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Tropical Ecology **57**(2): 361-368, 2016 ISSN 0564-3295

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Spatio-temporal changes in fringe mangrove extent in Pondicherry, India after two phenomenal perturbations: tsunami and cyclone Thane

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Abstract: Growing pressures on mangroves throughout the world, highlight the need for studies of vegetation across spatio-temporal scales even in relict patches for ecosystem conservation. Mangroves experience human pressure due to coastal development and are also subjected to environmental stress such as cyclones, tsunami, floods, and sea-level rise, often taking decades to recover from these stresses. We estimated changes in mangrove vegetation in the Ariankuppam estuary on the southeastern coast of peninsular India after two phenomenal perturbations, the 2004 tsunami and 2011 cyclone Thane. We compared land cover maps of mangroves from 2005, 2010, and 2011 with 2004 mangrove vegetation maps to detect change in areal extent of mangrove zones. We inventoried all stems ≥ 10 cm gbh in 34 quadrats (5 m × 5 m) prior to the 2011 cyclone, immediately following the cyclone, and eighteen months later to document damages and recovery. The site harbours 2988 trees ha^{-1} for stems ≥ 10 cm gbh. We found four distinct mangrove zones in 2005 (15.54 ha), and five distinct mangrove zones in 2010 (41.73 ha) and 2011 (40.65 ha). The tsunami and subsequent activities such as dragging the boats swept ashore and dredging resulted in 48 % loss of mangroves. The increase in mangrove area observed during 2010 and 2011 was due to the recovery potential of *Avicennia* and restoration programs. Cyclonic impact and recovery status inventories revealed that among the different zones, the monodominant *Avicennia* zone experienced severe damage and the mixed *Avicennia* zone showed slow recovery. The full impacts on the ecosystem from extreme stochastic events; however, can only be determined with long-term monitoring.

Key words: *Avicennia*, disturbance, dynamics, monodominance, recovery, tree density, vegetation cover.

Handling Editor: Donna Marie Bilkovic

Mangroves, a unique littoral plant community, are distributed in the intertidal region of tropical and subtropical coasts. Most of these areas experience heavy human pressure due to urban and industrial development along coastlines and are also subjected to environmental stress such as cyclones, storms, tsunami, floods, and sea-level rise, often taking decades to recover from these

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stresses. Since 1980, mangrove loss globally was estimated to be between 19 % and 35 % (Alongi 2002; FAO 2007; Valiela *et al.* 2001) and if the loss continues at this rate mangroves could be extinct in 100 years (Duke *et al.* 2007; Polidoro *et al.* 2010). On the contrary, the Forest Survey of India (FSI 2011) reported that there has been an increase in mangrove cover from 4046 to 4662.56 km^2 across the country during the period of 1987-2011. This increase was largely attributed to plantations and restoration projects in the Gujarat state, which harboured 427 km^2 of mangrove area in 1987 and 1058 km^2 in 2011. Chellamani *et al.* (2014) assessed the health status of Indian mangrove using multi-temporal remote sensing data (1999-2008). This study demonstrated that the overall health of Indian mangrove ecosystems has improved over the past decade. Puducherry state (formerly Pondicherry) reportedly possessed approximately 1 km^2 of mangroves in the Godavari delta of the Yanam district (FSI 2011). The other three districts of Puducherry viz., Mahé in the west coast region, Karaikal and Pondicherry districts in the eastern coastal region also harbour mangroves as relict fringe vegetation (Balachandran *et al.* 2009), but those regions were not included in the FSI (2011) due to their occurrence as small, fragmented and remnant patches.

Given the accelerating rate of degradation and destruction of the mangroves throughout the world, there is an urgent need to assess the status of all mangroves including remnant patches. This study was conducted on a patchy mangrove forest, distributed along the coastline of Ariankuppam estuary (Fig. 1) in the Pondicherry district on the southeastern coast of peninsular India.

Previous studies have described the presence of considerable patches of mangrove vegetation in the Ariankuppam estuary of Pondicherry district (Saravanan 2004; Saravanan *et al.* 2008), extending ca. 168 ha in the region, which is experiencing sewage pollution threats (Satheeshkumar & Khan 2009; Satheeshkumar *et al.* 2012a). The vegetation, in particular the *Rhizophora* species patches act as protective force against cyclone surges (Satheeshkumar *et al.* 2012b). Substantial attempts were also made to plant mangrove species of *Rhizophora* and *Avicinnia* in the Pondicherry since 1995 - 96 by Government and Non-Governmental organizations. A growth study on the planted seedling of *Rhizophora apiculata* Blume in the region showed that seedlings were successfully established with an average growth rate of 3.6 cm $month^{-1}$ (Kathiresan *et al.* 2000). This growth rate was relatively lower for the species (due to the degraded nature of the site) as compared to other inventories in the nearby sites: 6.3 cm $month^{-1}$ in Pitchavaram (Kathiresan *et al.* 1994) and 9.83 cm $month^{-1}$ in Vellar (Kathiresan *et al.* 1996). Floral and faunal diversity of the region have also been explored (Balachandran *et al.* 2009; Saravanan *et al.* 2008). Species such as *Acanthus ebracteatus* Vahl, *Acanthus ilicifolius* L., *Avicennia marina* (Forssk.) Vierh., *Avicennia officinalis* L., *Bruguiera cylinderica* (L.) Blume, *B. gymnorhiza* (L.) Lam., *Derris trifoliata* Lour., *Excoecaria agallocha* L., *Rhizophora apiculata* Blume, and *R. mucronata* Lam. were listed among the true mangrove species. Saravanan *et al.* (2008) recorded a total of 80 macrofaunal species, including 39 species of fishes, 5 penaeid prawns, 9 brachyuran crabs, 9 gastropods, 4 bivalves, and 14 birds in the study area. Recently, Kumar & Khan (2013) enumerated 76 invertebrate taxa including 35 molluscs (16 bivalves and 21 gastropods), 22 crustaceans, 7 amphipods, 6 polychaetes, 3 barnacles, and an oligochaete in four stations in the region. The major disturbances of the vegetation during the study period include dredging in the inner channel and mouth portion of the estuary (for easy navigability of fishing vessels) and bridge construction in the western part of the study area. The climate of Pondicherry region is humid and tropical. The mean monthly temperature ranges from 22 °C (between December and January) to 33 °C (May and June). The average annual rainfall in Pondicherry is about 1459 mm for the period between 2001 and 2011. The northeast monsoon contributes the majority of annual rainfall, which lasts between October and December.

This study reports the changes in vegetation after two phenomenal perturbations viz., the 2004 tsunami and 2011 cyclone Thane. On December 26, 2004, one of the largest seismic events in the last four decades occurred off the coast of Sumatra, which triggered tsunami waves. Initial post-impact studies revealed that tsunami run-up heights along the east coast of India varied between 2.5 and 5.2 m (Chadha *et al.* 2005) and caused damage to the ecology and biodiversity of coral reefs, mangroves, seagrass beds, and other coastal vegetation in the region (Alongi 2008; Chatenoux & Peduzzi 2007; Porwal *et al.* 2012; Ramachandran *et al.* 2005). Preliminary studies also suggested that mangrove forests offered significant protection to coastal communities and saved human lives (Chadha *et al.* 2005; Chang *et al.* 2006; Danielsen *et al.* 2005; Kathiresan & Rajendran 2005; Vermaat

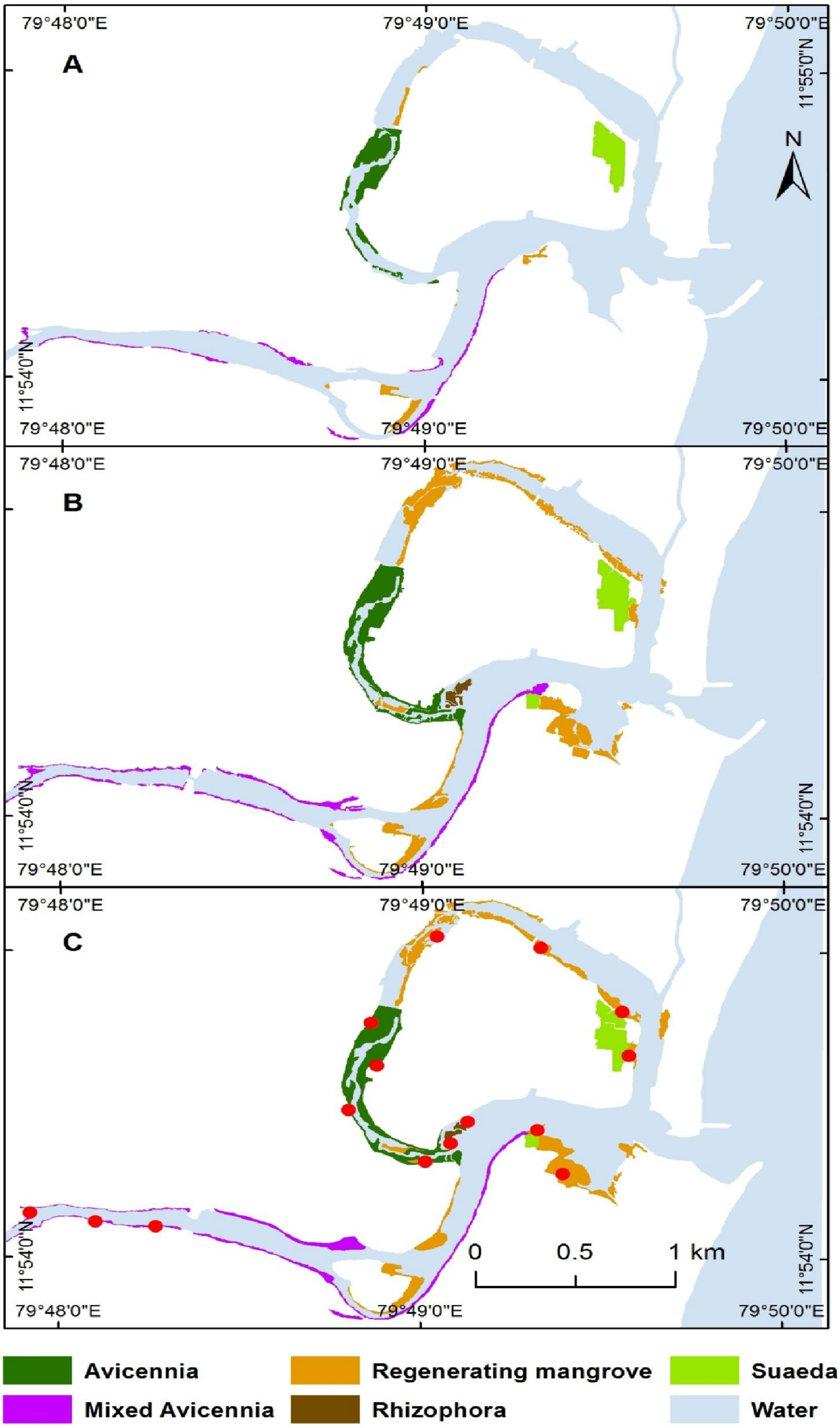

Fig. 1. A, B, C. Mangrove vegetation cover by zone for the year 2005 (A), 2010 (B) and 2011 (C) in Ariankuppam estuary of Pondicherry, India. Sampling locations are indicated in Fig. 1C.

& Thanpanya 2006). However, subsequent studies found no significant effect of the presence or absence of mangroves on human death toll (Cochard *et al*. 2008; Kerr & Baird 2007; Kerr *et al*. 2006). The rapid assessment of the tsunami impact on the mangroves revealed severe damage, ranging from broken and uprooted trees (UNEP 2005) to death due to prolonged inundation as in the case of *Rhizophora* in the South Andaman (Roy & Krishnan 2005). On December 30, 2011, a very severe cyclonic storm Thane hit the coastal region of south India between Cuddalore and Pondicherry with a wind speed of 120 - 140 km h^{-1}. In general, the high wind velocity of a cyclone can cause damage from complete defoliation to snapping of the main stem or branches (taller trees received more damage than trees in the sheltered sub-canopy layers), and occasional uprooting of trees (Baldwin *et al*. 2001; Ross *et al*. 2006; Smith *et al*. 1994; Ward *et al*. 2006; Woodroffe & Grime 1999).

A quantitative ecological inventory of the mangrove vegetation was carried out in October 2011 (just two months prior to cyclone Thane). During pre-cyclone sampling, we inventoried all stems ≥ 10 cm gbh (girth at breast height) in 34 quadrats (5 m × 5 m) installed randomly in 15 sampling locations (Fig. 1C) in the accessible region of the fringing vegetation. We laid between one to three quadrats at each sampling location. Tree height was measured using a Leica Disto D8 laser range finder. The quadrats were revisited a week after the cyclone Thane hit the area to assess the damages, and 18 months later in June - July 2013 to determine the recovery status. During post-cyclonic assessment, trees were categorized as snapped, uprooted, lost (95 % of its branches), slanting/leaning, or showing no damage.

We calculated the area of mangroves and other land uses using multitemporal high resolution satellite images obtained from Google Earth™ for 2005 (dated 31-01-2005), 2010 (22-03-2010), and 2011 (18-07-2011). We used a mangrove vegetation map from 2004 to represent reference conditions (Saravanan 2004). We collected the ground reference data using Trimble Juno SB GPS to guide the classification. The images were subjected to geometric correction employing ArcGIS software (RMS error 0.0032) based on ground control points (GCP). The projection applied in this study was World Geographic coordinate system (WGS) 1984. Universal Transverse Mercator (UTM) Projection Zone 44N was adopted for area calculation. We used permanent structures such as road crossings, bridges, and the other significant features for ground control points. Visual interpretation was used to determine mangrove boundaries. We classified seven categories of land use, which includes five distinct mangrove and mangrove associated vegetation zones (based on the composing species), other land uses, and water bodies. Following the classification, the land use/cover maps of 2005, 2010, and 2011 were overlaid to detect the change in areal extent of mangrove zones.

We estimated a tree density of 2988 stems ha^{-1} for stems ≥ 10 cm gbh based on the quantitative inventory during 2011. The estimated tree density was higher than the previous estimate of 1654-2036 stems ha^{-1} in the same region for the two sampling sites, which was based on the point-centred quarter method (Saravanan 2004). This difference in tree density may be due to the different sampling methods and/or the effect of consistent reforestation program and the regeneration potential of the species. The estimated tree density for stems ≥ 20 cm gbh was 1548 in our study area, which is moderate when compared to 832 to 1900 stems ha^{-1} encountered in Kachchh mangroves, Gujarat (Thivakaran *et al*. 2003).

We recognized four (in 2005) and five (in 2010 and 2011) distinct zones of mangrove and mangrove associates based on species dominance both in terms of quantitative (those species that had more than 90 % of tree density within the sampling quadrats) and qualitative surveys conducted across the forest, and the vegetation heights (with reference to 2004 mangrove vegetation map; Saravanan 2004) along the Ariankuppam estuary (Fig. 1; Table 1). The first and predominant zone consisted of young regenerating mangroves and accounted for 43 % of the total mangrove area in 2011. Characteristically, this zone was dominated by short-statured trees (ca. 3 m tall) particularly by *Avicennia marina* and rarely intermingled with tree clumps of *A. officinalis*, *Bruguiera cylinderica,* and *R. mucronata*. The second was the *Avicennia* zone, which harboured luxuriant vegetation with dense canopy and taller trees (ca. 10 m in height) of monodominant vegetation of *A. marina*. It covered ca. 26 % of the total mangrove area. Mixed *Avicennia* formed the third zone that harboured relatively medium sized trees of ca. 6 m tall, and occupied 17 % of the mangrove area. This zone was dominated by *A. marina* among the mangrove species, and largely intermixed with the other tree species belonging to mangrove associates and rarely with trees of *R. apiculata*, *R. mucronata*, and *B. cylinderica*. The fourth was the *Suaeda*

Table 1. Mangrove vegetation zones with composing species and their areal extent (in ha) on the fringe of Ariankuppam estuary in the Pondicherry in the years 2005, 2010, and 2011. Relative impact levels and recovery from cyclone Thane for each zone were assessed immediately following the cyclone in 2011 and in 2013.

Zone and species	Canopy height (m)	Area (ha)			Cyclone Thane effect				Recovery through coppice
		2005	2010	2011	Impact level	Trunk snapped %	Major branch loss %	Uprooted %	
Avicennia zone *A. marina*	10	5.98	10.84	10.54	Severe	72.0	6.8	4.6	Good
Mixed *Avicennia* zone *A. marina* *B. cylinderica* *R. apiculata* *R. mucronata*	6	3.18	7.18	7.08	Patchy	18.7	24.0	-	Poor
Regenerating mangrove zone *A. marina* *A. officinalis* *B. cylinderica* *R. Mucronata*	3	2.26	17.56	17.43	Minor and patchy	-	13.0	-	Good
Rhizophora zone *R. apiculata* *R. mucronata*	6	-	0.98	0.70	Meagre and intact	-	-	-	-
Suaeda zone *S. maritima* *S. monoica*	< 1	4.11	5.18	4.90	Meagre and intact	-	-	-	-
Total		15.53	41.74	40.65					

zone, which occupied 12 % of the total area and was comprised of *S. maritima* (L.) Dumort. and *S. monoica* Forssk. ex J.Gmelin. The fifth zone was made up of pure stands of *Rhizophora*, occupied just 2 % of the total area, and consisted of *R. apiculata* and *R. mucronata*.

Table 1 summarizes the areal extent of each zone during 2005, 2010, and 2011. Our study revealed that the area of mangrove and mangrove associated vegetation of the study site was 15.54 ha, 41.73 ha, and 40.65 ha in 2005, 2010, and 2011, respectively (Fig. 1). Previously Saravanan (2004) assessed the vegetation in the same region and found ca. 30 hectares as mangrove and mangrove associated vegetation. We estimated the lowest areal extent of the vegetation in 2005 which could be attributed to the tsunami impact (during 26th December 2004) and subsequent activities of dredging and dragging the boats swept ashore, which destroyed *Rhizophora* zone completely, wherein the existence of *Rhizophora* was reported by the earlier study (Saravanan 2004). The available data on mangrove damage and loss in tsunami-affected regions of Asia revealed that total mangrove area remained unchanged or gained a small percentage in India and Bangladesh, though the study did not map the mangrove patches smaller than the 1 ha area (Giri *et al.* 2008). Alongi (2008) reviewed the degree of resilience of mangrove forests to tsunami and found that only a modest percentage of forests was damaged or killed by the tsunami, and in most cases the impact was patchy due to the differences in stand location and angle of impact (Roy & Krishnan 2005).

The greater areal extent of mangrove vegetation during 2010 and 2011 could be due to the recovery potential of *Avicennia* as a typical pioneer species (known for coppice or resprout from cut boles and main branches) in addition to reforestation efforts. Clarke & Myerscough (1993) and Clarke & Allaway (1993) reviewed the regeneration of *Avicennia* in south-eastern Australia and suggested that at the initial seedling establishment stage most sites within intertidal limits are suitable for *Avicennia* (because establishment is independent of resources) and in contrast, survival after the post-cotyledonary phase appears to be largely resource-dependent. Kathiresan (2002) comprehensively studied the causes of natural degradation of mangroves across 30 different sites in the Pichavaram mangrove and revealed that degradation was due to high salinity, low levels of available nutrients, and poor microbial counts in the soil substrates. Our study area, as a typical estuarine system, receives a continuous supply of sediment resources (nutrients) along with domestic waste (Satheeshkumar & Khan 2009; Satheeshkumar *et al.* 2012a; Satheeshkumar & Senthilkumar 2011) and has relatively low salinity due to the monsoon runoff, which could be collectively contributing to the niche support, growth, further colonization of species, and increase in the areal extent of the vegetation.

All the five zones experienced loss in area between the year 2010 and 2011 (Table 1). By zone, areal loss varied between 0.10 ha (in mixed *Avicennia* zone) to 0.30 ha (*Avicennia* zone) with a total of 1.09 ha mangrove and its associates. Mostly, this loss in area was observed at the edges of each zone. At the same time, the areal extent of water was also higher in 2011 (237.65 ha in the study area) when compared to the 2010 image (233.99 ha). This change in water level could possibly be due to the differences in the tidal cycle because the 2011 imagery was obtained during the high tide period. We observed a loss of 0.057 ha area in the mixed *Avicennia* zone due to the bridge construction in the western side of the study region during the period.

All the inventoried quadrats and each defined zone were revisited a week after the cyclone Thane hit in 2011 to assess impact. Almost all trees in each zone were severely defoliated by the cyclone, including the understory plants, as also previously reported by Imbert *et al.* (1996). Among the five distinct zones, the monodominant *Avicennia* zone had severe tree damage (Table 1). Of the inventoried trees in the *Avicennia* zone, 72 % of trees were snapped off, 4.6 % were uprooted, 6.8 % had broken branches, and 1.3 % were slanting. All the other zones showed loss of twigs and defoliation with occasional breakage of main branches and leaning of trees except the *Rhizophora* zone, which was intact. This clearly illustrates that the impact of a cyclone will be greater for the taller vegetation, which is similar to the hurricane damage assessed in a mangrove forest of Guadeloupe wherein stem density of taller forests decreased by 78 %, while the dwarf type decreased by 26 % (Imbert *et al.* 1996). Subsequent investigation on the recovery status of each mangrove zone after cyclone Thane revealed that the monodominant *Avicennia* zone and regenerating mangrove zone showed higher recovery due to the profusely coppicing feature of *Avicennia marina*. The mixed *Avicennia* zone showed poor recovery whereas *Rhizophora* and *Suaeda* zones were intact (Table 1). Moreover, the death of damaged trees could have occurred several days after the cyclone hit. The full impact on the ecosystem of such stochastic events (cyclone and tsunami); however, can only be determined with long-term monitoring. Understanding the ecological effects of storm disturbance is critical because cyclonic activity is expected to increase globally, which could form an important selective factor in shaping forests by causing substantial damage to forests and species assemblages. Long-term monitoring would provide us the information crucial for conservation of the ecosystem and to build an effective bio-shield defence against pressures such as cyclones and tsunamis.

Acknowledgements

We thank A. Dharanidharan for the assistance during field works, S. Muthuramkumar for comments on early drafts of this manuscript, two anonymous reviewers and Dr. Donna Marie Bilkovic for their critical comments and constructive suggestions.

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(Received on 07.12.2013 and accepted after revisions, on 13.05.2014)