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Secondary Ecological Succession of Mangrove in the 2004 Tsunami Created Wetlands of South Andaman, India

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Abstract

Andaman and Nicobar Islands (ANI's) being situated in the Tropical zone is the cradle of multi-disasters viz., cyclones, floods, droughts, land degradation, runoff, soil erosion, shallow landslides, epidemics, earthquakes, volcanism, tsunami and storm surges. Mangroves are one of the first visible reciprocators above land and sea surface to cyclonic storms, storm surges, and tsunamis among the coastal wetlands. The Indian Ocean 2004 tsunami was denoted as one of the most catastrophic ever recorded in humankind's recent history. A mega-earthquake of Magnitude (9.3) near Indonesia ruptured the Andaman-Sunda plate triggered this tsunami. Physical fury, subsidence, upliftment, and prolonged water logging resulted in the massive loss of mangrove vegetation. A decade and half years after the 2004 tsunami, a study was initiated to assess the secondary ecological succession of mangrove in Tsunami Created Wetlands (TCWs) of south Andaman using Landsat satellite data products. Since natural ecological succession is a rather slow process and demands isotope techniques to establish a sequence of events succession. However, secondary ecological succession occurs in a short frame of time after any catastrophic event like a tsunami exemplifying nature's resilience. Band-5 (before tsunami, 2003) and Band-6 (after tsunami, 2018) of Landsat 7 and Landsat-8 satellite respectively were harnessed to delineate mangrove patches and TCWs in the focus area using ArcMap 10.5, Geographic Information Systems (GIS) software. From the study, it was understood that *Fimbristylis littoralis* is the pioneering key-stone plant followed by *Acrostichum aureum* and *Acanthus ilicifolius* facilitating *Avicennia spp/Rhizophora spp* for ecological succession in the TCWs.

Keywords: natural disasters, Landsat (7 & 8), satellite image, Short Wave Infra-Red, GIS (Geographic Information Systems), fluvial influx, mangrove biodiversity

1. Introduction

A befitting example of the interaction of Sea, land, and air is the 'coastal frontier'. This Coastal frontier comprises of fragile, sensitive, dynamic, and diverse ecosystems like forests, estuaries, coral reefs, tidal mudflats, salt marshes, seagrass,

and mangroves [1, 2]. Mangroves are circum-tropical halophytes representing an ecotone between terrestrial and marine habitats which are adapted to wet and saline conditions having a vital ecological and economic relevance at global, regional, and local scales [3]. These mangrove forests comprise of 65 true mangrove species and 6 hybrids [4], housed in one hundred and twenty-three countries between 32°N and 38°S covering an area of 1.5 million sq. Km [5]. The highest concentration (60%) of global mangrove species (44) are reported from southeast Asia [5, 6]. The mangroves of Andaman and Nicobar Islands (ANI's) represent the third-largest cover on the Indian subcontinent next to Gujarat and Sunderbans respectively [5]. ANI's comprise 38 true mangrove species belonging to 19 genera, and 13 families. Thus, ANI's houses 50% of the global mangrove species [7, 8].

Globally mangrove forests are known as among one of the most productive and biologically important ecosystems because they deliver a variety of vital and distinctive ecosystem goods and services to humankind and other coastal marine ecosystems like the mudflats, coral reefs, seagrass, etc [9]. Since time immemorial mangrove is been conventionally used for firewood, charcoal, alcohol, folk-lore therapeutics, roof thatching [10, 11]. They act as nursery and breeding ground for the juveniles of many commercial fish, crustaceans, including avifauna and reptiles [12–15]. Also, they reduce coastal erosion, stabilize the shoreline, provide sediment and nutrient retention, improve water quality, and provide both flood and flow control as well as protection against storms, hurricanes, and tsunamis [16–21]. Carbon sequestration is presently recognized as the most important service of the mangrove owing to the growing appreciation of the efficacy of these habitats in climate regulation through fixing carbon from the atmosphere [22–24].

The mangrove forests of the world are dwindling at a rate of 1–2% annually and if this trend continues the mangrove and its ecosystem shall be erased from the face of the earth by the 21st century [25–27]. The deterioration of mangrove is more alarming than any other ecosystem like the coral reef and marine forests. At this rate of destruction, the world would be deprived of mangrove and its ecosystem services by the end of this century [28]. The loss of mangrove forests can be attributed to anthropogenic and natural factors. Anthropogenic factors such as dumping of wet and solid wastes generated by the urban population, deforestation, conversion for aquaculture, agriculture, industrial discharge, petroleum spills, the combustion of fossil fuels, automobile exhaust are responsible for the loss of mangrove forests [25, 27, 29–33]. Although the mangrove forest act as a bio-shield against natural disasters such as climate change, cyclones, hurricanes, typhoons, storm surges, and tsunamis [3, 16–21]. On the contrary, these natural factors are also partly responsible for the loss of mangrove forests [34]. However, Mangroves demonstrates the ability to be resilient to natural eventualities [18, 35–40] by following the fluvial influx [39, 41].

The resilience of mangrove is naturally ensured by ecological succession. It is rather a slow process of development and adjustment of species compositions of the mangrove communities over time and space. Further, the ecological succession is dependent on the vital driving factors such as growth potential of the mangrove species, dispersal, settlement, competition, and external or biogenic changes in abiotic conditions [42]. The fluvial influx in the landmass subsided zones due to the 2004 tsunami created a conducive environment for mangrove colonization (ecological succession). Hence, the present study aims at understanding the secondary ecological succession of mangrove in Tsunami Created Wetlands (TCWs) of South Andaman so that it would help in initiating anthropogenically induced massive restoration and rehabilitation of it in the future [6, 28, 43–47].

2. Study area

ANI's is a union territory of India in the Bay of Bengal between peninsular India and Myanmar, trending in a north-south direction. Bounded by the coordinates (92° to 94° East and 6° to 14° North), it is an archipelago with > 500 islands/islets, stretching over 700 km [39]. They are closer to the Indonesian landmass than to mainland India (1200 km), with the southernmost island only 150 km from Sumatra and the northernmost landfall, 190 km south of West Myanmar. ANI's being the cradle of multi-disasters like cyclones, storm surges, earthquakes, and tsunami, the mangroves of this region are vulnerable to disaster. However, nature has its own plans for resilience after any disaster. The present study illustrates the ecological succession of mangrove in south Andaman after the 2004 devastating tsunami. Subsidence and Upliftment of landmass were observed in ANI's due to the 2004 tsunami [48]. Subsidence of landmass around the coastal frontiers rendered it to be permanently waterlogged thus creating wetlands that are very conducive for the mangroves to colonize [37–39]. The area under focus is bounded by the coordinates 11°27'00" and 11°45'00"N and 92°30'00" and 92°46'47"E (**Figure 1**) covering a land area of 333.18 km² that encountered destruction from the 2004 tsunami and subsidence as well [48, 49].

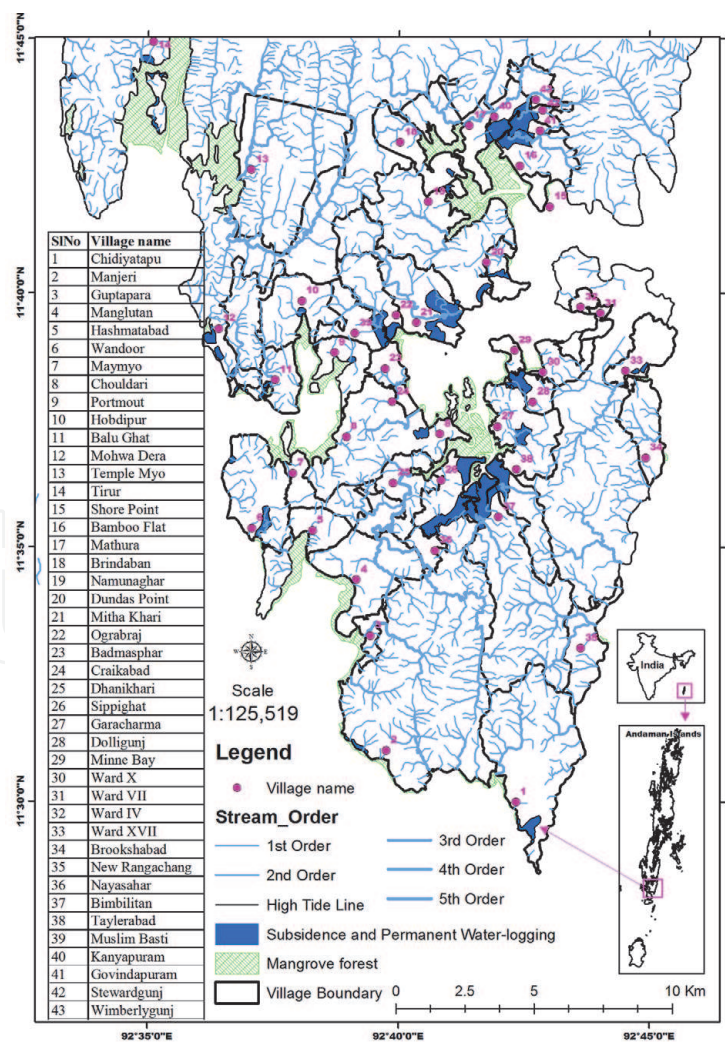


Figure 1.
Study area map showing TCWs with mangrove forest.

2.1 Geology, soils, geomorphology, and drainage

The origin of the Andaman-Nicobar islands is approximately dated as late Pliocene to Pleistocene [50]. The subsidence of landmass is defined by the rock type. Two types of rocks are encountered in the study area viz., (1) Sedimentary rock (Andaman flysch), and (2) Ophiolite suite of volcanic origin [51, 52]. Sedimentary rock comprises of greywacke, siltstone, chalk, limestone are soft and more susceptible to subsidence due to tectonic activity when compared to the Ophiolite suite (Figure 2a).

Geomorphologically the study area is dominated by the structural hill, valley trending N-S direction followed by pediments and coastal plains (Figure 2b). The coastal plains are dominated by alluvium and colluvium.

The soils of the study area have developed under the dominant influence of vegetation and climate and over diverse parent material. The soil is either present on the hill tops or deposited in the valleys or along the coast as escorted soil. Along the coast, the soil is sandy and contains shingles and old corals, etc. It is extremely porous. In the valley and in the lower slopes of hills, the soil is clayey loam. On the hills, it is rigid clay and dark red loam. There are three orders of soil Entisols, Inceptisols, and Alfisols [53] in six soil texture class viz., Clay, Clay loam, Loamy sand, Sandy, Sandy Clay, Sandy Clay loam. Clay loam is the dominant textural class of soil well distributed throughout the study area followed by clay. Sandy texture was seen along the coastal fringes (Figure 2c).

The drainage in the area under investigation exhibits dendritic and trellis patterns a typical structurally controlled drainage pattern of volcanic origin. In general, almost all the drainages are very young and terminate their first or second-order

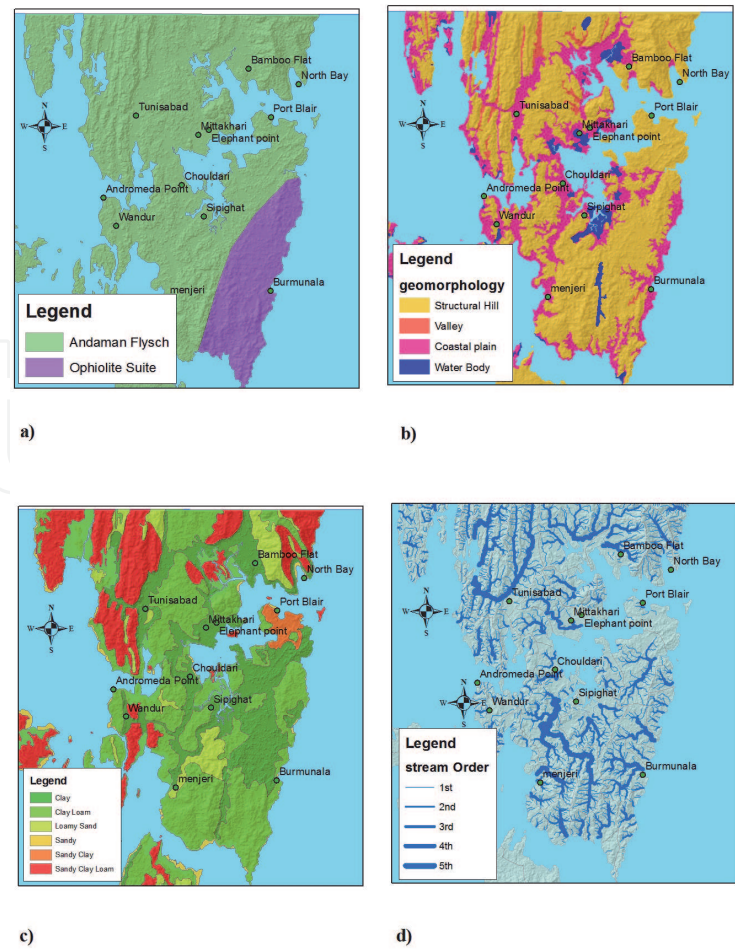


Figure 2. Maps of (a) Geology, (b) Geomorphology, (c) Soil texture, and (d) Drainage.

stream within a short distance. There are no landlocked watersheds hence all the streams empties into the adjacent sea (**Figure 2d**).

2.2 Meteorology

The study area is situated south of Tropic of Cancer and the region is surrounded by warm seas. The climate of this region is categorized as Warm and Humid. The recorded average temperature ranges from 25°C to 30.5°C. The prevalent temperature along with relatively high humidity gives rise to perceptible and sultry weather. However, this type of weather is moderated with pleasant sea breezes. The relative humidity is high throughout the year reaching > 90 % during the northeast monsoons. The maximum temperature recorded at Port Blair is 32°C. The average annual rainfall is around 3000 to 3500 mm. May to August is the rainiest months and April is the warmest month in this region. It is observed that the South-West monsoon brings in most of the rainfall. During May-June, the onset of the monsoon occurs and in September-October withdrawal of monsoon is observed. The North-East monsoons beginning in November and persists till the end of February. This transitional period is nonetheless disturbed by cyclonic storms which may be accompanied by thundershowers. Most of the storms experienced by the mainland and the area under investigation originate in the Bay of Bengal [54].

3. Conducive environment for mangrove ecosystem

The prevalent geology, soil, geomorphology, drainage system, and climatic conditions in the study area favour the tall and gregarious growth of mangrove flora. The rocks of sedimentary origin are more susceptible to weathering than volcanic rocks. Tropical rains weather the rock material and escort them to the coastal front through the natural drainage system along with abundant freshwater. The climate of any tropical intertidal zone acts as a vital and requisite factor for the natural growth, development, and succession of mangroves. Among these necessary climatic factors are (i) the temperature fluctuation-ranges between 20°C and 30°C [55, 56], (ii) the humidity is of a higher range [57], (iii) the total annual rainfall is above 1000 mm [58], (iv) there is regular wind flow, (v) the area is frost free [59], (vi) radiation and (vii) sedimentation along with upstream water supply plays a very dominant role for the growth and viability of mangrove in a holistic manner [60].

4. Materials and methodology

Landsat (7 & 8) satellite data products before (2003) and after (2018) tsunami respectively, for the study were downloaded from the website (www.earthexplorer.usgs.gov/). The study area is covered by the scene with path (134) and row (52). Mangrove patches and water bodies decipherably picked up very well by band-5 and band-6 by the short-wave infrared (SWIR) sensor of Landsat 7 and 8 satellites respectively from other features like the forest, human settlements, etc. Using ArcGIS Desktop 10.5 software mangrove patches and TCWs were demarcated.

Apart from the demarcation of TCWs, stream networks were delineated from the 1979 Survey of India (SOI) toposheet. An overlay analysis of stream network was comprehended over (1) satellite imageries, (2) geology map, (3) geomorphology map, (4) soil texture map, and (5) village administrative boundary map to understand the source of fluvial Influx dynamics and ecological succession.

Village-wise mangrove stand and TCWs (subsidised landmass and permanent waterlogging thereafter) were inferred from before and after tsunami satellite image interpretation. A fishnet grid of 1 km² covering mangroves and TCWs was generated with unique ID's and the same was converted into Global Positioning System (GPS) compatible format (*.gpx). These grids were loaded in the handheld Garmin 62CSX, GPS for field investigation. Enumeration of mangrove species was carried out through a 150 m line transect technique [61] with a 50 m interval between each transect within the 1 km² grid during the dry season (January-May, 2019 and March-April, 2020). These line transects were laid orthogonal to the coast either ways (land to sea and sea to land). A subplot of 4 m² dimension was laid for enumerating individual plants [8]. Mangrove phenology and habitat description were carried out as per Debnath 2004 [62].

5. Results and discussion

Through field survey, a total of twenty-eight mangrove species around existing mangrove and TCWs in forty-three village locations were enumerated and presented in **Table 1**. Also, village-wise pre-tsunami landuse with soil type and the maximum distance from the existing mangrove patch (km) were tabulated in **Table 2**.

Tsunami is rather a rare disaster in the Indian Ocean [63]. A mega-earthquake of magnitude 9.3 on the Richter scale struck near Indonesia On December 26th, 2004 at 07:58:53 local time [64, 65]. The epicenter was located 80km west of the coast of Northern Sumatra (at approximately 95°51' W and 3°25'N). The earthquake advanced thereafter approximately northward rupturing 1200 km to 1300 km (with an average rupture speed of 2.5 to 3 km/s) of the Andaman-Sunda plate in about 8 to 10 minutes [66–68] causing up to ~6 m of bottom subsidence and ~10 m of uplift parallel to the rupture and about 100-150 km wide across the subduction area [69]. Upliftment and subsidence of landmass [38] were generated as a consequence of earthquake elastic rebound, offshore of Banda Aceh, the northern tip of Sumatra [70]. Rupture of the plate and coseismic activities spontaneously triggered a tsunami catastrophic devastation ever witnessed in the modern history of humankind [70–73]. All the above sequential events just occurred in a short span of few hours resulting in unprecedented destruction and mangroves were one of the first visible responders of the tsunami [3, 74–77].

Voluminous literature speaks about mangrove demonstrating resilience after a disaster like hurricane, cyclone, and tsunami [18, 35–40, 78, 79]. However, very few studies were conducted to understand the dynamics of the ecological succession of mangroves after natural disasters like hurricanes and tsunamis [80]. The mangroves of the study area faced the double impact of mortality due to 26th December 2004 tsunami viz., (1) physical fury, and (2) prolonged submergence due to subsidence of land mass [38–48]. Zones of subsidised landmass were waterlogged permanently resulting in (TCWs). Nudation of mangrove (**Figure 3**) occurred due to a catastrophic event [81].

Overlay analysis of geology geomorphology and stream network of pre-post-tsunami satellite imageries suggest that subsidence of landmass (TCWs) has occurred in the regions of sedimentary rock and on the coastal plains. Sedimentary rocks (Andaman flysh) being soft are more susceptible to deformation due to tectonic activity when compared to volcanic rock (Ophiolite suite). Also, the streams once which were emptying itself in the shallow depths of the coastal frontiers started depositing in the TCWs (**Figures 1, 3, and 4**). Mineral-rich fine sediments and abundant freshwater were deposited into TCWs through the

Species Name	1*	2*	3	4	5	6*	7	8*	9*	10*	11*	12*	13	14*	15	16	17	18	19*	20*	21*	22*	23	24	25	26*	27*	28*	29	30	31	32	33*	34	35	36**	37**	38**	39**	40**	41**	42**	43**		
<i>Acanthus ebracteatus</i>	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	+	+	+	*+	+	+	+	+	-	-	-	-	-	+	+	+	-	-	-	-	-	
<i>Acanthus ilicifolius</i>	* +	* +	+	+	+	*+	+	*+	*+	*+	*+	*+	+	*+	+	+	+	+	+	*+	*+	+	*+	+	+	+	*+	*+	+	+	+	-	-	*+	+	+	+	+	+	+	+	+	+	+	
<i>Acrostichum aureum</i>	* +	* +	+	+	+	*+	+	*+	*+	*+	*+	*+	+	*+	+	+	+	+	+	*+	*+	+	*+	+	+	+	*+	*+	*+	+	+	+	+	*+	+	+	+	+	+	+	+	+	+	+	
<i>Aegiceras corniculatum</i>	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	+	+	+	-	-	-	-	-	-	-	-	
<i>Avicennia marina</i>	* +	* +	+	+	+	*+	+	*+	*+	*+	-	-	+	*+	+	+	+	+	+	*+	*+	*+	*+	+	+	+	*+	*+	*+	+	+	+	+	+	*+	+	+	-	+	+	+	+	+	+	+
<i>Avicennia officinalis</i>	* +	* +	+	+	+	*+	+	*+	*+	*+	-	-	+	*+	+	+	+	+	+	*+	*+	*+	-	+	+	+	*+	*+	*+	+	+	+	+	+	*+	+	+	+	+	+	+	+	+	+	
<i>Bruguiera cylindrica</i>	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	-	-	-	-	-	-	-	-	-	-	-	-	-	
<i>Bruguiera gymnorhiza</i>	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	-	-	-	+	+	-	-	-	-	-	-	-	-	
<i>Bruguiera parviflora</i>	+	-	-	-	-	+	+	+	+	+	-	-	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	-	-	+	-	-	-	-	-	-	-	-	-	-	-
<i>Ceriops tagal</i>	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	-	-	+	-	-	-	-	-	-	-	-	-	-	
<i>Cynometra iripa</i>	+	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	+	+	-	-	-	-	-	-	-		
<i>Dolichandrone spathacea</i>	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	-	-	+	+	+	-	-	-	-	-	-	-	-	
<i>Excoecaria agallocha</i>	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	-	-	+	+	+	-	-	-	-	-	-	-	-	
<i>Heritiera littoralis</i>	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	-	-	+	+	+	-	-	-	-	-	-	-	-	
<i>Lumnitzera littorea</i>	+	+	+	+	+	-	-	-	-	-	+	+	-	-	-	-	-	-	-	-	-	+	+	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	
<i>Lumnitzera racemosa</i>	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	+	+	-	-	-	-	-	-	-	-	

Species Name	1*	2*	3	4	5	6*	7	8*	9*	10*	11*	12*	13	14*	15	16	17	18	19*	20*	21*	22*	23	24	25	26*	27*	28*	29	30	31	32	33*	34	35	36**	37**	38**	39**	40**	41**	42**	43**				
<i>Nypa fruticans</i>	—	—	—	—	—	—	—	—	—	—	—	—	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	—	—	+	+	+	—	—	—	—	—	—	—	—	—	—			
<i>Pemphis acidula</i>	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	+	—	—	—	—	—	—	—	—	—	—	—	—		
<i>Phoenix paludosa</i>	—	—	—	—	—	—	—	—	—	—	+	+	+	+	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	
<i>Pandanus tectorius</i>	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	+	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	
<i>Rhizophora apiculata</i>	*	*	+	+	+	*+	+	*+	*+	*+	*+	*+	+	*+	+	+	+	+	+	*+	*+	*+	*+	+	+	+	+	*+	*+	*+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	
<i>Rhizophora mucronata</i>	*	*	+	+	+	*+	+	*+	*+	*+	*+	*+	+	*+	+	+	+	+	+	*+	*+	*+	*+	+	+	+	+	*+	*+	*+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	
<i>Rhizophora stylosa</i>	+	+	—	+	+	+	+	+	+	+	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	+	+	+	—	—	—	—	—	—	—	—	—	—	
<i>Scyphiphora hydrophylacea</i>	—	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	
<i>Sonneratia alba</i>	+	+	—	+	+	+	+	+	+	+	+	+	—	—	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	—	—	+	+	+	—	—	—	—	—	—	—	—	—	—	—	—
<i>Sonneratia ovata</i>	+	—	—	+	+	+	+	+	+	+	—	—	—	—	+	+	+	+	+	+	—	—	—	—	—	—	—	—	—	—	—	—	—	—	+	+	—	—	—	—	—	—	—	—	—	—	—
<i>Xylocarpus granatum</i>	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	—	—	+	+	+	—	—	—	—	—	—	—	—	—	—	—	
<i>Fimbristylis littoralis</i>	*	*	+	+	+	*+	+	*+	*+	*+	*+	*+	+	*+	+	+	+	+	+	*+	*+	*+	*+	+	+	+	+	*+	*+	*+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	
* [†] - Village-wise distribution of Mangroves, ** [†] - Village-wise distribution of Mangrove in new venues of TCWs, “—” - Indicates absence of Mangrove species, “+” - Indicates presence of Mangrove Species, “*+” - Indicates presence of Mangrove species in TCWs																																															

[†] - Village-wise distribution of Mangroves, ^{**} - Village-wise distribution of Mangrove in new venues of TCWs, “-” - Indicates absence of Mangrove species, “+” - Indicates presence of Mangrove Species, “*+” - Indicates presence of Mangrove species in TCWs

Table 1.
Village-wise distribution of mangrove and its associated species.

Sl no	Village name	Soil texture type	Pre-tsunami land use land cover	Max distance from the existing mangrove patch (km)
1*	Chidiyatapu	Clay loam	Agricultural Land & Settlement	1.2
2*	Manjeri	Clay loam	Agricultural Land & Settlement	0.12
3	Guptapara	Clay and loamy sand	—	—
4	Manglutan	Clay loam	—	—
5	Hashmatabad	Sandy clay loam	—	—
6*	Wandoor	Clay	Agricultural Land	1.14
7	Maymyo	Clay	—	—
8*	Chouldari	Loamy sand	Agricultural Land & Settlement	0.55
9*	Portmout	Clay loam	Agricultural Land & Settlement	0.29
10*	Hobdipur	Clay	Agricultural Land & Settlement	0.35
11*	Balu Ghat	Clay loam and sandy clay loam	Open jungle	0.15
12*	Mohwa Dera	Sandy and sandy clay loam	Open jungle	1.5
13	Temple Myo	Clay loam	—	—
14*	Tirur	Clay loam, Loamy sand, clay, sandy clay loam	Agricultural Land & Settlement	0.25
15	Shore Point	Clay loam	—	—
16	Bamboo Flat	Clay loam and clay	—	—
17	Mathura	Clay and clay loam	—	—
18	Brindaban	Clay and clay loam	—	—
19*	Namunaghar	Clay and clay loam	Agricultural Land & Settlement	0.27
20*	Dundas Point	Clay loam	OpenJungle	0.65
21*	Mitha Khari	Clay	Plantation/ Agricultural land	1.5
22*	Ograbraj	Clay and clay loam	Agricultural Land & Settlement	0.22
23	Badmasphar	Clay and clay loam	—	—
24	Craikabad	Sandy and clay loam	—	—
25	Dhanikhari	Clay and clay loam	—	—
26*	Sippighat	Clay and clay loam	Agricultural Land & Settlement	1.01
27*	Garacharma	Clay and clay loam	Agricultural Land & Settlement	0.45
28*	Dolligunj	Clay and clay loam	OpenJungle	1.05
29	Minne Bay	Clay and clay loam	—	—
30	Ward X	Clay loam	—	—

Sl no	Village name	Soil texture type	Pre-tsunami land use land cover	Max distance from the existing mangrove patch (km)
31	Ward VII	Sandy clay	—	—
32	Ward IV	Sandy clay	—	—
33*	Ward XVII	Clay	Agricultural Land	1.01
34	Brookshabad	Clay	—	—
35	New Rangachang	Clay loam	—	—
36**	Nayasahar	Clay and clay loam	Agricultural Land & Settlement	2.5
37**	Bimblitian	Clay and clay loam	Agricultural Land & Settlement	1.2
38**	Taylerabad	Clay and clay loam	Agricultural Land & Settlement	0.87
39**	Muslim Basti	Clay and clay loam	Agricultural Land & Settlement	1.32
40**	Kanyapuram	Clay loam and clay	Agricultural Land & Settlement	0.95
41**	Govindapuram	Clay loam and clay	Agricultural Land & Settlement	1.47
42**	Stewardgunj	Clay loam and clay	Agricultural Land & Settlement	1.91
43**	Wimberlygunj	Clay loam and clay	Agricultural Land	2.02
*Indicates TCWs in the vicinity of pre-existing mangrove.				
**Indicates new venues of TCWs.				

Table 2. Village-wise soil texture, pre-tsunami landuse pattern and maximum distance from the existing mangrove patch.

conduits of natural streams network (**Figure 4**). Freshly deposited fine sediments are barren and are called as mud banks.

These mud banks in the TCWs were wet, saline, and poorly aerated proves unfavourable for higher plants [82] so, microbes and algae prepare the mud banks for the utilization of higher plants by aerating them [83, 84]. Also, sediments are counteracted by compaction and consolidation of both mud and peat [82]. Coaction of non-woody key-stone species like *Fimbristylis littoralis*, *Acrostichum aureum*, and *Acanthus ilicifolius* subsequently colonized the TCWs (**Figure 5, Tables 1–3**). The aforementioned key-stone species were the pioneer plants to colonize the landmass subsided zones thus trapping the sediments and nutrients resulting in the invasion of novel mangrove species [85, 86]. Basically, key-stone species for the initial succession perform the role of nurse plants which start on the bare aerated soil, modifying its conditions like decreasing interstitial salinity and increasing nutrient, enabling the succession of mangroves and can thus be called facilitator species [87, 88]. key-stone species like *Fimbristylis littoralis* and *Acrostichum aureum* were invariably found in all the forty-three sites. Similarly, mangrove species like *Rhizophora* and *Avicennia spp* were also encountered in all the stations. *Pandanus tectorius* and *Pemphis acidula* were found in Mitha Khari and Ward XVII respectively (**Table 1**). Basic soil textures like clay, sand, and loam in different

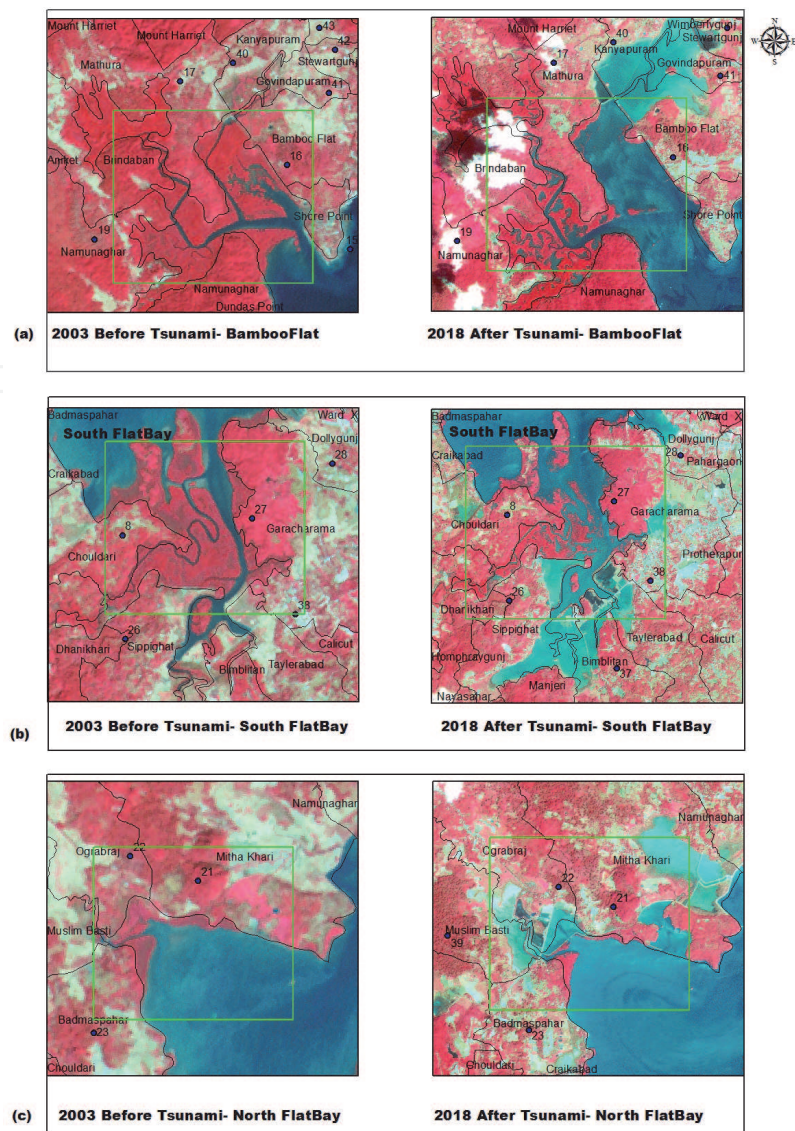


Figure 3.
Satellite image showing before and nudation of mangrove after tsunami (a) Bambooflat, (b) South Flat Bay and (c) North Flat Bay.

combinations were found in the focus area (**Table 2**). The flowering and fruiting phenology along with the habitat descriptions are presented in **Table 3**.

The mangrove seedlings were transported to the TCWs through the tidal influx from pre-existing mangrove (**Tables 1 and 2**) and thus had a stable environment. TCWs being situated in the shallow sheltered bays with low tidal amplitude favours the rooting of propagules [82, 89]. Mangroves follow the existing patterns of fluvial influx and their distribution is determined by the formation of banks, deltas, channels, levees, lagoons, and bays [55, 90–92]. Mangroves respond to geomorphic changes [93, 94] and attain a steady-state system in low energy tropical saline environments [95]. Mangrove succession is a continuous process, where the species recruitment and replacement is systematic and anticipated [96]. It has to be noted here that the likelihood of this phenomenon is of enormous benefit in assessing the evolution towards the climax species complex. The ecological succession from land towards the sea in TCWS in south Andaman is as follows: *Fimbristylis littoralis* is the pioneering key-stone plant followed by *Acrostichum aureum* and *Acanthus ilicifolius*. *Avicennia spp/Rhizophora spp* are the prime mangroves to colonize. The ecological succession of mangrove in TCWs are

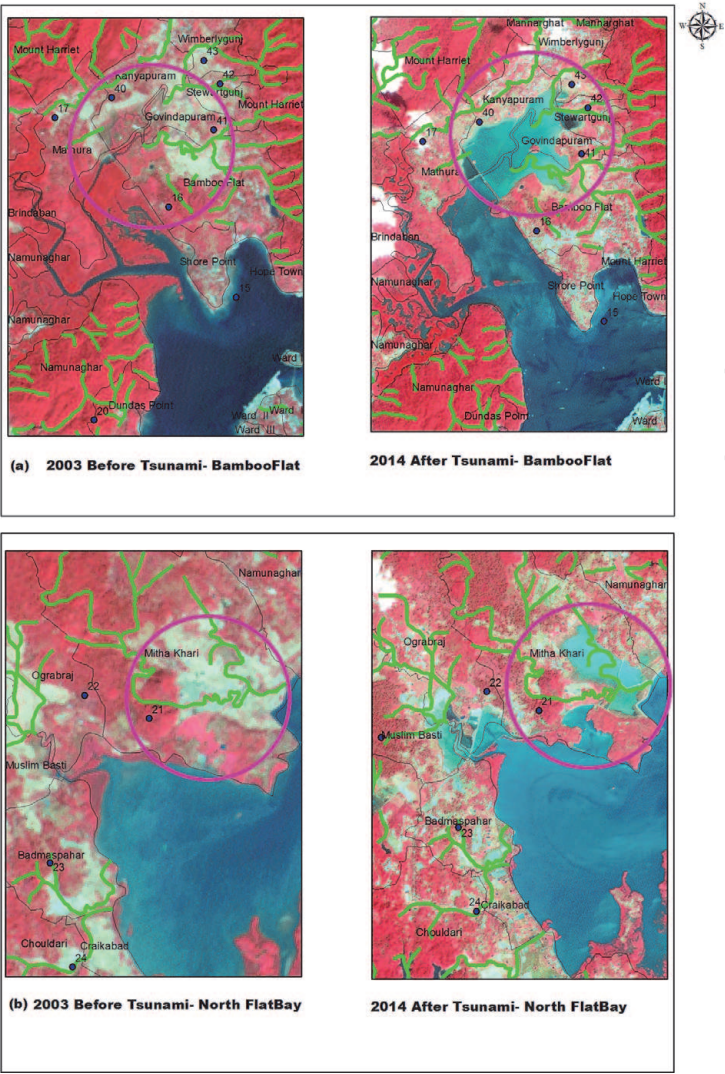


Figure 4.
Siltation and freshwater influx by natural stream network in TCWs.

considered as secondary ecological succession, which is caused by a natural disaster like the tsunami, subsidence of landmass followed by permanent waterlogging. This type of succession was studied worldwide [35, 37, 38, 80].

6. Conclusion

From the present study, it is understood that secondary ecological succession has occurred in Andaman after the catastrophic 2004 tsunami. Key-stone species like *Fimbristylis littoralis*, *Acrostichum aureum* and *Acanthus ilicifolius* acting as a facilitator species were first to colonize the TCWs and followed by mangrove species like *Avicennia spp/Rhizophora spp*. Infact the key-stone species were the pioneer lower plants to colonize the landmass subsided zones of the 2004 tsunami. The nutrient-rich upstream sediments trapped amongst the roots of the key-stone species provides a conducive environment for the mangrove to colonize. The present study provides a window for anthropogenically induced rehabilitation and restoration of mangrove forests. For any rehabilitation and restoration endeavor of mangrove firstly, the area should be seeded with key-stone species after couple of years mangrove species like *Avicennia spp* and *Rhizophora spp* has to planted. Thereafter it may take 15–20 years for dense patch of mangrove. A broad avenues for future

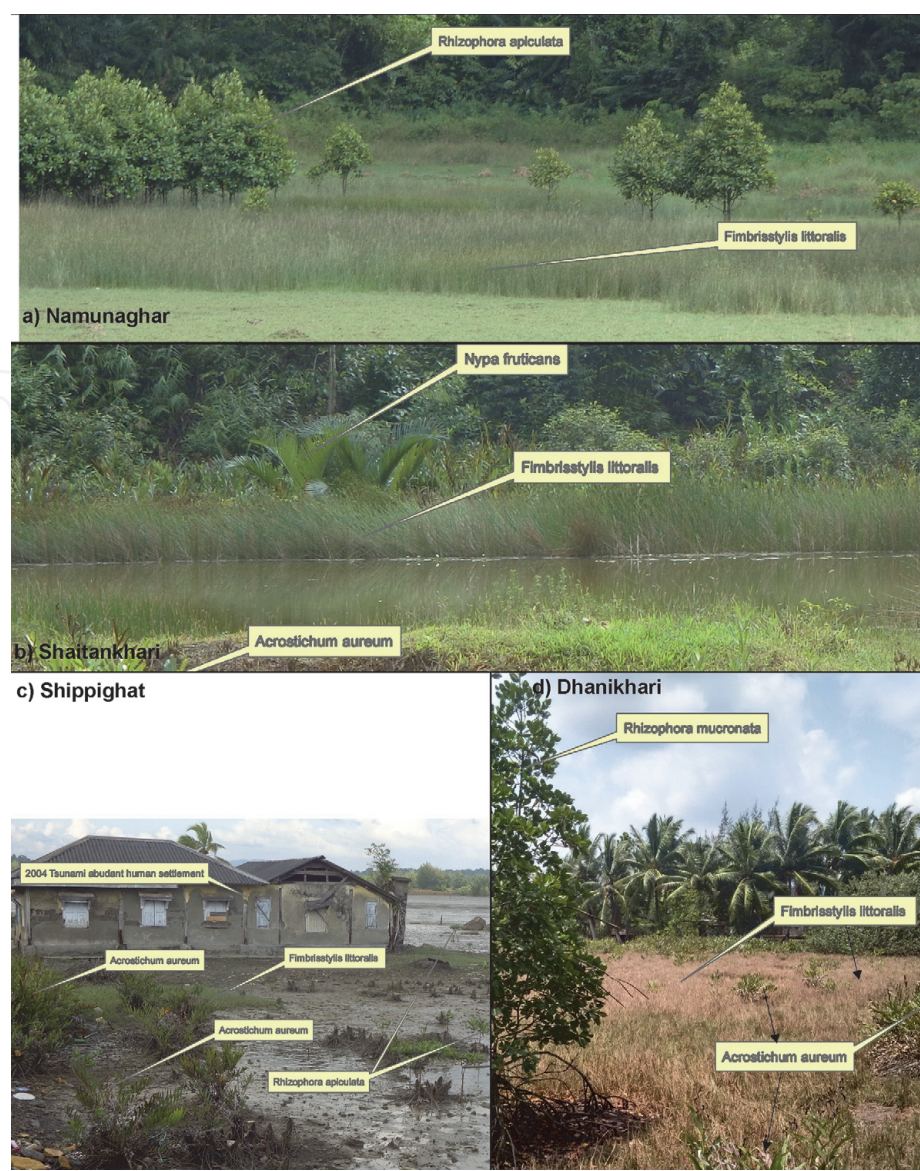


Figure 5.
Field photos of key-stone species and mangroves TCWs.

Sl no	Species name	Phenology		Habitat
		Flowering	Fruiting	
1	<i>Acanthus ebracteatus</i>	Mar-Jun	Jun-Aug	Common along tidal streams, inland borders of Mangrove swamps under the influence of salt or Brackish water
2	<i>Acanthus ilicifolius</i>	Apr-Jun	Jun-Aug	Gregarious in brackish swamps along the seashore and tidal streams
3	<i>Acrostichum aureum</i>	NA	NA	Landward side of mangrove, survives in TCWs completely cut off from sea
4	<i>Aegiceras corniculatum</i>	Throughout the year		Often found in inner mangroves along with <i>Bruguiera</i> spp., <i>Ceriops</i> spp., and <i>Xylocarpus</i> spp. Also present at landward margin of mangroves inundated during normal high tides and fringing the banks at upstream region.
5	<i>Avicennia marina</i>	Apr-Jun	Jun-Aug	Often found in high intertidal and intermediate estuarine position also present in downstream and low intertidal areas. It is a dominant species in highly polluted areas

Sl no	Species name	Phenology		Habitat
		Flowering	Fruiting	
6	<i>Avicennia officinalis</i>	Jun-Aug	Aug-Oct	Often found in low and high intertidal position and also occur in mid and upper estuarine position along the banks of the creek.
7	<i>Bruguiera cylindrica</i>	Mar-Jun	Jun-Aug	Gregarious on stiff clay behind <i>Avicennia</i> , sometimes in association with <i>Bruguiera gymnorhiza</i>
8	<i>Bruguiera gymnorhiza</i>	Throughout the year		Commonly occur in intertidal zone, along creeks, usually associated with <i>Rhizophora apiculata</i> and <i>R. mucronata</i>
9	<i>Bruguiera parviflora</i>	Apr-Jul	Jul-Sep	Occur in intertidal zones of estuarine swamps in association with <i>Bruguiera gymnorhiza</i> , <i>Rhizophora apiculata</i> and <i>R. mucronata</i>
10	<i>Ceriops tagal</i>	Mar-Jul	Jul-Oct	Occur in intertidal banks of mangrove, also in areas nearer to and under estuarine influence
11	<i>Cynometra iripa</i>	Sep-Nov	Dec-Feb	Frequent to back mangrove in the <i>Heritiera littoralis</i> zones
12	<i>Dolichandrone spathacea</i>	May-Jun	Jun-Aug	Sporadic occurrence, found around the inner edge of mangrove swamps in association with <i>Sonneratia caseolaris</i> and <i>Heritiera littoralis</i>
13	<i>Excoecaria agallocha</i>	Mar-Jun	Jun-Aug	Occurs in muddy or sandy shores, commonly found in intertidal
14	<i>Heritiera littoralis</i>	Mar-Jun	Jun-Aug	Commonly found in intertidal zone, frequently extending into muddy or sandy shores
15	<i>Lumnitzera littorea</i>	Jan-Apr	Apr-Oct	Occurs in middle zone of mangrove forest, where soluble salts are more
16	<i>Lumnitzera racemosa</i>	Jan-Apr	Apr-Jul	Occurs in muddy or sandy elevated zones of estuarine and backwater
17	<i>Nypa fruticans</i>	Feb-Jun	Jun-Sep	Sheltered intertidal creeks of mangrove swamps, preferably low saline regions
18	<i>Pemphis acidula</i>	Aug-Dec	Dec-Apr	Occur along the edge of mangrove forests
19	<i>Phoenix paludosa</i>	Jan-May	May-Aug	Elevated muddy swamps, estuarine banks, can tolerate higher percentage of salt, even found on the sea coast too
20	<i>Pandanus tectorius</i>	Sep-Nov	Nov-Mar	Littoral shrub, often found in the tidal forests
21	<i>Rhizophora apiculata</i>	May-Jul	Jul-Sep	Occur in intertidal regions of the creek in the sheltered parts of mangrove
22	<i>Rhizophora mucronata</i>	Jul-Sep	Sep-Nov	Occur in intertidal banks of creeks or in estuaries
23	<i>Rhizophora stylosa</i>	Jul-Sep	Sep-Nov	Often found in mid to low intertidal and downstream tidal creeks; grows in a variety of habitats and disrupted mangrove areas. One distinctive niche is its ability to grow on edges of small coral islands, establishing on the coral substrate.
24	<i>Scyphiphora hydrophyllacea</i>	Mar-Aug	Mar-Aug	Along mangrove creeks
25	<i>Sonneratia alba</i>	Mar-Jun	Jun-Sep	Occurs along the mouth of tidal creeks, grows on sandy or rocky soil

Sl no	Species name	Phenology		Habitait
		Flowering	Fruiting	
26	<i>Sonneratia ovata</i>	Mar-Jun	Jun-Sep	Often occurs on the landward edge of mangrove swamps in brackish water and muddy soil.
27	<i>Xylocarpus granatum</i>	Throughout the year		Occur in the sheltered banks in association with Kandelia candel, Rhizophora sp and Sonneratia alba

Pehonology and habitat description is as per Ref. [62].

Table 3.
Phenology of mangrove and it associated species.

research are generated like role of benthic community, avian population, physico-chemical and biological parametric studies, etc., in TCWs.

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Conflict of interest

None.

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