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

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

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Received: 24 August 2009; accepted 9 November 2009.

doi: 10.1111/j.1755-263X.2009.00087.x

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.

(3) Remote sensing-based work, which uses imagery to correlate damages with vegetative cover (e.g., Iverson & Prasad 2007; Das & Vincent 2009). Work in this area is still limited by the physical factors that conflate the vegetative effect (Baird & Kerr 2008) and the lack of high-resolution elevation data sets in the study areas.

(4) 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 nonresponsive 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

Figure 1 (A) Storm surge destruction as caused by September 2008's Hurricane Ike, Bolivar Peninsula, Texas, USA. (B) Tsunami destruction as caused by the December 2004 Indian Ocean Tsunami, Aceh, Indonesia. Buoyancy is a surprisingly powerful force as evidenced by the barge. In both cases, the rising base water level over a relatively long time period was the major cause of death and destruction. Images courtesy of the Texas General Land Office and the United States Geological Survey, respectively.

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 km^2) planting of *Casuarina* along the Kariakal and Nagapattinam coast (Mukherjee *et al.* 2009), taking up to 41% of the coastline in

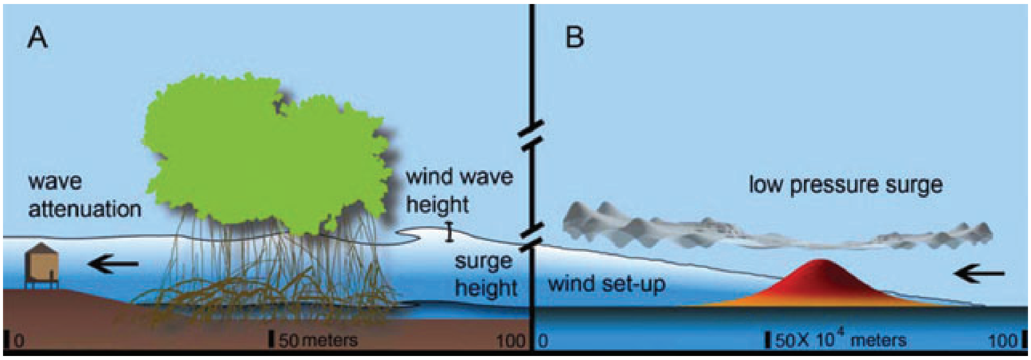

Figure 2 (A) While vegetation may be able to dampen wind waves that pass in a period of seconds and have a wavelength measureable in meters, it cannot stop storm surges which are often on the scale of 10^5–10^6 m in wavelength, and take several hours to inundate an area. A storm surge behaves more like 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 area (Rodriguez *et al.* 2008). Yet, Tamil Nadu Forest Department records show that the policy of raising *Casuarina* plantations has been a consistent practice on the coast, promoted since the late 1960s, if not earlier. Thus, while what we are witnessing on the east coast of India today is a continuation of a several decades-old trend, the scale of planting exotic trees is likely greater than at any time in the past and is now facilitated by the inputs of international funds (Mukherjee *et al.* 2009).

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

Figure 3 A native sand dune habitat is bulldozed to make way for an exotic *Casuarina equisetifolia* plantation on the east coast of India.

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 *Prosopsis 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).

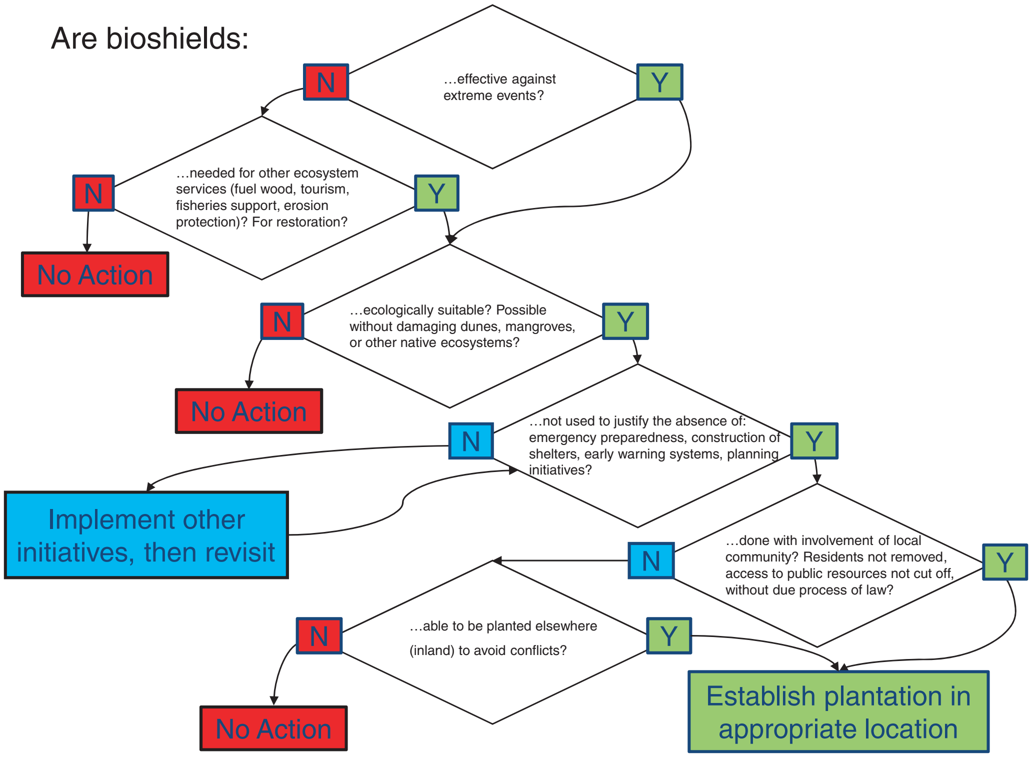

Figure 4 Decision tree for the establishment of bioshields in appropriate locations.

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 armoring of the coast, that is, seawalls, 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

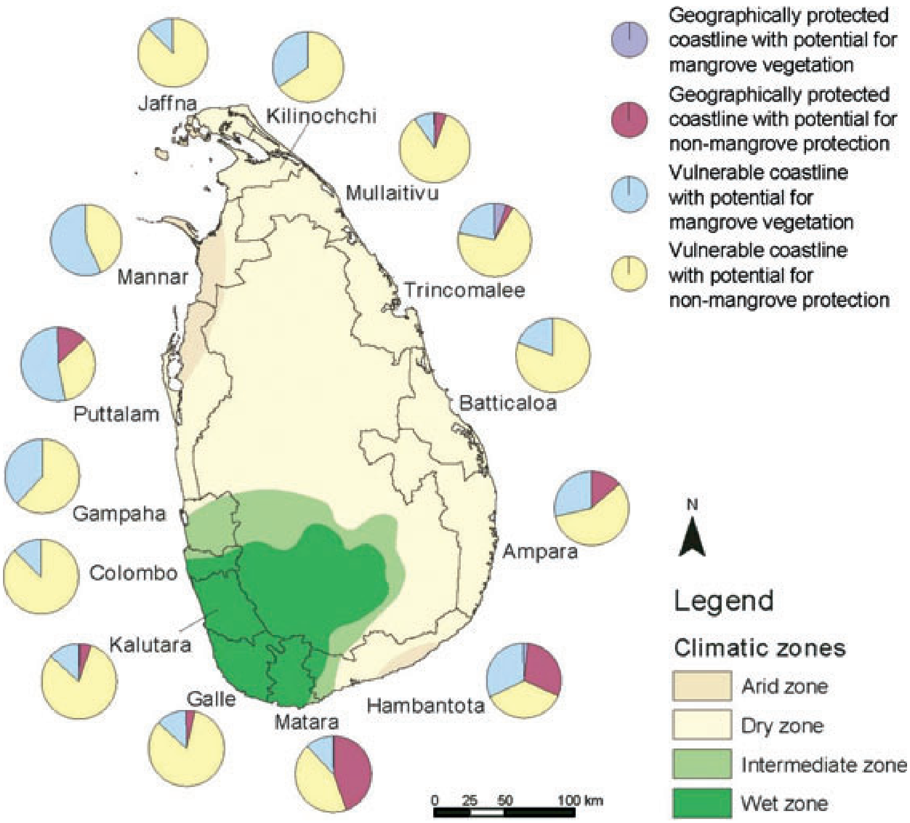

Figure 5 Potential for mangrove or non-mangrove growth along protected and vulnerable areas of the Sri Lankan coastline. The map of Sri Lanka, with major climatic zones according to Pemadasa (1996), shows categorizations of coastline per district. Out of the 90% of the coastline classified as vulnerable, less than one-third can contain mangrove forests.

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 mangoves 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 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 (Rodriguez *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.

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Editor: Dr. Corey Bradshaw

SUPPORTING INFORMATION

FIGURE 5 METHODS & RESULTS

This supplementary section describes the method and overall result of Figure 5.

METHODS

Base maps and satellite data

GIS layers (digitised from Sri Lanka 1:50,000 scale toposheets) for hydrological and road networks, as well as administrative divisions, were obtained from the International Water Management Institute (IWMI, Colombo) and the Survey Department of Sri Lanka (Colombo). Where needed during the analysis, as for example near river mouths and lagoons, further toposheet information was either digitised or used as geocorrected scanned images below other GIS layers.

As explained below, the 10 m contour line is a reference level used in the present analysis. Unfortunately, contour lines lower than 20 m are not shown on Sri Lanka 1:50,000 scale toposheets, while the most detailed 1:10,000 scale maps, for which the 10 m contour line is present, cover only a limited part of the country. The best alternative, readily available source of data to approach the 10 m contour line was found to be the SRTM – DEM (Shuttle Radar Topographic Mission – Digital Elevation Model) distributed by USGS (United States Geological Survey). The SRTM 3 second arc Digital Elevation Data used in the study was made available by the ‘Consultative Group for International Agricultural Research’ (CGIAR – Consortium for Spatial Information) after processing to fill the ‘no-data’ voids present in the USGS dataset. The SRTM elevation data of Sri Lanka was used to generate 10 m interval contour lines of the coastal areas. The generated 20 m and 40 m contour lines were checked against the contour lines given in 1:50,000 scale toposheets in order to correct for possible horizontal or vertical shifts in the SRTM data, and hence to minimise the effect of the reported relative vertical accuracy of ± 6 m of the data (Rabus *et al.* 2003). Missing data were completed and inaccurate data corrected.

Vulnerable areas along the coast

Vulnerability of the coastal land area to wave-related hazards depends in part on the elevation of the coastal land from the mean sea. Considering that the run up height of the 2004 tsunami event at the shore was reported to be about 10 m (Liu *et al.* 2005), the coastal land area lying under the 10 m contour line was considered as the most vulnerable area for a tsunami and hereafter referred to as '**vulnerable area**'. Vulnerable area of the country was extracted from the GIS layer of contour lines with 10 m intervals, which was generated using SRTM - DEM data. However, before this extraction, evident errors due to the presence of buildings and some 'temporary elevations' along the coastline were corrected manually.

Except at places with coastal cliffs rising more than 10 m directly from the sea level, the polygon of vulnerable area overlaps with the polygon delineating the coastline of the country. The total length of all these overlapping parts of the coastline is hereafter referred as '**vulnerable coastline**' of the country. The rest of the coastline is considered as the '**geographically protected coastline**'.

Mangrove areas along the coastline

In general, intertidal areas of lagoons, river mouths and sheltered bays in coastal areas of tropical countries are ideal habitats for mangroves when the substrate is muddy or sandy. There are historic archives reporting that, such areas in Sri Lanka were covered by extensive mangrove forests in the past (Tennent 1859). However, until today the accurate extent and composition of mangroves for the entire country is not known. Analysing this would necessitate country-wide very high resolution remote sensing data, which is currently not available and constitutes an unrealistic cost. Instead, the areas considered in this study are based on reliable physical site conditions that form **potential mangrove areas**, many of which are known to have today or to have had mangroves in the past. However, judged from the coast geomorphology and hydrogeography, it should be highlighted that, should mangroves be absent today, restoration of mangroves in these areas is possible and is even advised. Identification of potential mangrove areas was done by overlaying the hydrological network of coastal areas (from 1:50000 toposheets) with a layer of contour lines of the ground in a GIS-environment. Where a water body with an inflow of sea water (overland or through seepage), was located within the first 500 m zone and below the 10 m contour line, its margin or intertidal area was considered as a potential mangrove habitat. A coastline segment having a potential mangrove habitat behind it, is considered part of the 'mangrove coastline' of the country. In figure 5, '**mangrove coastline**' refers to the total length of such segments for the whole country, or in a particular administrative division. Hence, the rest of the coastline is referred to as '**non-mangrove coastline**'. The area within the first 1 km belt of the mangrove coastline is considered the area potentially protected by mangroves. The total of all such areas for the whole country or in an administrative division is referred in this paper as the '**mangrove-protected area**'.

RESULTS

Table S1 shows that approximately 90% of the Sri Lankan coastline is vulnerable, but that less than a third of this vulnerable coastline can be protected by mangrove vegetation. The breakdown of the categories in Table S1 per coastal district is given in Figure 5 of the main article.

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

	Coastline with potential for mangrove vegetation (km)	**Coastline with potential for non-mangrove vegetation (km)**	**Total (km)**
Vulnerable coastline (km)	523	1057	1580
Geographically protected coastline (km)	15	143	158
Total (km)	538	1200	**1738**

References used in this supporting information section

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