distance from riverbank to 50 m, 100 m, 150 m, and 200 m consecutively and the vertical axis represent the level of damage.

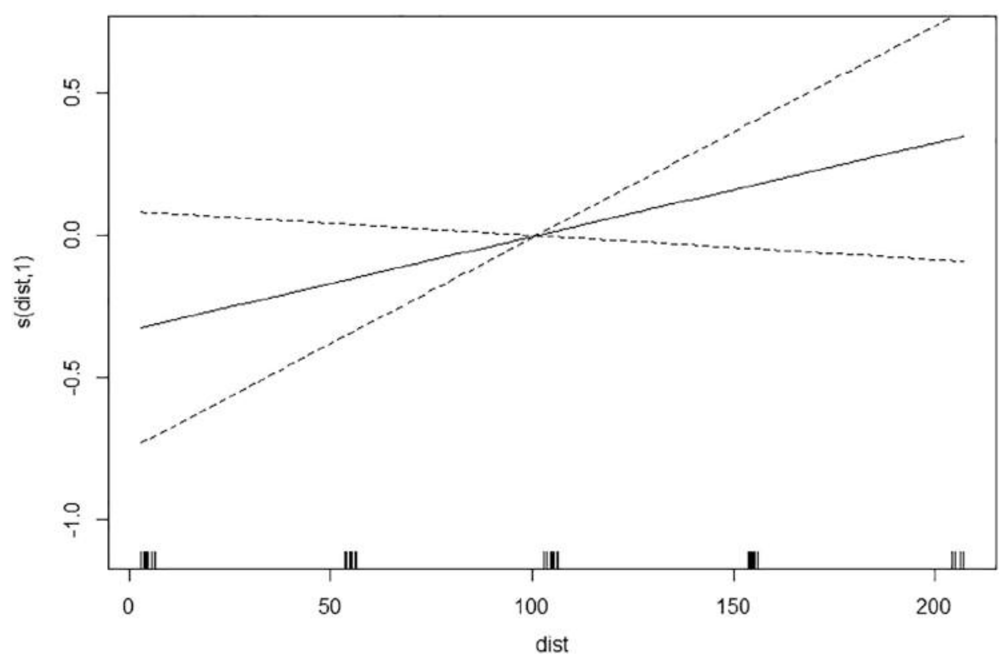

Fig. 8. Damage proportion in *E. agallocha* in relation to distance from the riverbank. The dotted lines represent the estimated smoothing curve and point-wise 95% confidence bands. The horizontal axis represents distance from riverbank to 50 m, 100 m, 150 m, and 200 m consecutively and the vertical axis represent the level of damage.

Table 3
Intercept and parameter of the dbh difference between *H. fomes* and *E. agallocha*.

	β estimate	Standard Error	*p* value of fixed effect	*p* value of smooth terms	R^2 (adjusted)
Intercept	0.088	0.038	0.025	0.003	0.228
dbh	0.028	0.008	0.004	–	–

species were of similar size. Webb et al. (2014) found that species differed widely in their resistance during cyclone events in American Samoa and several species traits influenced the probability of species survival during such events. John et al. (2001), for instance, found that *Rhizophora* sp. are more resistant to hurricane damage than *Avicennia* sp., although, Sherman et al. (2001) and Smith et al. (2009) observed no difference in wind damage in both species which may be attributed to differences in site characteristics including stand condition (Imbert, 2018).

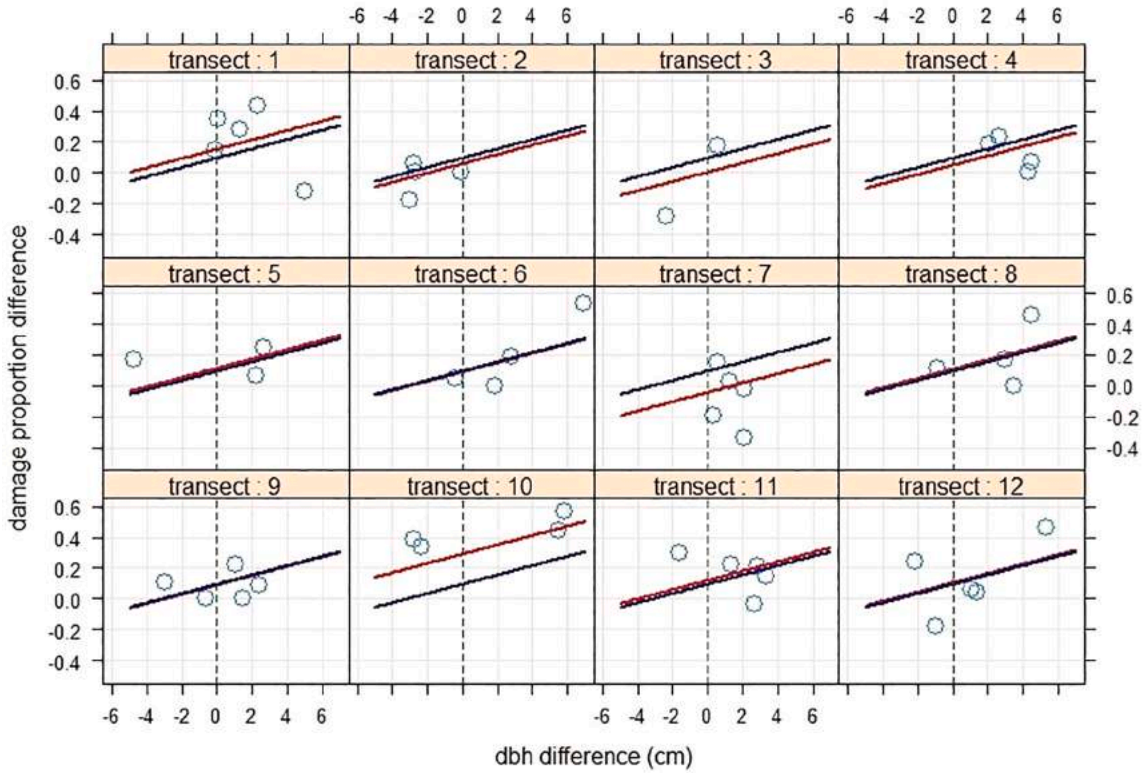

Fig. 9. Differences in damage proportion in relation to dbh difference between *H. fomes* and *E. agallocha*. The dark blue curve represents the overall model (without random effect and without the effect of distance to the riverbank) while the red curve represents the adjustment of the model in respective transects. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Mangroves vary in their recovery time from years to decades, from cyclone disturbances based on a scale of damages (Piou et al., 2006; Putz and Chan, 1986; Ball, 1980). Mangrove species also have different tolerance and recovery abilities in response to high cyclonic intensities (Hutchings and Saenger, 1987). Forest stand structures, e.g. tree density, species, and tree dimension can be devastated by high wind speed (Karim et al., 2020; Mason, 2002), whereas with low wind speed only some tree species might be broken or uprooted indicating significant variability in tolerance capacity throughout the forest (Chirici et al., 2018). Stand structure variation encountered a variable level of susceptibility to wind damages (Mason, 2002; Gardiner and Quine, 2000), and differences among trees show individual behavior (Gardiner et al., 2000). The way mangroves respond within time scales and in patterns after cyclone disturbances are similar to other tropical forests (Uddin et al., 2013; Chazdon, 2003, Sheil and Burslem, 2003). Sherman et al. (2001) found that mangrove recovery is mostly facilitated by adjacent forest propagules that advance natural regeneration after such disturbances. The most direct effects of cyclonic storms on mangroves are the damage of branches, broken crown, uprooting, and defoliation of trees (Harun-or-Rashid et al., 2009). Poor development of taproot systems of mangroves also imparts its susceptibility to wind damage (Hutchings and Saenger, 1987).

Smith et al. (1994) found forest stand size also as an important factor in the severity of storm damage. Instantaneous mechanical stress within hurricane conditions transfers energy from the crown to the bole and to the tree root system (Drouineau et al., 2000). Individual stems may bend, break, tip (full or partial uprooting), or remains standing with the root system intact or broken loose from soil contact. Predicting damage is difficult because of variation within the windfall due to distance and position relative to the centre of the storm, wind speed, direction, and duration of gusts (Stanturf et al., 2007). Intensity of branch loss and defoliation decreased exponentially with increasing distance from the storm track (Doyle et al., 1995), and trees are likely to fall if the breaking stress of the stem exceeds critical value for stem breakage (Petty and Swain, 1985) in absence of support from neighboring trees.

In even-aged stands, increasing stem diameter correlates with a decrease in slenderness ratio and with an increase in the critical bending moment. Thus, as a result, it enhances the critical wind speed for breakage than overturning (Ancelin et al., 2004b). Likewise, tree height seems to be also relevant in predicting storm damage (Locatelli et al., 2017). Besides the sheer height effect, the effect of an increasing damage probability with decreasing tapering or increasing height/dbh ratio was described in many investigations (see –Gardiner et al., 1997; Peltola and Kellomäki, 1993). Schütz et al. (2006), however, reported a negligible influence of height/dbh ratio whereas Peltola and Kellomäki (1993) reported an increase in damage probability with decreasing tapering of tree species which is also consistent with a model developed by Schmidt et al. (2010).

Mangrove canopy height globally related to cyclone frequency (Simard et al., 2019). Ruck et al. (2012) in their experiment found that cyclone effect in forest extends to a distance to the edge of up to a length of about eight tree heights. As the edge trees in our samples have an average diameter of less than 10 cm, which corresponds to an average of approximate tree height of 20 m, we derived a distance of 160 m into the forest which is most vulnerable to cyclonic damage. In our model, we, however, did not consider the exposition of the forest edge to the main cyclone power into account. Stanturf et al. (2007) in their study found that tree damage was most likely along all windward edges in severely damaged areas of a forest, but for low damaged area, tree height was not found to be an important factor rather than tree spacing. In our study, we had limitations of modelling for wind damage probability with respect to tree height, although, we found species wise variation of wind damage which was prominent at the riverbank or edge of the forest stand.

5. Conclusion

We found that cyclonic damage in mangroves is sensitive to species and dbh and largely depends on site factors. In the Sundarbans, *H. fomes* showed more vulnerability to wind damage with increasing mean dbh than *E. agallocha*. As *H. fomes* is the dominant tree species in the Sundarbans, we suggest silvicultural treatments, such as increasing the tapering of crown or decreasing height/dbh ratio of mangrove species in order to reduce the cyclonic damage. *E. agallocha* was found to be less susceptible to wind damage, thus it may possible to enhance its development in mixed stands with increasing tapering which is particularly important at the sites located in riverbanks and forest edges. This may also act as a barrier to the interior part of the forest, where the more valuable *H. fomes* can then be grown in more sheltered conditions.

Further investigation, however, is necessary on the prospect of salvage operations that may improve forest productivity by manipulating physical and mechanistic properties of tree species, thereby their responses to cyclonic damage. Future studies should also emphasise spatial patterns in cyclonic damage from the coast to the inland in respect to variation in forest composition and structure. Our findings have implications for forest managers in improving the management of mangroves both in Sundarbans and globally, which are frequently encountered cyclones under a rapidly changing climate.

CRediT authorship contribution statement

Nirmol Kumar Halder: Conceptualization, Methodology, Investigation, Data curation, Formal analysis, Writing - original draft, Project administration. **Andrew Merchant:** Methodology, Writing - review & editing. **Khaled Misbahuzzaman:** Methodology, Writing - review & editing. **Sven Wagner:** Methodology, Supervision, Investigation, Formal analysis, Writing - review & editing. **Sharif A. Mukul:** Conceptualization, Methodology, Investigation, Formal analysis, Writing - original draft.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This research was supported by a grant from the German Academic Exchange Service (DAAD) to the first author - Dr. Nirmol Kumar Halder. The authors would like to thank Dr. rer. silv. Hubertus Pohris (Technische Universität Dresden, Germany), Mr. Zaheer Iqbal, and Mr. Mihir Kumar Doe (Bangladesh Forest Department). The valuable comments by Dr. J. Aaaron Hogan (Florida International University, USA) substantially improved the quality of the manuscript. Thanks also due to all staff member of Khulna Forest Circle who provided tremendous assistance during fieldwork in the Sundarbans. Dr. Sharif A. Mukul was supported by a grant from the British Ecological Society (Grant no. LRB20/1006).

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.foreco.2021.119117.

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