Shelter from the storm? Use and misuse of coastal vegetation bioshields for managing natural disasters

Rusty A. Feagin¹, Nibedita Mukherjee²,³,⁴, Kartik Shanker⁴,⁵,⁶, Andrew H. Baird⁷, Joshua Cinner⁷, Alexander M. Kerr⁷,⁸, Nico Koedam⁵,³, Aarthi Sridhar⁴,⁵, Rohan Arthur⁹, L.P. Jayatissa¹⁰, Danny Lo Seen¹¹, Manju Menon¹², Sudarshan Rodriguez⁴,⁵, Md. Shamsuddoha¹³, & Farid Dahdouh-Guebas²,³

¹ Spatial Sciences Laboratory, Department of Ecosystem Science & Management, Texas A&M University, College Station, TX 77845, USA
² Laboratory of Plant Biology and Nature Management, Faculty of Sciences and Bio-engineering Sciences, Vrije Universiteit Brussel-VUB, Pleinlaan 2, B-1050 Brussels, Belgium
³ Laboratory of Complexity and Dynamics of Tropical Systems, Département de Biologie des Organismes, Faculté des Sciences, Université Libre de Bruxelles—ULB, CP 169, Avenue F.D. Roosevelt 50, B-1050 Bruxelles, Belgium
⁴ Ashoka Trust for Research in Ecology and the Environment, No. 659, 5th ‘A’ Main Road, Hebbal, Bangalore 560024, India
⁵ Dakshin Foundation, Second Floor, Gowri Nilaya, Behind Baptist Hospital, Vinayak Nagar, Hebbal, Bangalore 560024, India
⁶ Centre for Ecological Sciences, Indian Institute of Science, Bangalore 560012, India
⁷ ARC Centre of Excellence for Coral Reef Studies, James Cook University, Townsville, Queensland 4811, Australia
⁸ The Marine Laboratory, University of Guam, Mangilao, Guam 96915, USA
⁹ Nature Conservation Foundation, 3076/5, 4th Cross, Gokulam Park, Mysore 570002, India
¹⁰ Department of Botany, University of Ruhuna, Matara, Sri Lanka
¹¹ CIRAD–Territories, Environment, Remote Sensing and Spatial Information Joint Research Unit (UMR TETIS), F-34093 Montpellier Cedex 5, France
¹² Kalpavriksh, 134, Tower 10, Supreme Enclave, Mayur Vihar, Phase 1, Delhi 110 091, India
¹³ Participatory Research and Development Initiative, Tejgoan, Dhaka 1215, Bangladesh

Keywords
Bioshields; hurricanes; tsunami; coastal vegetation; wave attenuation; storm surge; disaster management.

Abstract
Vegetated coastal ecosystems provide goods and services to billions of people. In the aftermath of a series of recent natural disasters, including the Indian Ocean Tsunami, Hurricane Katrina and Cyclone Nargis, coastal vegetation has been widely promoted for the purpose of reducing the impact of large storm surges and tsunami. In this paper, we review the use of coastal vegetation as a “bioshield” against these extreme events. Our objective is to alter bioshield policy and reduce the long-term negative consequences for biodiversity and human capital. We begin with an overview of the scientific literature, in particular focusing on studies published since the Indian Ocean Tsunami in 2004 and discuss the science of wave attenuation by vegetation. We then explore case studies from the Indian subcontinent and evaluate the detrimental impacts bioshield plantations can have upon native ecosystems, drawing a distinction between coastal restoration and the introduction of exotic species in inappropriate locations. Finally, we place bioshield policies into a political context, and outline a new direction for coastal vegetation policy and research.

Introduction
Vegetated coastal ecosystems provide goods and services to billions of people. However, there has been considerable effort since the Indian Ocean Tsunami in 2004 to promote the maintenance of coastal vegetation primarily for the purpose of disaster management, a concept first discussed in Fosberg & Chapman (1971). Driven by policy-makers, donor agencies such as the Food and Agriculture Organization (FAO) and the United Nations Environmental Programme (UNEP) have spent considerable resources planting coastal vegetation to act as “bioshields” to protect against natural disasters such as tsunami and storm surges. Following convention, we use the term “bioshield” to refer specifically to the use of vegetation for protection from these extreme events. For a more detailed review of the agencies that are building bioshields, their funding sources and pathways, and the extent of
land covered by bioshields, we refer the reader to a companion review, Mukherjee et al. (2009).

The recent interest in bioshields fits within a longer history of humans attempting to stabilize vulnerable or eroding coastlines. Native vegetation within the first kilometer of the coast is typically adapted to a dynamic environment, including among other features: episodic conditions of salt water inundation or salt spray, mass sediment movement, and relatively rapid succession or spatial migration after disturbance. Along much of the world’s coastlines, exotic species have been introduced for the purposes of stabilizing the substrate and reducing this dynamism, including Casuarina equisetifolia L. in the Indian Ocean and Caribbean Sea regions, Tamarix gallica L. in the Gulf of Mexico, Acacia spp. in the Mediterranean Sea, Pinus spp. in the Great Lakes of Canada, Rhizophora mangle L., and Spartina alterniflora Loisel in Pacific Ocean region mud flats, and Ammophila spp. on Pacific Ocean region beaches and dunes, among a long list of others (Cronk & Fuller 2001; Global Invasive Species Database 2009). In each of these examples, short-term stabilization of the substratum has been achieved at the expense of long-term ecological sustainability. For a more detailed review of law, policy, history, and ecology as it relates to the conflict between stabilization and sustainability, we refer the reader to a companion review, Feagin et al. (2010).

Our objective in the present review is to inform and alter policy—we are responsible for basing actions upon the best scientific knowledge available. Our intent is not to denigrate the difficult work that conservation and donor agencies have put into conserving coastal ecosystems; in fact, nearly all of the authors of this review have been involved in projects where vegetation was either restored or introduced for the stated purpose of reducing the impact of natural disasters. Yet as this review notes, there are distinct differences between the restoration or conservation of native habitats and the introduction of exotic species into non-native habitats. While the scientific literature on bioshields focuses on restoration and conservation, often this knowledge is used to defend and activate policies that implement introduction. We hope that this review ensures that policy-makers, donors, scientists, managers, and the public are aware of the threats to both biodiversity and human capital.

The call for coastal bioshields after recent extreme events

Bioshields have been advocated as natural barriers following several recent coastal disasters. For example, after the devastation of the Indian Ocean Tsunami of 26 December 2004, a January 2005 report claimed a strong protective function of coastal vegetation (UNEP 2005). This report was soon followed by articles in the scientific literature that supported the bioshield concept with observational and remotely sensed data (Danielsen et al. 2005; Kar & Kar 2005; Kathiresan & Rajendran 2005). The result was a strong call for the donor community to invest in planting bioshields throughout South-East Asia.

However, subsequent work suggested that the correlation between area of coastal forest and tsunami damage was spurious, using the same datasets (Kerr et al. 2006; Bhalla 2007; Kerr & Baird 2007). This subsequent work found that when factors of topography and distance from shore where included in the regression equations, vegetation could explain only a slight reduction in damage. In a follow-up study sponsored by the UNEP, vegetation was found to have no effect on tsunami inundation at 52 sites from throughout the Indian Ocean (Chatenoux & Peduzzi 2007).

In 2005, the concept of bioshields gained more support after Hurricane Katrina hit the USA coast, with many stories in the press and primary literature viewing it as a policy-focusing event. In May 2008, a Category Four cyclone, Cyclone Nargis, struck Myanmar (Burma) causing over 100,000 fatalities (Rodriguez et al. 2009). While damage from the 200 km/hr winds and rain was extensive, the 4 m storm surge inundated large areas of low-lying country. Many authors suggested that the destructive power of the storm surge was exacerbated by recent loss of mangrove forest in Myanmar (FAO 2008; IUCN 2008; Spencer 2008), although no primary evidence to support these statements was presented.

The number of studies assessing the role of vegetation in mitigating coastal natural disasters has grown rapidly since 2004 (see Supporting Information material online for a full list of Additional References), and typically follows one of several paths:

(1) Anecdotal evidence, which details the opinions of those who witnessed the extreme event (e.g., Venkatachalam et al. 2009). Because these offer personal accounts, they are not falsifiable, nor testable in a scientific sense. Nonetheless, these observations are important as the basis of forming specific hypothesis to be tested in a formal framework.

(2) Post-hoc observational studies, which use questionnaires distributed to residents of areas affected by extreme events (e.g., Chang et al. 2006) or ground-based surveys of apparent damage (e.g., Granek & Ruttenberg 2007; Tanaka et al. 2007). These studies must infer causation, as they are based only on those accounts collected or features assessed after the event. Still, they must also be integrated as elements in a critical evaluation.
Remote sensing-based work, which uses imagery to correlate damages with vegetative cover (e.g., Iversen & Prasad 2007; Das & Vincent 2009). Work in this area is still limited by the physical factors that confine the vegetative effect (Baird & Kerr 2008) and the lack of high-resolution elevation data sets in the study areas.

Modeling, which uses mathematical equations to calculate friction and drag of vegetation in tsunami (e.g., Tanaka et al. 2008) or storm surges (Dean & Bender 2006) at field scale. These studies are theoretical in approach. One can also conduct laboratory studies that operate at prototype scale (e.g., Irtem et al. 2009), but typically the field-scale water forces are not scaleable down to the prototype scale for extreme events (Lynett 2007) and this remains a challenge.

None of these paths follow the most rigorous test in science, the construction of properly controlled, experimental investigation of the actual phenomena in the field. Though previous research has been valuable, Feagin et al. (2009) demonstrates the importance of testing such initial forms of evidence gathering with field-based work where vegetation has been removed prior to an event, with paired vegetated controls of similar elevation—in this case, overturning the paradigm that roots directly prevent wave erosion on the edges of wetlands (rather, the vegetation indirectly reduces erosion by increasing the organic matter content and reducing the average grain size of the soil, yet this accretion-related process typically takes decades while the direct vegetation effect is nonresponsible to immediate wave impact).

The paths of research outlined above suffer from the fact that it can be difficult to constrain confounding factors. The impacts of these extreme events often depend on topography, near-shore bathymetry, distance from the shore and other physical factors (Cochard et al. 2008). Additionally, the vulnerability of coastal populations to episodic events can also be due to inappropriate coastal development, that is, simply placing more people in harm’s way (Dahdouh-Guebas et al. 2005a; Dahdouh-Guebas & Koedam 2006), or socio-economic factors such as lack of education regarding evacuation, physical exposure due to a substandard built environment, and a lack of post-event emergency response measures (Osti et al. 2008). Each of these factors must be removed during statistical analyses before conclusions can be drawn about the independent effect of vegetation. Although this process can be difficult for complex phenomena, it can be handled with a proper use of multiple regression and other statistical methods (Kerr & Baird 2007). Finally, there has been only one study that has addressed the actual cause of disaster, that is, rising water levels (Krauss et al. 2009); protection from waves is different from protection from rising water, and rising water (and associated debris) is the leading cause of death during these events (Feagin 2008).

Therefore we must pursue inductive research to address these questions, insofar as it is possible. The inductive scientific method demands that we treat the null hypothesis as valid only after failing to reject it—rather than trying to prove the null hypothesis itself. In the interim, a ‘precautionary principle’ is advised before basing any policy upon the current body of work, either for or against bioshields.

Can coastal vegetation alter storm surge or tsunami water levels?

While there is much general literature on the ability of vegetation to attenuate short-period waves (e.g., Mazda et al. 1997; Möller et al. 1999; Vo-Luong & Massel 2008), storm surges and tsunami are categorically different from waves. These extreme events raise the base water level over a much longer period of time than happens when individual waves pass through vegetation, with a much greater net force, and a much larger spatial extent (Figure 1). They behave more like the tide, a long-period wave rather than a series of wind waves (even large wind waves tens of meters high and long).

A storm surge consists of a large body of water, typically 300–700 km across in a tropical system, produced both by the rising of sea level due to atmospheric low pressure within the system and by set-up, which is the tendency for water levels to accumulate downwind (Figure 2). Surges often penetrate far inland, backfilling tidal distributaries and raising water levels over several hours, even in areas where there are no waves present. For example, most deaths during Hurricane Katrina in 2005 (the costliest natural disaster in U.S. history) were caused by rising water levels (not waves) that crept through a strait, into a lake, and finally spilled into the city of New Orleans from a direction opposite to that of the approach of the storm—and this water rise happened primarily during the day after the storm had passed.

A tsunami is also a long-period wave, but one that amplifies and shortens as it approaches the coast. The long-period form of a tsunami is different from the short-period form of typical waves, even when these short-period waves are large in height (Yeh et al. 1994). Wave celerity is high (about 10 to 100 times faster than standard ocean waves) and the wave quickly floods the coast over several minutes to hours. The scale at which vegetation can attenuate waves on the immediate coast (centimeters to tens of meters; seconds) simply does not...
match the much larger wave form that causes coastal damage during extreme events (hundreds of kilometers; minutes to days). Thus, we should not assume that the science on short-period wave attenuation supports the conclusion that vegetation can reduce the effects of storm surges or tsunami.

**A case study from India**

In India, the concept of bioshields has moved actively to developing vast plantations of exotic trees (mainly *Casuarina equisetifolia* L.) to act as bioshields, despite a range of issues including the selective application of science to support predetermined agendas, violations of indigenous land rights, and loss of biodiversity (Shanker et al. 2008). These bioshield plantations are funded and facilitated by various nongovernment organizations and international bodies like the World Bank. For instance, under the Emergency Tsunami Rehabilitation Project funded by the World Bank, the Tamil Nadu Forest Department has initiated large-scale (~20 km²) planting of *Casuarina* along the Kariakal and Nagapattinam coast (Mukherjee et al. 2009), taking up to 41% of the coastline in
R.A. Feagin et al.

Shelter from the storm

Figure 2  (A) While vegetation may be able to dampen wind waves that pass in a period of seconds and have a wavelength measureable in meters, it cannot stop storm surges which are often on the scale of $10^5$–$10^6$ m in wavelength, and take several hours to inundate an area. A storm surge behaves more like tidal forces, able to penetrate diffuse vegetation and back-fill tidal distributaries. (B) A storm surge is primarily composed of large-scale wind “set-up” and an increase in water level due to lower barometric pressure over the storm. Wind waves, even when large, simply travel on top of this surge.

The socio-economic aspects of exotic bioshields appear to be drivers of plantation efforts, perhaps more so than the coastal protection function. While international organizations have cited scientific evidence in support of their effectiveness as barriers, they have also been careful to list other values such as their use as community fuelwood. In the eastern state of Andhra Pradesh for instance, plantations are currently being funded by a World Bank initiative, the Andhra Pradesh Community Forest Management project (APCFM 2009). The bioshields here are nested within the Joint Forest Management or Community Forest Management program, which aims to reduce natural resource dependence on Reserve Forests and improve rural livelihoods. The economic returns from Casuarina plantations are substantial for the local communities engaged in these activities in Andhra Pradesh (Rs. 25,000/ha = USD $600/ha after 4 years) (APCFM 2009). This money has been agreed to be shared equally, half by the community and the other half to raise more plantations. In addition, local communities gain access to fuel wood and small timber after the fourth year of plantation (though tree removal would seem to counter the justification of the bioshield plantation). For marginalized fisherfolk living in remote areas along the coast, this could provide a vital monetary and material resource to meet household needs.

However, local coastal communities themselves appear to have divergent opinions about coastal plantations, and fisherfolk communities in many hamlets have been known to oppose strongly and even uproot Casuarina saplings from plantations (Rodriguez et al. 2008). The main causes for this conflict concern indigenous rights to coastal lands and accessibility for boats to the sea; both of which can be compromised by plantations. Although well intentioned, conflicts often arose because participation of communities was poor in many instances, which was reflected through inappropriateness of the plantation locations, inequity in distribution of benefits and poor management of these plantations themselves (Rodriguez et al. 2008). The villages and hamlets in this area did not have mangroves or Casuarina near them in the recent past. Ironically, in most areas, bioshields have not been planted in front of the villages and hamlets for protection from the dominant direction of oceanic energy, but in areas adjacent to or behind them. Of the 40 villages surveyed in Kariakal and Nagapattinam district, only one actually had Casuarina plantations seaward of the village (Rodriguez et al. 2008). This was a small village with few active fishermen and boats.

If done effectively, Casuarina plantations can be an important supplemental livelihood for marginalized coastal communities, but should be pursued as such. In their current form, Casuarina plantations appear to have little support from communities. Yet, bioshield plantations located adjacent to or behind coastal communities are often the primary disaster management strategy along this coast, possibly giving a misleading feeling of security to policymakers. Thus, the opportunity costs of this focus on
exotic bioshields in India is that work on developing disaster preparation efforts and building resilience in the wider social-ecological system has been neglected.

Displacement of native ecosystems and people

Bioshield plantations have displaced native vegetated ecosystems in many areas. In some locations, exotic Casuarina plantations have been promoted as a better alternative to native vegetation species. For example, in India Prosopis spicigera L. was blamed for laceration-caused deaths during the tsunami due to thorny plant structures (Kathiresan & Rajendran 2005). Other native species from this area are typically ignored as alternatives, for example Hibiscus tiliaceus L., Tamarix troupii Hole, Clerodendrum (Clerodendron) inerme (L.) Gaertn. (APCFM 2009). Unfortunately, most native trees grow slowly in the absence of regular watering except for Pongamia pinnata (L.) Pierre and Thespesia populnea L. Sol. ex Correa, but neither of these provide the fuel wood to supplement livelihoods. The use of exotic rather than native species, for protection and stabilization, is common practice in many other coastal areas as well.

In India, sand dunes have been flattened to make way for these plantations (Figure 3), destroying sea turtle nesting habitat and reducing the natural effectiveness of coastal dune topography to provide protection from storms. Further, Casuarina roots have a direct negative effect on sea turtles in India, as they can prevent females from digging their nests above the high tide line (Cronk & Fuller 2001). Casuarina is also known to have a negative impact upon tropical birds and invade mangrove ecosystems as well (Global Invasive Species Database 2009).

Moreover, plantation projects often demand the displacement of indigenous peoples from the coast (e.g., Sri Lanka, Ingram et al. 2006; Wong 2009a), allowing their undocumented land rights to disappear while filling the coast with new developments (e.g., India, Rodriguez et al. 2008). The construction of such plantations has serious consequences for indigenous land tenure as central government regulations currently do not recognize various undocumented customary uses of coastal areas (e.g., India, Menon & Sridhar 2007).
Are bioshields:

- ...effective against extreme events?
  - **Y**
  - **N**

- ...needed for other ecosystem services (fuel wood, tourism, fisheries support, erosion protection)? For restoration?
  - **Y**
  - **N**

- ...ecologically suitable? Possible without damaging dunes, mangroves, or other native ecosystems?
  - **Y**
  - **N**

- ...not used to justify the absence of emergency preparedness, construction of shelters, early warning systems, planning initiatives?
  - **Y**
  - **N**

- ...done with involvement of local community? Residents not removed, access to public resources not cut off, without due process of law?
  - **Y**
  - **N**

- ...able to be planted elsewhere (inland) to avoid conflicts?
  - **Y**
  - **N**

**Establish plantation in appropriate location**

**No Action**

**Implement other initiatives, then revisit**

**No Action**

**Figure 4** Decision tree for the establishment of bioshields in appropriate locations.

---

**Changing bioshield policies**

Though there is considerable emphasis from government and civil society on the use of scientific evidence in decision making, it appears that long-standing political agendas rather than science have driven bioshield policies in many developing countries. Extreme events on the coast are currently being used to justify bioshields, essentially ignoring the fact that vegetation can offer protection against a wide series of other water-related events such as excessive river or slope runoff (Bradshaw et al. 2007), daily tidal and short-period wind-wave erosion. Ironically, some of the same international institutions that advocate bioshields (e.g., FAO & CIFOR) have also understated the capacity of forests to reduce rainfall-induced flood frequency and intensity in inland areas in order to promote a political agenda of deforestation and forest harvesting (Alila et al. 2009); this is in stark contrast to overstating the benefits of coastal vegetation during extreme water surge events—yet in both cases the goal is the same, to promote a pre-determined policy outcome.

The advocacy of bioshields also devalues the many other non-“extreme event protection” functions and services that native vegetation provides, ignoring the more difficult work of defending these ecosystems for their other benefits. For example, mangrove ecosystems are valuable for ecosystem services (Barbier et al. 2008) such as fisheries support, water filtration, carbon sequestration, nutrient cycling, medicinal and food sources, habitat and cover for a wide range of species, land-building processes, tourism support, and aesthetics (Duke et al. 2007). Yet, there is a risk of losing these ecosystems if we overvalue the protection service (Sanford 2009) at the expense of the many other ecosystem services. If direct protection is recognized as the most important service that an ecosystem can provide, then society may eventually choose to replace it by arming the coast, that is, sea-walls, bulkheads, levees, etc. (Koch et al. 2009).

To avoid the potentially negative impacts of bioshield policies and emphasize their positive roles, we propose the use of a decision tree for policy-makers (Figure 4). At critical branches within this decision tree, policy-makers must ascertain that the policies produce realistic and sustainable outcomes. Such decisions will rely upon site selection, and placing native species in appropriate locations. For example, we conducted a site-selection analysis for planting mangrove forests in Sri Lanka in response to the country’s interest in using vegetation for potential protection (see Supporting Information material online for detailed Methods and Results). We found that
two-thirds of the vulnerable coastline did not have the appropriate environmental settings for mangrove forests to develop (Figure 5). Their introduction in the wrong settings would have replaced other native ecosystems, particularly sand dunes; although for previously degraded mangrove sites, we strongly advocated their restoration provided that the physico-chemical conditions were suitable. Planting any trees for stabilization in sand dune areas would have been short-sighted since sand dune plants are adapted to survival in dynamic sediment movement conditions and would re-build the landscape after such an extreme event (as is happening after the 2004 Indian Ocean tsunami, as Wong 2009b points out). *Casuarina* or mangrove trees do not promote dune accretion processes, and in the long term, ecosystem sustainability would be lost. For Sri Lanka, planting or restoring mangrove trees would be most suitable, and most likely to succeed, in the areas we outline in Figure 5. In such areas mangroves can, over the long-term, alter topography and bathymetry through processes of sediment accretion, reducing the vulnerability of the landscape to future inundation. Additionally, site-selection analysis can be done in partnership with an assessment of cryptic ecological degradation, where a ‘native’ species expands beyond its traditional niche due to anthropogenic impacts, thereby reducing long-term ecological sustainability (e.g., humans disturb *Rhizophora* spp. mangrove habitat in Sri Lanka, then allow *Acrostichum aureum* L. to predominate during regeneration process, leading to the impoverishment of overall forest biodiversity, as Dahdouh-Guebas *et al.* 2005b points out).

We propose that a similar site selection procedure occur globally for potential bioshield projects, in order to minimize exotic introduction into improper locations and maximize the restoration opportunities. A related goal could be to calculate the extent of coastal lands currently ‘stabilized’ by exotic species and bioshield plantations, globally.

**Ways forward**

The best ways to reduce the impact of extreme episodic events are: (1) to reduce physical exposure by
promoting sensible coastal development; (2) to develop adequate disaster preparation; and (3) to enhance the capacity of social-ecological systems to cope with and adapt to surprise. Poorly planned development can increase the exposure of coastal communities to extreme events, particularly where such development is encouraged or unregulated. For example, the U.S. government’s National Flood Insurance Program encourages construction in low-lying areas by providing insurance below the market rate, while local governments encourage these developments to expand their tax-base (Bagstad et al. 2007). In areas such as India, increasing population pressure is driving development onto marginal lands and this represents the greatest source of conflating risk (UNDP 2004). A responsible strategy for reducing future impacts must ultimately address this primary cause.

Natural disaster management must include the development of early-warning systems, community educational initiatives on disaster preparedness, and evacuation plans at all governmental levels; these have been credited for saving millions of lives in Bangladesh since these systems were put in place with the help of the United Nations in the early 1980s. Comparing the effects of 2008s Cyclone Nargis with previous cyclones in the Bay of Bengal is informative, as another Category Four cyclone, Cyclone Sidr, struck Bangladesh in November 2007, yet resulted in less than 3,500 deaths (as also compared with Cyclone Sidr, struck Bangladesh in November 2007, yet resulted in less than 3,500 deaths (as also compared with Bhola in 1970 with over 300,000 deaths). The difference in death toll between Nargis, Bhola, and Sidr was likely the result of a much higher level of preparedness (Rodríguez et al. 2009). Contingency plans for tropical storms in Bangladesh include elevated shelters close to population centers, which provide a quick and effective means of vertical evacuation, the only effective way to escape a storm surge or tsunami (Sieh 2006). Indeed, 2–4 m in many storm events can be the difference between life and death. Likewise, in the case of the Indian Ocean tsunami, the construction of an early-warning system for the Indian Ocean is certainly the best use of limited resources for reducing the human toll of the next tsunami, as long as the warning is timely (Kerr et al. 2006). The benefits from plantations of exotic trees as bioshields will be lower when compared to the results gained when similar energy and expenditure is directed to increasing preparedness. A recent empirical analysis of the effects of an early warning given to the populace in India during the Orissa Super Cyclone in 1999 suggested the warning saved as many as 5 lives per village, compared with 1.72 lives given full vegetative cover (Das & Vincent 2009).

Coastal vegetation such as mangrove ecosystems is critical to the resilience and vitality of many coastal social-ecological systems and we believe that their conservation is necessary. In the long-term, the goods and services (e.g., carbon storage, increased fisheries production, or water purification) provided by mangrove forests are likely to be more valuable than gains from unsustainable agriculture or aquaculture (Huitric et al. 2002), even without the protection service values included. Indeed, conservation organizations can play a role in enhancing the resilience of coastal social-ecological systems. However, conventional efforts to conserve and restore coastal vegetation will be a limited component of building resilience in the wider social-ecological system. Considerable efforts will also need to be directed at building adaptive capacity in coastal communities—an element in how these communities may cope with and respond to natural disasters (Adger et al. 2005). Enhancing adaptive capacity might include the development of robust governance institutions, maintenance of local knowledge about disaster preparedness, increasing livelihood options, and meaningful investments in poverty reduction (Brooks et al. 2005; McClanahan et al. 2008).

Even the strongest supporters of natural barriers recognize the limits of bioshields against extreme coastal events (FAO 2006). The values of coastal ecological systems are best realized over the long-term and we must find better ways to communicate the value of conserving these ecosystems. Additionally, we should acknowledge that natural forces are only part of the problem. Poor policy and planning is turning these natural hazards into disasters.

Acknowledgments
We thank the United Nations Development Programme Post Tsunami Environment Initiative project for supporting a portion of this project. We acknowledge the support of the Vlaamse Inter-universitaire Raad (VLIR), GREEN DYKE Project ZEIN2008PR347, the Australian Academy of Science, and the Stockholm Resilience Centre. We thank the Forest Department officials in Tamil Nadu, Andhra Pradesh and Kerala for their co-operation. We also thank four anonymous reviewers and the subject matter editor for their many helpful suggestions.

Supporting Information
Additional Supporting Information may be found in the online version of this article:

Table S1 Total coastline of Sri Lanka and its breakdown into different categories.

Please note: Wiley-Blackwell is not responsible for the content or functionality of any supporting materials supplied by the authors. Any queries (other than
missing material) should be directed to the corresponding author for the article.

**References**


Editor: Dr. Corey Bradshaw