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The protective service of mangrove ecosystems: A review of valuation methods

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ABSTRACT

Concern over the loss of mangrove ecosystems often focuses on their role in protecting coastal communities from storms that damage property and cause deaths and injury. With climate change, mangrove loss may also result in less protection against coastal storms as well as sea-level rise, saline intrusion and erosion. Past valuations of the storm protection benefit of mangroves have relied on the second-best replacement cost method, such as estimating this protective value with the cost of building human-made storm barriers. More reliable methods instead model the production of the protection service of mangroves and estimate its value in terms of reducing the expected damages or deaths avoided by coastal communities. This paper reviews recent methods of valuing the storm protection service of mangroves and their role in protecting coastal areas and communities of tropical developing countries.

1. Introduction

Although approximately 150,000 km^2 of mangroves exist worldwide, over two thirds of the remaining area are located in just eighteen countries — Indonesia, Brazil, Australia, Mexico, Nigeria, Malaysia, Myanmar, Bangladesh, Cuba, India, Papua New Guinea and Colombia (Giri et al., 2011; Spalding et al., 2010). Other major mangrove areas are found in Guinea Bissau, Mozambique, Madagascar, the Philippines, Thailand and Vietnam (Giri et al., 2011). However, around one quarter of the world's mangroves have been lost due to human action, mainly through conversion to aquaculture, agriculture and urban land uses (Barbier and Cox, 2003; Duke et al., 2007; Friess and Webb, 2014; Spalding et al., 2010). With the exception of Australia, which is a high-income economy, these development pressures are mounting in all the major mangrove countries. Finally, the global disappearance of mangroves is having a major impact on the vulnerability of coastal populations and property in developing countries, especially with respect to damaging and life-threatening storms and floods (Alongi, 2008; Barbier, 2014; Cochard et al., 2008; Spalding et al., 2014).

There is mounting evidence that mangroves provide some type of protection against storms and coastal floods, mainly through their ability to attenuate waves or buffer winds (Barbier, 2012b; Barbier et al., 2008, 2011; Gedan et al., 2011; Koch et al., 2009; Marois and Mitsch, 2015; McIvor et al., 2012a, 2012b; Sandilyan and Kathiresan, 2015; Spalding et al., 2014). As this article will discuss, there are now a number of economic studies that have attempted to estimate the value of this benefit. In addition, these studies represent an evolution in methods of valuation of the storm protection service of mangroves. Past valuations of the storm protection benefit of mangroves have relied on the second-best replacement cost method, which employs the cost of building human-made storm barriers to approximate the value of this service. More reliable methods instead model the production of the protection service of mangroves and estimate its value in terms of reducing the expected damages or deaths avoided by coastal communities.

In addition, there is also concern over the increasing vulnerability to climate change of rural populations in the low-elevation coastal zone (LECZ) of developing countries, which is the contiguous area along the coast with less than 10 meters (m) elevation (Barbier, 2015). As mangrove ecosystems disappear or are degraded, there will be less protection against short-lived natural disasters with immediate and often extreme impacts, such as flooding and storm surge, as well as long-term climatic changes with more gradual impacts, such as sea-level rise, saline intrusion and erosion (Barbier, 2014, 2015; Barbier et al., 2011; Gedan et al., 2011; IPCC Working Group II, 2014; Spalding et al., 2014; Temmerman et al., 2013). In addition, the changes in precipitation, temperature and hydrology accompanying climate change are likely to threaten remaining coastal and near-shore ecosystems (Dasgupta et al., 2011, 2014; Doney et al., 2012; Elliott et al., 2014; Erwin, 2009; IPCC Working Group II, 2014; Spalding et al., 2014; Webb et al., 2013). Thus, understanding the value of mangroves for providing protection against storm, flood damages and other coastal

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hazards is important for the broader policy issue of determining the vulnerability of the rural poor in LECZ of the continual loss of mangroves.

The paper proceeds as follows. The next section reviews a few representative studies of the economic value of the coastal protection benefit provided by mangroves. These studies indicate an important transformation in valuation methods, which is discussed in a subsequent section. The paper then discusses some of the important issues surrounding valuing the protective benefits of mangroves. The paper concludes by discussing further research priorities with respect to analyzing the protective value of mangrove ecosystems.

2. Economic valuation of mangrove protection benefits

Since the 2004 Indian Ocean tsunami, there has been strong interest globally in both restoring mangrove ecosystems and in their ability to protect coastlines and people from damaging storms. There is also an ongoing debate over whether or not the cost of mangrove restoration is higher than the value of the coastal protection service provided by these ecosystems (Sandilyan and Kathiresan, 2015). Successful mangrove restoration can certainly be expensive and variable, ranging from US$225 to US$216,000 per hectare (ha), excluding the costs of the land (Lewis, 2005). However, most estimates are around US$5000 to US$10,000 per ha; for example, in the Caribbean, restoration site costs are US$5077 per ha (Adame et al., 2015), and in Thailand US$8812 to US$9318 per ha (Barbier, 2007). In addition, mangrove ecosystems provide other important economic benefits other than storm protection, including carbon sequestration, collected wood and non-wood products, and support for off-shore fisheries (Barbier, 2007; Barbier et al., 2011; Huxham et al., 2015).

To date, there are still only a few economic studies that estimate the protective value of mangrove ecosystems, but more estimates have been emerging. Table 1 provides a representative selection of recent studies from tropical developing countries. Although many more studies exist than those listed in Table 1, there are problems of reliability in the estimates of protection benefits produced by some studies because of the arbitrary valuation methods often employed (Barbier, 2007, 2012b).

As Table 1 indicates, the protective value of mangrove ecosystems is directly related to their ability to attenuate, or reduce the height, of the storm surges and waves as they approach shorelines. This wave attenuation function derives from the vegetation and root structure of mangroves, which are an important source of friction to moving water and sediment (Bao, 2011; Gedan et al., 2011; Koch et al., 2009; Massel et al., 1999; Mazda et al., 1997; McIvor et al., 2012b). In addition, mangrove trees also have the capacity to buffer winds (Das and Crépin, 2013; McIvor et al., 2012a). The value of mangroves in providing such protection against high-speed and damaging winds is an often over-looked, but nonetheless very important, benefit. The growing evidence indicating that mangroves have significant wave attenuation and wind buffering functions has led to interest in valuing their storm protection benefit, and also provided better understanding of the underlying ecological structure and functions contributing to this benefit, including how it varies across mangrove landscapes and different tide levels (Barbier, 2012a; Barbier et al., 2008; Koch et al., 2009; McIvor et al., 2012a, 2012b).

Despite the importance of the coastal protection service of mangroves, the geographic coverage of valuation studies remains limited (see Table 1). Moreover, even recent studies (e.g., Huxham et al., 2015) have continued to employ ad hoc valuation methods, such as benefit transfer and replacement cost, which have been criticized for their reliability (see Barbier, 2007; Chong, 2005; and further discussion below). Nevertheless, the studies listed in Table 1 provide an indication of the economic importance of the storm protection benefits of mangrove ecosystems.

For example, mangroves significantly reduced the number of deaths and damages to property, livestock, agriculture, fisheries and other assets during the 1999 cyclone that struck Orissa, India (Badola and Hussain, 2005; Das and Vincent, 2009). Statistical analysis indicates that there would have been 1.72 additional deaths per village within 10 km of the coast if mangroves had been absent (Das and Vincent, 2009). Economic losses incurred per household were greater (US$154) in a village that was protected by a constructed embankment compared to those (US$33) in a village protected by mangrove forests (Badola and Hussain, 2005).

Since the 2004 Indian Ocean tsunami, there has been considerable debate as to whether the presence of mangroves reduced the impacts of the extremely large wave surges associated with this event, thus protecting lives and property (see Cochard, 2011; Marois and Mitsch, 2015 for reviews). As one post-tsunami assessment concluded, “mangroves play a critical role in storm protection, but with the subtle point that this all depends on the quality of the mangrove forest” (Dahdouh-Guebas et al., 2005, p. 446). In a definitive study for one of the worst affected regions, Aceh, Indonesia, Laso Bayas et al. (2011) confirm that not only coastal topography and near-shore bathymetry, but also vegetation including the presence of mangroves, plantations and other coastal forests, were effective in reducing the deaths and damages caused by the tsunami. Mangroves, forests and plantations situated between villages and the coastline may have decreased loss of life by 3% to 8%, as the trees appear to have slowed or diverted the waves. If these natural barriers were located behind the villages, casualties increased by 3% to 6%, because of the debris from the trees that increased the risk of death.

A series of studies for Thailand also indicate a significant protective value of mangroves against the damages caused by frequent storm events (Barbier, 2007; Barbier et al., 2008; Sathirathai and Barbier, 2001). Sathirathai and Barbier (2001) employed the replacement cost method to estimate the value of coastal protection and stabilization provided by mangroves in Surat Thani Province, Thailand. Using the cost of constructing breakwaters to replace protection by mangroves, the authors calculate that the present value over 20 years of mangrove protection and stabilization service is $12,263 ha^{-1}. The contribution of mangrove deforestation to economic damages of storms was estimated for 39 coastal storm events affecting Southern Thailand from 1975 to 2004 (Barbier, 2007). Over 1979 to 1996, the marginal effect of a one square kilometer loss of mangrove area was an increase in expected storm damages of about US$585,000 km^{-2}, and from 1996 to 2004, the expected increase in damages from a 1 km^2 loss in mangroves was around US$187,898 km^{-2} ($1879 ha^{-1}). Barbier et al. (2008) further show how variation in this protective value of mangroves across a 10 km^2 landscape could lead to substantial change in land use decisions, including the conversion of mangroves to shrimp farms. Barbier (2012a, 2012b) further shows how the type of declining wave attenuation function affects the mangrove conversion decision, including the

Table 1
Examples of studies of the protective value of mangrove ecosystems.

Ecosystem structure and function	Ecosystem service	Valuation examples	Valuation method
Attenuates and/or dissipates waves, buffers wind	Protection of coastal communities against property damage, loss of life and/or injuries.	Badola and Hussain (2005), India	Damage cost avoided
		Barbier (2007), Thailand	Expected damage function
		Das and Crépin (2013), India	Expected damage function
		Das and Vincent (2009), India	Storm-related deaths avoided
		Huxham et al. (2015), Kenya	Replacement cost
		Laso Bayas et al. (2011), Indonesia	Deaths and damages avoided
		Sathirathai and Barbier (2001), Thailand	Replacement cost

optimal location of shrimp ponds in the mangrove ecosystem, as well as the risk of ecological collapse.

In Kenya, Huxham et al. (2015) show that the protective benefit of mangroves is one of the several regulating services that are currently mostly without markets yet have some of the most substantial values from a range of mangrove ecosystem services. What is more, these protective benefits are important to the "triple win" coastal strategy that integrates economic development, environmental conservation and adaptation to climate change.

3. Valuation methods

Despite the growing interest in and number of studies of the protective value of mangroves systems, improving the methodology for estimating their coastal protection benefits is urgently needed. The above review of selective valuation studies suggests that an important development has occurred in the methods used to estimate these protective benefits. Previously, many studies that have attempted to value the storm prevention and flood mitigation services of the "natural" storm barrier function of mangroves have employed the replacement cost method by simply estimating the costs of replacing coastal habitat by constructing physical barriers to perform the same services (Chong, 2005; Huxham et al., 2015; Sathirathai and Barbier, 2001). However, economists recommend that the replacement cost approach should be used with caution in estimating value of ecosystem services such as storm protection because, first, one is essentially estimating a benefit (e.g., storm protection) by a cost (e.g., the costs of constructing seawalls, groins and other structures), and second, the human-built alternative is rarely the most cost-effective means of providing the service (Barbier, 2007; Freeman, 2003; Shabman and Batie, 1978).

Fig. 1 illustrates the limitation of using the replacement cost method to estimate the protective value of an estuarine and coastal ecosystem. Assume that the ecosystem comprises a coastal wetland, such as a marsh or mangrove, of initial landscape area S_0. The cost of the storm protection service provided by the ecosystem is "free" and thus corresponds to the horizontal axis, $0S_0$. That is, the marginal cost of the wetlands supplying this service MC_S is zero. However, suppose part of the wetland is lost or converted, and so the ecological landscape decreases to S_1. The replacement cost method would suggest that the value of this loss in wetland area could be estimated by the cost of "replacing" the lost wetlands with seawalls, breakwaters, levies and other human-built structures to reduce storm surge and waves.

In Fig. 1, the marginal cost of an alternative, human-built coastal storm barrier is MC_H. Thus, the "replacement cost" of using the human built barrier to provide the same storm protection service as the S_0S_1 amount of wetlands lost is the difference between the two supply curves, or area S_0ABS_1. However, this overestimates the benefit of having the wetlands provide the storm protection service. Instead, this benefit should be estimated by how much people are willing to pay for more of this service, which is represented by the area under the demand curve $W(S)$, less the costs of providing protection. Note that the $W(S)$ curve declines because more wetland area means more protection, and thus people are willing to pay less for each additional hectare of wetland. But of course wetlands provide this protection service for free (i.e. $MC_S = 0$), so when S_0S_1 amount of wetlands is converted, then as Fig. 1 shows, the corresponding decrease in human welfare amounts to area S_0CDS_1. Thus, the replacement cost method overestimates the loss in net benefits of the storm protection service by area ABCD.

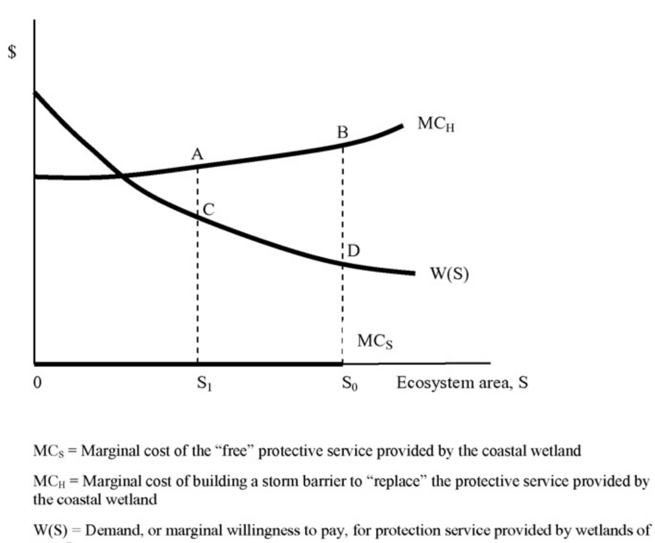

Fig. 1. Replacement cost vs. expected damage function estimation of protective value.

Instead of using the replacement cost method, some valuation studies have used the expected damage function approach to estimate the protective value of mangroves (see Table 1). In such cases, the mangrove ecosystem may be thought of as producing a non-marketed service, such as "protection" of economic activity, property and even human lives, which benefits individuals through limiting damages. As a result, the expected damage function approach is an adaptation of the production function methodology of valuing the environment as an input into a final benefit (Barbier, 2007; Barbier and Enchelmeyer, 2014). Utilizing this approach requires modeling the "production" of this protection service and estimating its value as an environmental input in terms of the expected damages avoided.

If implemented correctly, the expected damage function approach can be a more reliable method for estimating directly the net benefit of the storm protection service, or area S_0CDS_1 in Fig. 1. If there is an increase in wetland area, such as through ecological restoration, then the value of this change is the total amount of expected flood damage losses avoided. If there is a reduction in wetland area, as shown in Fig. 1, then the welfare loss is the total increase in expected flood damages resulting from a storm event. In both instances, the valuation would be a compensation surplus measure of a change in the area of wetlands and the storm protection service that they provide (Barbier, 2007; Barbier and Enchelmeyer, 2014).

A comparison of using an expected damage function approach and replacement cost method of estimating the welfare impacts of a loss of the storm protection service due to mangrove deforestation in Thailand confirms that the latter method tends to produce extremely high estimates compared to the EDF approach (Barbier, 2007). The comparison of annual and net present values produced by the two methods is depicted in Table 2.

But the expected damage function has its own limitations, especially when households are risk averse, and in such circumstances can be a poor proxy for the ex ante willingness to pay to reduce or avoid the risk from storm damages (Barbier, 2007; Freeman, 2003, pp. 243–247). Nevertheless, because the EDF approach is a direct compensation surplus measure of a change in the area of estuarine and coastal ecosystems and the storm protection service that they provide, it is a promising method of estimating the protective value of these ecosystems.

Also, Shabman and Batie (1978) suggest that the replacement cost method can provide a reliable valuation estimation for an ecological service, but only if the following conditions are met: (1) the human-built construction project considered provides the same service as the ecosystem; (2) the project compared for cost comparison should be the least-cost alternative; and (3) there should be substantial evidence that the service would be demanded by society if it were provided by that least-cost alternative. Unfortunately, very few replacement cost studies meet all three conditions.

Another approach that is becoming more frequently employed to overcome the lack of reliable protective benefit estimates for mangrove ecosystems is *benefit* or *value transfer*. This method involves taking estimates of economic value from one site and "transferring" them to a similar location elsewhere (Johnston and Rosenberger, 2010;

Table 2
Valuation of storm protection service of mangroves, Thailand, 1996–2004.

Annual deforestation rate	FAO[a] 18.0 km^2	Thailand[b] 3.44 km^2
Valuation approach (US$)		
Replacement cost method:[c]		
Annual welfare loss	25,504,821	4,869,720
Net present value (10% discount rate)	146,882,870	28,044,836
Net present value (12% discount rate)	135,896,056	25,947,087
Net present value (15% discount rate)	121,698,392	23,236,280
Expected damage function approach:		
Annual welfare loss	3,382,169	645,769
Net present value (10% discount rate)	19,477,994	3,718,998
Net present value (12% discount rate)	18,021,043	3,440,818
Net present value (15% discount rate)	16,138,305	3,081,340

Source: Adapted from Barbier (2007).
[a] FAO estimates from FAO (2003). 2000 and 2004 data are estimated from 1990 to 2000 annual average mangrove loss of 18.0 km^2.
[b] Thailand estimates from various Royal Thailand Forestry Department sources reported in Aksornkoae and Tokrisna (2004). 2000 and 2004 data are estimated from 1993 to 1996 annual average mangrove loss of 3.44 km^2.
[c] Based on replacement cost method assumptions of Sathirathai and Barbier (2001).

Plummer, 2009; Richardson et al., 2015; Rosenberger and Stanley, 2006; Troy and Wilson, 2006). In the benefit transfer literature, the location from which the valuation estimates are taken is called the *study* site, because it is the site that has already been "studied" in some way to obtain the original valuation estimate. The location to which the estimates are applied is called the *policy* site.

Plummer (2009) reviews the extensive environmental economics literature on the limits to implementing benefit transfer, especially in the context of the various goods and services provided by coastal and marine ecosystems, including mangroves. He concludes that the errors in applying this technique can be minimized provided that there is sufficient ecological and economic correspondence between the study and policy sites. Plummer (2009) suggests that "lack of correspondence" can be reduced when:

- the ecosystem at the study site is a good match for the ecosystem under consideration at the policy site (i.e. *ecological correspondence*), or;
- the respective populations of the study and policy sites do not differ considerably in terms of income levels, benefits derived from the ecosystem, preferences, employment and economic opportunities, household characteristics (e.g., occupation, education, number of adults and children, etc.), and other attributes that would cause wide variances in willingness to pay estimates between populations at the study site and populations at the policy site (*economic correspondence*).

The advancement in benefit transfer methods and modeling techniques, including the application of geographical information systems (GIS) and meta-regression analysis, means that there are more opportunities to use these methods as a way of extrapolating and transferring estimated ecosystem service values from one location, population, and time to other locations, populations, and periods. However, this technique is not a substitute for reliability. If there is a lack of economic and ecological correspondence between study and policy sites, transferring values between the two sites through GIS and other methods will simply lead to inaccurate valuation estimates (Troy and Wilson, 2006).

Similarly, there are potential drawbacks of applying benefit transfer through meta-analysis regression. This requires knowledge of the values of the independent variables for the policy site of interest, and assumes that the statistical relationship between the dependent and independent variables is the same between the study and policy sites (Richardson et al., 2015; Rosenberger and Stanley, 2006). If one can statistically control for these differences in ecological and economic correspondence, this reduces the benefit transfer errors. In addition, there needs to be a sufficient number and variety of reliable policy site valuation studies to make the meta-analysis regression applicable in the first place. For example, as Table 1 shows, only a handful of valuation studies of the protective benefits of mangroves may serve this purpose. Unfortunately, this suggests that benefit transfers may be less helpful in overcoming the lack of reliable estimates for the benefits associated with the coastal and storm protection provided by mangroves.

4. Discussion

Given the growing interest in the protective value of mangrove ecosystems, there will be continual progress in the valuation methods employed to estimate this benefit. Improvements in the hydrodynamic modeling of storm surges, accounting for the influence of coastal topography of near-shore bathymetry, and allowing for the varying attributes of storms will also lead to better estimates of the protective benefits of mangroves.

For example, one of the most important innovations in recent assessments of the role of coastal forests, including mangroves, in protecting against the damages and casualties caused by the 2004 Indian Ocean tsunami has been separating out the influence of coastal topography, such as shoreline slope, distance of villages to shore and other coastal features, from the protection provided by forests (Cochard, 2011). For example, while the analysis by Laso Bayas et al. (2011) confirms that the presence of coastal vegetation significantly reduced the casualties caused by the tsunami in Acheh, Indonesia, distance to coast was the dominant determinant of casualties and infrastructure damage. Similarly, in determining whether mangrove trees have the capacity to buffer winds, thus enabling them to estimate the expected protective benefits, Das and Crépin (2013) account for wind speeds, direction of storms, distance to coast and other key natural features.

A growing number of field studies and experiments are showing that the wave attenuation function of mangroves, which is critical to their protective value, may vary spatially and temporally. For example, wave attenuation by mangroves will vary spatially across the extent of these habitats, as well by species composition, tides and root structure (Bao, 2011; Gedan et al., 2011; Koch et al., 2009; Massel et al., 1999; Mazda et al., 1997). Only recently are valuation studies taking into account spatial and temporal variability of wave attenuation by estuarine and coastal ecosystems in estimating their potential protective value (Barbier, 2012a; Barbier et al., 2008; Koch et al., 2009).

Another unique feature of mangroves is that they occur at the interface between the coast, land, and watersheds. The location of these ecosystems in the land–sea interface suggests a high degree of "interconnectedness" or "connectivity" across these systems, which could lead to the linked provision of the storm protection service by more than one estuarine and coastal ecosystem. For example, Alongi (2008) suggests that the extent to which mangroves offer protection against catastrophic natural disasters, such as tsunamis, may depend not only on the relevant features and conditions within the mangrove ecosystem, such as width of forest, slope of forest floor, forest density, tree diameter and height, proportion of above-ground biomass in the roots, soil texture and forest location (open coast versus lagoon), but also on the presence of foreshore habitats, such as coral reefs, seagrass beds, and dunes. In the Caribbean, mangroves appear not only to protect shorelines from coastal storms but may also enhance the recovery of coral reef fish populations from disturbances due to hurricanes and other violent storms (Mumby and Hastings, 2008). Modeling simulations for an interconnected reef–seagrass–mangrove seascape confirm that the storm protection service of the whole system is greater than for a single coastal habitat on its own (Sanchirico and Springborn, 2012). In addition, modeling of this connectivity in providing storm protection and other benefits of a reef–seagrass–mangrove seascape may also determine the spatial location of development activities in the mangrove portion of the seascape (Barbier and Lee, 2014).

5. Conclusion

As the world's mangroves continue to disappear due to human population and development pressures, it becomes increasingly essential to assess the values of these important systems. Existing valuation studies suggest that the protective value of mangroves may be one of the more significant benefits sacrificed when these habitats are lost or degraded. As we improve our understanding of how various mangrove ecosystems attenuate waves and buffer winds, we must also develop better methods of assessing the protective benefits of these ecosystems.

Understanding the role of vegetation and other mangrove attributes in storm protection compared to coastal topography and near-shore bathymetry is also essential, as is better hydrodynamic modeling of the storm surge and wind characteristics of various storm events. Finally, perhaps the biggest but most interesting challenge lies in allowing for the connectivity between mangroves and other estuarine and coastal habitats to assess the wave attenuation and wind buffering functions underling coastal protection. Only recently have valuation studies begun to model this connectivity and assess the cumulative implications for protective values across various estuarine and coastal seascapes (Sanchirico and Springborn, 2012; Barbier and Lee, 2014).

Although this paper has focused on the coastal protection service provided by mangroves, this benefit is only one of many services provided by these ecosystems. Mangrove habitats are also important maintenance of fisheries, nutrient cycling, tourism, recreation, education and research (Barbier et al., 2011; Huxham et al., 2015). In assessing the overall value of these ecosystems, it is important not to focus just on their protective value, at the exclusion of the wide range of benefits and synergistic relationships that these vital habitats provide. The fact that mangroves provide not just storm protection but multiple benefits gives them also an advantage over human-made structures built solely to protect coastlines. Such considerations are becoming important to decisions as to whether or not to invest in mangrove restoration, either in combination with or as an alternative to human-made structures (Barbier, 2014; Spalding et al., 2014; Temmerman et al., 2013). Improving the valuation of the protective service of mangroves, as well as the other benefits provided by these critical habitats, may prove important in these future coastal management decisions.

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