Environmental Management
DOI 10.1007/s00267-010-9523-1

From Bathymetry to Bioshields: A Review of Post-Tsunami Ecological Research in India and its Implications for Policy

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Received: 19 October 2009 / Accepted: 18 June 2010

Abstract More than half a decade has passed since the December 26th 2004 tsunami hit the Indian coast leaving a trail of ecological, economic and human destruction in its wake. We reviewed the coastal ecological research carried out in India in the light of the tsunami. In addition, we also briefly reviewed the ecological research in other tsunami affected countries in Asia namely Sri Lanka, Indonesia, Thailand and Maldives in order to provide a broader perspective of ecological research after tsunami. A basic search in ISI Web of Knowledge using keywords "tsunami" and "India" resulted in 127 peer reviewed journal articles, of which 39 articles were pertaining to ecological sciences. In comparison, Sri Lanka, Indonesia, Thailand and Maldives had, respectively, eight, four, 21 and two articles pertaining to ecology. In India, bioshields received the major share of scientific interest (14 out of 39) while only one study (each) was dedicated to corals, seagrasses, seaweeds and meiofauna, pointing to the paucity of research attention dedicated to these critical ecosystems. We noted that very few interdisciplinary studies looked at linkages between pure/applied sciences and the social sciences in India. In addition, there appears to be little correlation between the limited research that was done and its influence on policy in India. This review points to gap areas in ecological research in India and highlights the lessons learnt from research in other tsunami-affected countries. It also provides guidance on the links between science and policy that are required for effective coastal zone management.

Keywords Tsunami · Review · Coastal ecology · India · Policy

Electronic supplementary material The online version of this article (doi:10.1007/s00267-010-9523-1) contains supplementary material, which is available to authorized users.

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Introduction

The impact of natural disasters on coastal ecosystems and the relevance of coastal protection structures have been globally debated in the recent past (Dahdouh-Guebas and Koedam 2006; Kerr and Baird 2007; Barbier and others 2008; Koedam and Dahdouh-Guebas 2008; Das and Vincent 2009; Feagin and others 2010). Every major storm surge, super cyclone or tsunami is followed by a suite of research articles aimed at addressing issues of coastal

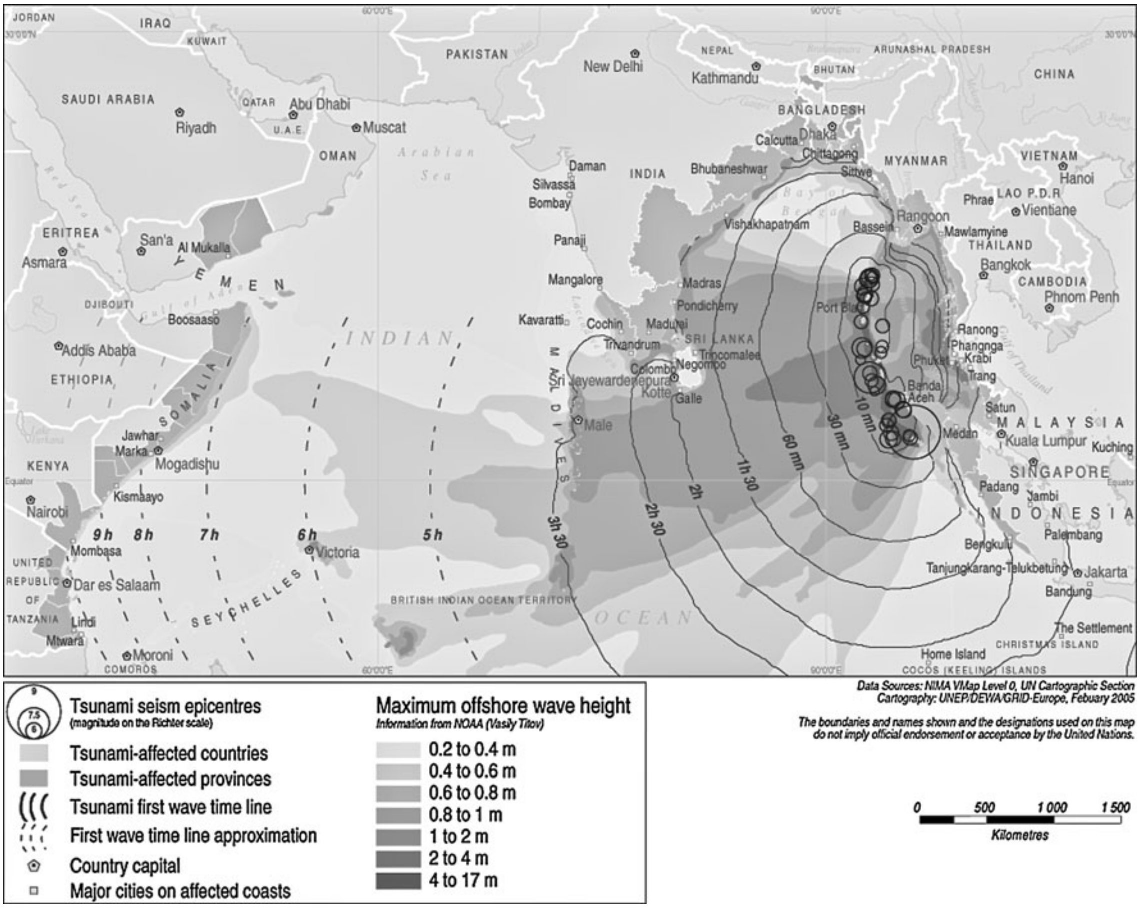

Fig. 1 Countries affected by the tsunami. (Adapted from UNEP-DEWA/GRIDEurope). (http://www.grid.unep.ch/product/map/images/tsunami_wave_propb.gif)

stability and human vulnerability. The Indian Ocean tsunami, one of the worst natural disasters in recent history, formed a critical watershed in this context (see Fig. 1). Official United Nations figures quote a global death toll of 162,000 people with almost 143,000 people missing (presumed dead) and 943,000 people homeless directly due to this tsunami (UNICEF 2005). Indirect effects such as loss of livelihood and its aftermath are not quantified or estimated. India was one of the countries severely impacted by the tsunami. Coastal vulnerability, an issue that had long since been neglected in India, was exposed in an unprecedented way. Therefore, it evoked considerable interest in scientific circles within India regarding a range of coastal issues, which had hitherto not received adequate attention. Notable among them are topics pertaining to bioshields, sea walls, sand dunes and disaster mitigation (Bhalla 2007; Kathiresan and Rajendran 2005; Mascarenhas and Jayakumar 2008).

It is necessary to analyse the recent rise in coastal vulnerability research against the backdrop of coastal ecological research in India, which unfortunately has not received adequate attention as compared to terrestrial ecological research (PTEI 2007). This is indeed surprising since India has a coastline of over 7000 km and its marine areas contain a great wealth of biological diversity ranging from mangroves to coral reefs. For instance, India is home to half of the largest mangrove forest in the world- the Sunderbans (Selvam 2003). Five of the seven sea turtle species currently occurring in the world are found in India (Shanker and Choudhury 2006). In addition, South Asian waters have high diversity coral reef ecosystems, which, particularly on the oceanic islands of the Andaman and Nicobar and the Lakshadweep Archipelago, are in a relatively pristine condition (Bakus and others 2000). Extensive seagrass meadows on the mainland and offshore islands support important green turtle populations and are essential for the survival of the endangered dugong (*Dugong dugon*); the Gulf of Mannar and Palk Bay represent some of the most species-rich tropical seagrass meadows (Jagtap and others 2003). The rich biodiversity notwithstanding, there are very few reliable baselines or long term ecological monitoring of any marine ecosystem in India (PTEI 2007). This paucity of information renders it difficult to assess the impact of any natural disaster.

The United Nations Development Programme launched a project titled "Post-tsunami Environment Initiative" [henceforth PTEI] implemented in mainland India from March 2006 to September 2008. One of the aims of this project was to address the gaps in knowledge with regard to the December 2004 tsunami and coastal research; this review is one of the outcomes of the project. We begin with an extensive bibliometric analysis of all the topics that addressed the Indian Ocean tsunami in India to provide a cross disciplinary overview of post-tsunami studies. We then narrow our focus and selectively discuss peer reviewed journal articles pertaining to the theme of ecological research on tsunami related issues in India. We compare these results with other tsunami affected countries in the same region namely Sri Lanka, Indonesia, Thailand and Maldives.

Coastal management policy is another over arching domain, which is under researched. Often there is a marked discrepancy between the outcomes of ecological research, the implications it has for policy and the actual implementation of the policy itself (Mukherjee and others 2009). We therefore examine whether research on coastal ecosystems in India after the tsunami had any bearing on coastal policy and its implementation in tsunami affected areas.

This review has the following specific objectives:

- To provide a comprehensive interdisciplinary scenario of the current state of ecological knowledge about the impact of the tsunami in India.
- To review the ecological research that was carried out during four years following the tsunami in India and the four other tsunami-affected countries in South East Asia and to discuss the gaps in research.
- To discuss the lessons learnt from other tsunami affected countries and outline the linkages between scientific research and policy and its implementation

Methods

This review is restricted to studies conducted in India (mainland India and Andaman and Nicobar Islands) relating to the Indian Ocean tsunami. We used a three step method to address the first objective. First, we performed a basic search in ISI Web of Knowledge (www.isiwebofknowledge.com) database on 28th March, 2009 using the following criteria:

- Topic: tsunami and India
- Year published: 2004–2009 (March, 2009)

We then refined the results according to document types, selecting only peer reviewed articles, and then conducted the following bibliometric analysis of the results. A complete list of these articles is attached in the Electronic supplementary material. We repeated the same method for Sri Lanka, Indonesia, Thailand and Maldives.

Thematic Area of the Research

The refined results were ranked by subject area in Web of Science to show the top 25 results. The minimum record count threshold was set to one and sorted by record count. Based on the above generic search, we manually selected a subset of articles, which were primarily based in India and were based exclusively on the impact of the tsunami and pertained to ecology. We repeated the same for the other four countries.

We then sorted the articles based on:

Type of journal published: This is important for the gap analysis to quantitatively estimate which journal categories (and thereby which research areas) received the major scientific attention.
Year of publishing: This is important from the temporal perspective to estimate the trends in tsunami related research.

As part of the PTEI project we had conducted a structured literature survey to build a database of coastal and marine research in India. On the basis of the above articles and our database created during the PTEI project, we qualitatively selected articles which focused only on environmental sciences and ecology. We categorized the articles based on the broad thematic areas that they focused on, namely:

Coastal vegetation and bioshields
Sand dunes
Others, including: 2.6.1. Meiofauna, 2.6.2 Foraminifers, 2.6.3 Seaweeds, 2.6.4 Microbiology, 2.6.5 Coral reefs
Generic: this category refers to those studies which were broad in their scope and covered multiple thematic areas.

The review of the articles was directed toward identifying the gaps in research. We thereby looked at

- the number of articles in each thematic area (as an indicator of the amount of research attention on that topic).
- specific geographical areas covered by the articles within each thematic area and which aspects of the tsunami impact were dealt with
- limitations of the studies carried out after the tsunami

Results

We obtained 174 documents on the basic search which consisted of a variety of document types (Table 1). Of

Table 1 Document types obtained using the keywords "tsunami" and "India"

Document type	Number of documents
Article	127
Meeting	19
Letter	10
Editorial	8
News	6

these, 127 were peer reviewed research articles. For the purpose of subsequent analysis in this paper, we restrict our focus to these 127 research articles.

Thematic Area of Research

There is considerable overlap among the subject areas in the articles published and hence the total number of articles in the Table 1 exceeds the number of articles under study (127). Table 2 shows the subject areas ranked among the top 25 in the 127 peer reviewed articles. In general, environmental sciences (39) and science and technology (27) received the major share of scientific attention (Table 2). Coastal geology and water resources follow closely with 23 and 22 articles respectively. This is followed by a string of thematic areas ranging from engineering to sociology with at least 5 articles covering each of these themes. We refined our search among the 127 articles and manually selected 93 articles which were specific to India alone and pertained to the tsunami (Electronic supplementary material).

Table 2 Subject areas covered in the 127 peer reviewed articles

Subject areas	Count	Percentage
Environmental Sciences & Ecology	39	30.71
Science & Technology—Other Topics	27	21.26
Geology	23	18.11
Water Resources	22	17.32
Engineering	13	10.24
Geochemistry & Geophysics	11	8.66
Marine & Freshwater Biology	11	8.66
Biodiversity & Conservation	10	7.87
Oceanography	10	7.87
Agriculture	9	7.09
Forestry	9	7.09
Meteorology & Atmospheric Sciences	9	7.09
Psychiatry	9	7.09
Remote Sensing	7	5.51
Psychology	6	4.72
Geography	5	3.94
Public, Environmental & Occupational Health	5	3.94
Sociology	5	3.94
Behavioral Sciences	4	3.15
Business & Economics	4	3.15
Infectious Diseases	4	3.15
Social Sciences—Other Topics	4	3.15
Public Administration	3	2.36
Chemistry	2	1.57
Government & Law	2	1.57

Type of Journal Published

These 93 articles have been published in 39 journals. Since there was a considerable diversity of topics covered within these 93 articles, an equivalent proportion of journal categories have also been represented. Out of these, a few journals received most of the research articles pertaining to the 2004 tsunami (Table 3). The majority (20) of the articles were published in an Indian journal named Current Science catering to a wide scientific audience while discipline specific journals had fewer research articles. Policy or governance oriented journals were also under represented.

Year Published

Most of the articles were published in 2006 (34) followed by 25 articles in 2008 (Table 4). There was no clear trend observed within the study period. However, the initial articles published in 2005 were mostly opinion based papers. This was followed by articles focusing on data based analysis in later years.

These 93 articles covered a plethora of topics ranging from socio-economic implications of the tsunami on

Table 3 Number of articles published in each of the first four journals

Name of journal	Number of articles
Current Science	20
Earthquake Spectra	10
Journal of Environmental Management	6
International Review of Psychiatry	5

Table 4 Year-wise number of post tsunami articles (from 2005 till 28th March 2009)

Year	Number of articles
2005	19
2006	34
2007	12
2008	25
2009 (till 28.3.09)	4

Table 5 Number of articles pertaining to each ecosystem

Topics	Vegetation	Sand dunes/vegetation	Others	Generic
No. of articles	14	2	7	3

fisherfolk to chemical assessment of the sediment along the Nagapattinam coast (Nirupama 2009; Sujatha and others 2008). It appears that the majority of the studies focused on the impact of the tsunami while few empirical studies actually looked at resilience or suggested of remedial action in the face of future tsunamis. Lack of baseline data before the tsunami could be the main reason behind such research. For instance, Ramachandran and others' (2005) article is perhaps the only study which compares field observations in both pre- and post-tsunami scenarios. Interestingly, some articles focused on the occurrence of paleo-tsunamis after the occurrence of the December 2004 tsunami (Nigam and Chaturvedi 2006), but they have not been included in this analysis.

Out of the 39 articles that belonged to the thematic area of ecology and environmental sciences, we focused on 26 research articles based on their relevance to the Indian Ocean tsunami. We present a broad outline of these topics that have been published so far in peer reviewed journals in connection with the tsunami. Table 5 gives a generic overview of the studies done on the various ecosystems in the light of the tsunami. The majority of studies (14 out of 26) focused on coastal vegetation while one study each (termed as others in the table) covered fisheries (Marimuthu and others 2005), foraminiferans, meiofauna, seaweeds, coral reefs and microbiology. Only three studies looked at sand dunes, but in close association with coastal vegetation.

Coastal Vegetation: Debates Over Their Protective Function

A substantial number of research articles focused on coastal vegetation and account for more than half (14 out of 26) of the articles published on ecosystems after the tsunami. These focus on the damage caused to mangroves and the role of costal vegetation in protecting the coast (and/or people) from the tsunami.

Kar and Kar (2005) were perhaps the first to point out the protective role of mangroves in minimizing the impact of the tsunami. The authors expressed the opinion that government and non-governmental organisations should restore mangroves to protect the people living close to the shore and also to prevent coastal erosion in the event of future tsunamis. However, as pointed out by studies on the Indian subcontinent and beyond, mangrove restoration should follow a number of steps presenting possible mangrove restoration pathways depending on site conditions (Bosire and others 2008; Feagin and others 2010). Kathiresan and Rajendran (2005) conducted a study after the tsunami in 18 coastal hamlets along a 25 km coastline in Tamil Nadu, India, and concluded that the human death and loss of wealth due to the tsunami decreased with the area of coastal vegetation, distance and elevation of human inhabitation from the sea. Following this, Kerr and others (2006) reanalyzed the data and found that 87% of the mortality was explained by distance from the sea and elevation, while distance inland explained 61% of the loss in wealth. In response, Kathiresan and Rajendran (2006) pointed out that the study was limited to 18 hamlets of a particular area and the tsunami run up there was lower than other areas (only 2.8 m). They concluded that their results were very similar to Danielsen and others (2005) and substantiated their argument by citing past studies by Massel and others (1999) and Hiraishi and Harada (2003). Vermaat and Thampanya (2006) re-analysed Kathiresan's data and stated that the first conclusion of Kathiresan and Rajendran (2005) "holds" true and that "mortality and property loss were less behind mangroves". However, in an erratum to this article, Vermaat and Thampanya (2007) mentioned that their statistical analysis was flawed and they could not maintain their earlier conclusion that mortality was less behind mangroves.

Danielsen and others (2005) suggested that mangroves and *Casuarina* plantations were effective in reducing the intensity of the tsunami induced waves and in shoreline protection. However, Dahdouh-Guebas and Koedam (2005a) addressed some *caveats* in Danielsen and others (2005). They remarked that the authors did not utilize the satellite imagery to the fullest potential to ascertain the "cryptic ecological degradation" of the mangrove forests prior to the tsunami. Secondly, the authors did not consider the possibility of variation in housing construction and within-site variation in tree cover as critical factors influencing damage to hamlets. As a response to this critique, Danielsen and others stated that (a) their field sites were relatively homogeneous, (b) high resolution images to compare the effect of the tsunami were not available and (c) housing constructions was relatively uniform. They concluded their response by strongly re-affirming the beneficial roles of coastal forests, wetlands and dunes in the light of the tsunami.

Olwig and others (2007) investigated the protective role of bioshields against the December 26th 2004 tsunami. They compared the pre-tsunami and post-tsunami Ikonos and Quick Bird satellite images and concluded that coastal vegetation structures like mangroves and coastal shelterbelts had provided protection from the tsunami. However, Bhalla (2007) tested the assumption that coastal vegetation affected tsunami inundation using field based mapping and remote sensing and found that there was no significant correlation between vegetation cover (Normalised Difference Vegetation Index) and inundation caused by tsunami. The author also discussed the detrimental impact of planting exotic trees like *Casuarina* on natural sand dunes (non-indigenous for the respective areas). Mascarenhas and Jayakumar (2007) looked at the effectiveness of *Casuarina* plantations and sand dunes as bioshields. They noted that uprooting of *Casuarina* trees was limited to a frontal strip that ranged from 5 to 25 m (average width, 14 m). They emphasized the importance of sand dunes and coastal vegetation in shore line protection and concluded by highlighting the significance of the Coastal Regulation Zone Notification, 1991—India's most comprehensive coastal protection legislation.

Wolanski (2007) has given a detailed account of the value of mangroves as bioshields. The author has argued based on secondary literature that coastal forests including mangroves need to be restored urgently for shoreline protection as well as for ecohydrological services. In a general discussion on the protective role of mangroves against tsunami, Dahdouh-Guebas and Koedam (2006) have touched upon the beneficial role of mangroves from an interdisciplinary perspective in the context of the December 2004 tsunami. Chatenoux and Peduzzi (2007) looked at both geomorphologic and biological parameters determining the vulnerability of a site to tsunamis. Results of this study indicate that mangroves identified by the authors naturally flourish in geomorphologically sheltered areas and were therefore not the most effective tool to address the issue of coastal protection. According to the data, seagrass beds appear to have attenuated the impact of the tsunami, while coral reefs may have exacerbated the impacts.

In a review on mangrove forests covering aspects of resilience, protection from tsunamis and vulnerability to climate change, Alongi (2008) points out that mangroves may offer limited protection from tsunamis in some cases. The author mentions that some models have suggested marked reduction in tsunami wave flow pressure for forests that are at least 100 m in width. Two papers have quantified the damage caused by the tsunami to mangroves in Andaman and Nicobar islands (Ramachandran and others 2005; Roy and Krishnan 2005). The results of these studies indicate that 51-100% of mangroves in Nicobar Islands and 30-80% of mangroves in South Andaman Islands were affected by the tsunami. The need for bioshields was also pointed out, such as within the framework of Integrated Coastal Zone Mangament [ICZM] (Sonak and others 2008)

Sand Dunes/Vegetation

Two articles highlight the protective role of sand dunes against the tsunami (Mascarenhas and Jayakumar 2007, Bhalla 2007). The former looks at inundation limits, run-up heights and measurement of cross-section profiles in 24 major locations along the coast from Chennai southwards for 350 km. The authors also assessed damage to coastal dwellings and impact on vegetation. Bhalla (2007) highlights the threats to sand dunes due to indiscriminate exotic plantations and points out the need to protect sand dunes as a natural barrier to tsunamis and storm surges. Among three generic studies, only one had quantified the damage in four Nicobar Islands (Ramachandran and others 2005). This is perhaps the only published scientific paper that has compared and quantified changes in sandy beaches between 21st December, 2004 and 4th January, 2005 . The authors report an increase in two of the four islands in Nicobar (Trinkat: 18.7 ha. and Katchal 1242.02 ha.), while sand cover decreased in Camorta 368.72 ha. (103.43%) and Nancowry 78.98 ha. (31%).

Others

Meiofauna

A study of the impact of tsunami on meiofauna at Marina beach in Chennai showed that meiofauna responded quickly to the physical disturbance caused by the December 2004 tsunami (Altaff and others 2005). Though meiofaunal density reduced one and two days after the tsunami, they recolonised to much higher densities especially on the 3rd and 4th day after the tsunami. While oligochaetes, nematodes and harpacticoids showed reduced populations, polychaetes and turbellarians occurred at a higher density after the tsunami. The authors attribute this to the fact that the latter groups might be able to withstand the impact of disturbance better than the other groups and to altered granulometric conditions of the beach itself.

Foraminifers

Only one study attempted to ascertain the change in diversity of foraminifera due to the tsunami (Gadi and Rajashekhar 2007). Inter-tidal samples collected after the tsunami in January 2005 were compared with shore samples collected pre-tsunami in December 2004, showing that total foraminiferal number, organic matter and calcium carbonate had increased in post-tsunami samples. The change in species diversity was also found to be significant. The authors had further observed a significant increase in foraminiferal relicts in post-tsunami samples which indicated a large-scale transportation of deeper water offshore sediment to the intertidal zone.

Seaweeds

The only study on seaweeds was carried out at intertidal locations of different islands of Andaman and Nicobar, viz.

South Point Port Blair and Obragza, South Andaman Island; Mayabandar, Middle Andaman Island and Malakka, Car Nicobar Island (Mantri 2005). All these islands showed destruction of seaweed habitats and seaweeds were observed to colonise newly formed habitats like the submerged roads, debris and remains of destroyed houses and coconut orchards.

Microbiology

The impact of the tsunami on microbial density was studied on microbial populations in four locations of the Chennai coast of the Bay of Bengal (Ramesh and others 2006). The main finding of the study was a sudden increase in the microbial population 5-10 h after the tsunami in all the marine samples irrespective of the location. It was also noted that populations of pathogenic bacteria such as coliform and vibrios did not increase after the tsunami.

Coral Reefs

Out of the four papers reviewed, only one of them is dedicated specifically to the assessment of damage caused to corals (Kumaraguru and others 2005) while three generic studies, while highlighting the ecological impact of the tsunami, also focused partly on corals (Chatenoux and Peduzzi 2007; Krishnankutty 2006; Ramachandran and others 2005). This study was carried out using remote sensing and reported that live coral cover in the Gulf of Mannar declined from 48.5% to 36% after the tsunami. About 30% of the coral cover was under silt deposition and roughly 6.7% of corals were killed, upturned or broken. The situation was similar in Palk Bay though the losses were more moderate than the Gulf of Mannar. Studies of coral reef ecosystem using remotely sensed data from the four Nicobar Islands (Camorta, Katchal, Nancowry and Trinkat) found that 41% to 100% of the reef ecosystem was affected by the tsunami (Ramachandran and others 2005) in those areas. Chatenoux and Peduzzi (2007) looked at the protective function of environmental features against tsunami, in which the authors suggest that coral reefs had a positive correlation with damage caused by tsunami. The authors reasoned that this was because corals occur in shallow areas, which might offer protection against mild/small waves but in case of the tsunami, the wave energy continued to build up in such an area. The third paper suggests that corals would provide an excellent system to study the ecological disturbance caused by the tsunami to the marine ecosystems (Krishnankutty 2006).

Generic

Three comprehensive studies broadly encompassed all the major ecosystems (termed as generic in the Table 5). These were Ramachandran and others (2005), Krishnankutty (2006) and Chatenoux and Peduzzi (2007). Each of these studies has been elaborated upon based on the ecosystems they have focused upon.

Research in Other Countries

Sri Lanka: There were a total of 84 journal articles pertaining to the tsunami. Out of these only eight articles were relevant to ecology. Protective effects of coastal vegetation (Kaplan and others 2009) impact of the tsunami on terrestrial ecosystems (Fernando and others 2006), sea turtle populations (Brodie and others 2008) were some of the topics covered in the published literature. A notable difference from the published research in India is the emphasis on post tsunami recovery and protection of coastal ecosystems (Mattsson and others 2009). The authors have evaluated the potential to restore and protect coastal land based on the context of Kyoto Protocol's Clean Development Mechanism. There was another study on the lessons learnt from the tsunami on the environmental implications for disaster preparedness (Srinivas and Nakagawa 2008).

Indonesia: A total of 94 peer-reviewed articles were published from 2004-09 December of which only 4 articles were related to ecology. Though a vast plethora of topics was covered ranging from early warning systems to studies on mental health, the number of articles on ecology was remarkably low. One of the articles was a bibliometric analysis of all documents published on the December 2004 tsunami. Amongst the four ecology related articles, two overlapped with that in Sri Lanka (Giri and others 2008; Srinivas and Nakagawa 2008).

Thailand: Out of a total of 132 articles published on the tsunami, 21 articles pertained to ecology. These articles covered many aspects of coastal ecosystems that were affected by the tsunami. The impact of the tsunami on mangroves (Yanagisawa and others 2009), macroalgae (Prathep and others 2008), corals (Chavanich and others 2008; Worachananant and others 2007), meiofauna (Grzelak and others 2009), littorinid molluscs (Sanpanich and others 2006) and sandy beaches (Hayasaka and others 2009; Szczucinski and others 2006) has been documented. Post tsunami restoration and recovery of coastal ecosystems have also been studied (Biswas and others 2009; Hayasaka and others 2009). Overall, Thailand had the most diverse range of ecological studies amongst all the tsunami-affected countries reviewed in our article.

Maldives: There were 16 articles published on tsunami in Maldives as of 16th December 2009. Most of the articles (12) were on geomorphology and two articles related to ecology. One of studies looked at impact of tsunami on coral reefs in Maldives (Goffredo and others 2007). The authors report extensive damage with the passes in South Male atoll being more damaged than the northern ones. The other study was a generic one, which looked at lessons, learnt from the four tsunami-affected countries on disaster preparedness and environmental aspects of the tsunami (Srinivas and Nakagawa 2008).

Discussion

An Overview of Research

The tsunami has stirred considerable interest in scientific circles. However, compared to the massive damage caused to life and property and the coastal ecosystems, the volume of literature on its impacts in India is still relatively small. The major emphasis of scientific debate was on the protective role of bioshields with very few empirical or observational studies or mathematical models comparing scenarios before and after tsunami. The rhetoric that followed each article focused unilaterally on one function of coastal vegetation (that of coastal protection) while many other ecological services that are provided by coastal vegetation were not explored at all (see reviews by Nagelkerken and others 2008 and Walters and others 2008). One study each was dedicated to corals, seagrasses, seaweeds and meiofauna pointing to the paucity of information and research attention dedicated to these ecosystems. One possible hindrance to evaluating tsunami-related changes is the near complete lack of baseline studies of coastal ecosystems in India. To put this into perspective, research on past severe natural disasters elsewhere (like the Krakatoa eruption in 1883 or the more recent Pinatubo eruption in 1991) are better documented in literature (see Gaillard 2008; Gleckler and others 2006; and Kelman and Mather 2008). A basic search on Pinatubo in Web of Science using the key words “Pinatubo”, “volcanic” and “eruption” yields 568 articles of which 24 are reviews as of 14th August, 2009.

Comparison of Ecological Research in India with Other Tsunami Affected Countries

Emphasis on documenting the impact of the tsunami on a large range of taxa (as was done in Thailand) could have been beneficial for India as well. This would help us in understanding better the consequences of a natural disaster at such a scale. It would also lead to informed decision making about management of these natural resources.

Post tsunami recovery studies are another area, which could be developed further. In Sri Lanka and Thailand for instance, post tsunami restoration and rehabilitation has been studied. While in social sciences, the recovery of mental health from trauma or stress has received adequate emphasis (both in India and in the other four nations), ecological recovery studies are relatively fewer. Human induced ecological restoration efforts often involve huge international funds and need large inputs of local labor. It is thereby critical to document the success or failure of such efforts and the possible causes that it could be attributed to (see Feagin and others 2010).

Gaps in Research

The dearth of baseline geological studies along the coast is perhaps the most critical issue that needs to be addressed. For instance, bathymetry of the entire coastline has still not been documented even four and a half years after the tsunami even though several studies have suggested that bathymetry of the coast plays a major role in determining vulnerability of the coast and coastal ecosystems to storm surges (Kerr and others 2009). The seasonal and long term changes in coastal geomorphology and ocean currents are critical factors which have considerable consequences on coastal ecology. Unfortunately, there are few studies which have documented such changes along the Indian coastline, partly due to difficulties in accessing data.

While we do not attempt to provide a comprehensive research agenda for coastal ecosystems, it is clear that effective baseline studies need to address a few lacunae. For example, accurate distributional information is required for many subtidal ecosystems like seagrass meadows, coral reefs and soft-sediment ecosystems, and this mapping is an essential first step in describing these systems. In addition, many of these ecosystems are not well surveyed for their species and community composition. Equally important is an assessment of the current state of these ecosystems and species in terms of ecosystem function, population processes, anthropogenic impact, and resilience to global change processes. In addition, long term monitoring studies for coastal ecosystems need to be established to assess trends in the context of climate change, local anthropogenic impact and conservation prioritization. The ecosystem services provided by native ecosystems should be documented in detail. Socio-economic surveys are expected to help in this regard. The lack of knowledge and awareness about such services are often the biggest obstacles to the conservation and management of these ecosystems.

Linkages Between Science and Policy and its Implementation

The role played by coastal vegetation in preventing extreme storm surges was debated by several authors. Though Das and Vincent (2009) have demonstrated the importance of mangroves as natural barriers against cyclones in Orissa, more studies are needed in other coastal areas and for plantations like *Casuarina*. There is an increasing consensus among many authors that there is no experimental evidence to support the idea that vegetation can reduce the effect of long-period waves such as a storm surge or tsunami (Kerr and Baird 2007; Feagin and others 2010), but many also advocate the precautionary principle (Dahdouh-Guebas and others 2005b; Feagin and others 2010). Other studies have also suggested that the impacts of these extreme events are highly dependent on other physical factors like topography, near-shore bathymetry and distance from the shore (Bhalla 2007; Chatenoux and Peduzzi 2007; Kerr and others 2009). It has also been pointed out that protection from waves is different from protection from rising water levels, which is the leading cause of death during these events (Feagin 2008). The issue of exotics is also problematic; plantations of exotics have been shown to have negative impacts on coastal habitats and species, one example being the nesting beaches of sea turtles in Orissa (Pandav 2005). However a recent study has shown that beach vegetation can act as an effective barrier against artificial beach lighting and thereby aids in sea finding behavior of sea turtles, provided the vegetation exists 50 m away from the high tide line (Karnad and others 2009).

There appears to be little correlation between the limited research that was carried out after the tsunami and its influence on policy decision making. Studies demonstrating the positive role of coastal vegetation have often been used selectively to advocate the propagation of exotics like *Casuarina* or of native vegetation (mangroves) in areas, which are generally not appropriate for their development. Often, there are drivers other than coastal protection behind such policy implementation (Feagin and others 2010). What is worse is that native ecosystems like sand dunes are destroyed in the name of coastal protection for planting exotics. For instance, the Tamil Nadu Forest Department in southern part of India has initiated large scale planting of *Casuarina equisetifolia* along the coast (Mukherjee and others 2009). About 20 km^2 of *Casuarina* is currently being planted under the Emergency Tsunami Rehabilitation Project in this state alone. Ironically, bioshields are not being planted in most areas in front of villages and hamlets, but in areas adjacent to them, and hence it is highly unlikely that they can play a protective role (PTEI 2007).

Coastal Protection Policy

There is clearly a dearth of articles relating to policy and governance related issues in peer reviewed journals. Very few interdisciplinary studies have looked at linkages between pure/applied sciences and the social sciences. The Coastal Regulation Zone Notification, 1991 (hereafter CRZ Notification) issued under the central legislation—Environment (Protection) Act, 1986, is India's most comprehensive legislation that affords a measure of protection to coastal habitats and sensitive areas. It declared coastal stretches within 500 m of the High Tide Line, in mainland India and the Andaman and Nicobar Islands and the Lakshadweep Islands, as the 'Coastal Regulation Zone'—an area where activities were restricted or prohibited. These areas were further categorized as CRZ –I, II, III and IV areas with differing protection measures. There are several overlaps in the jurisdiction of the central government and the state governments over coastal areas and their natural resources, which make the management of these resources extremely ambiguous and difficult. The situation is further worsened in a socio-political context where each state government desires to develop its economy and seeks maximum autonomy from the centre in decision-making. Therefore, despite containing clauses that outline the management of the CRZ, and coastal natural resources like sandy beaches or mangroves, the implementation of this law has been poor and the notification had been amended and diluted on over 19 occasions prior to the tsunami (Menon and Sridhar 2007).

Due to these amendments and the ambiguity of the clauses in the notification, a UNDP study showed that immediately after the 2004 tsunami, there was much confusion about where reconstruction and rehabilitation could take place along the coast; whether coastal habitations of fisherfolk were permitted or prohibited and what the official position should be on 'bioshields' (Sridhar 2005). The tsunami drew a great deal of attention to the subject of coastal legislation and in fact galvanized the Indian Ministry of Environment and Forests into stepping up their intentions of revising the CRZ Notification. Several versions of the new draft legislation have been issued, each meeting with criticism and skepticism from environmentalists and fishworker groups who argue that these drafts pay scant attention to actual protection. Instead these notifications appear to dilute government control and restrictions over activities in coastal areas, and even 'open up' these regions to non-coastal industries affecting both coastal communities and ecosystems (Menon and others 2007).

All the literature on the subject of coastal management is found in reports commissioned by aid agencies (including UNDP, FAO, World Bank and ADB) and in special reports published by non-government organisations and independent researchers. While better knowledge of coastal ecological systems is required through long term monitoring of habitats and ecosystems, it is equally critical to study environmental governance, policy-making and implementation. This will provide insights into the links between knowledge generation, law and policy, which would have implications on ecological and social systems.

Acknowledgments The authors would like to thank Arunachalam Gokul, B. Muthuraman and all others involved in the PTEI project in Ashoka Trust for Research in Ecology and Environment, Nature Conservation Foundation and Foundation for Ecological Research Advocacy. This study was funded by the Centre for Ecological Studies, Post tsunami Environment Project and Inlaks Foundation.

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