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Valuing the storm protection service of estuarine and coastal ecosystems

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ABSTRACT

Recent concern over the loss of estuarine and coastal ecosystems (ECEs) often focuses on an important service provided by these ecosystems, their role in protecting coastal communities from storms that damage property and cause deaths and injury. Past valuations of this benefit have relied on the second-best replacement cost method, estimating the protective value of ECEs with the cost of building human-made storm barriers. A promising alternative methodological approach to incorporate these factors is using the expected damage function (EDF) method, which requires modeling the production of this protection service of ECEs and estimating its value in terms of reducing the expected damages or deaths avoided by coastal communities. This paper illustrates the EDF approach to value the storm protection service of ECEs, using the example of mangroves in Thailand to compare and contrast the EDF with the replacement cost approach to estimate the protective value of ECEs. In addition, the example of marshes in the US Gulf Coast is employed to show how the EDF approach can be combined with hydrodynamic analysis of simulated hurricane storm surges to determine the economic value of expected property damages reduced through the presence of marsh wetlands and their vegetation along a storm surge path.

1. Introduction

Since Hurricanes Katrina and Rita in 2005 and the Indian Ocean tsunami in 2004, attention has focused on how the continuing worldwide loss of estuarine and coastal ecosystems (ECEs) is making coastlines and coastal communities vulnerable to flooding and storm events (Arkema et al., 2013; Braatz et al., 2007; Cochard et al., 2008; Day et al., 2007). There is mounting evidence that a variety of ECEs, including marshes, mangroves, near-shore coral reefs, seagrass beds, and sand beaches and dunes, provide some type of protection against storms and coastal floods, mainly through their ability to attenuate waves or buffer winds (Barbier, 2011; Barbier et al., 2008, 2011; Bouma et al., 2010; Gedan et al., 2011; Koch et al., 2009; Paul and Amos, 2011; Shephard et al., 2012). However, to date, there are few economic studies that estimate the protective value of many systems, although some estimates are beginning to emerge for marsh and mangroves (see Table 1). Although many more studies exist than those indicated in Table 1, there are problems of reliability in the estimates of protection value produced by some of these earlier studies because of the arbitrary valuation methods often employed (Barbier, 2007, 2011).

As Table 1 indicates, the protective value of estuarine and coastal ecosystems (ECEs) 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 contained in some ECEs, such as marsh, seagrass beds and mangroves, which are an important source of friction to moving water (Bouma et al., 2010; Gedan et al., 2011; Koch et al., 2009; Massel et al., 1999; Mazda et al., 1997; Paul and Amos, 2011; Shephard et al., 2012). In the case of coral reefs, beaches and sand dunes, it is their reticulated structure that acts as a natural barrier to storm waves, although the presence of grasses on dunes and beaches enhances wave attenuation (Barbier et al., 2008; Madin and Connolly, 2006; Pompe and Rinehart, 1994; Stockdon et al., 2007).

The growing evidence indicating that a number of estuarine and coastal ecosystems (ECEs) have a significant wave attenuation function has led to interest in valuing their storm protection benefit. But despite the importance of this coastal protection service, very few economic studies have estimated a value for it. Those studies that have been conducted tend to use benefit transfer and replacement cost methods of valuation in an ad hoc manner, which undermine the reliability of the value estimates

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Table 1
Examples of studies of the protective value of estuarine and coastal ecosystems.

Ecosystem structure and function	Ecosystem service	Valuation examples
Attenuates and/or dissipates waves, buffers wind	Protection of coastal communities against property damage, loss of life and/or injuries	Badola and Hussain (2005), Das and Crépin (2013) and Das and Vincent (2009), mangroves, India Barbier (2007, 2012), Barbier et al. (2008) and Sathirathai and Barbier (2001), mangroves, Thailand Barbier and Enchelmeyer (2014) and Barbier et al. (2013), marsh, SE Louisiana, US Chong (2005), mangroves and coral reefs, various regions Costanza et al. (2008), marsh, US Atlantic and Gulf Coasts Farber (1987), marsh, Louisiana, US King and Lester (1995) and Mangi et al. (2011), marsh, United Kingdom Landry et al. (2011), coastal wetland restoration, US Laso Bayas et al. (2011), mangroves, Aceh, Indonesia Petrolia and Kim (2009), barrier islands, Mississippi, US Petrolia and Kim (2011) and Kim and Petrolia (2013), marsh, Louisiana, US Petrolia et al. (2014), coastal wetland and barrier island restoration, Louisiana, US Pompe and Rinehart (1994), beaches, South Carolina, US Wilkinson et al. (1999), coral reefs, Indian Ocean

(see Barbier, 2007; Chong, 2005; and further discussion below). For example, for the storm protection valuation studies indicated in Table 1, only a few are considered reliable. Most of these studies of the protective value of ECEs have focused on marshes and mangroves.

Widespread reef destruction caused by catastrophic events and global change, such as hurricanes, typhoons and coral bleaching, gives some indication of the value of the lost storm protection services. For example, as a result of the 1998 bleaching event in the Indian Ocean, the expected loss in property values from declining reef protection is estimated to be \$174 ha^{-1} year^{-1} (Wilkinson et al., 1999). Evidence from the Seychelles documents how rising coral reef mortality and deterioration have increased significantly the wave energy reaching shores that are normally protected from erosion and storm surges by these reefs (Sheppard et al., 2005). However, to date, this effect has not been valued explicitly.

Although field studies indicate that seagrass meadows and sand dunes may have a significant impact on reducing storm waves, no valuation studies currently exist of the resulting protection benefit. For seagrasses, one problem is that coastal protection can vary significantly if damaging storm events occur when plant biomass and/or density are low (Koch et al., 2009; Paul and Amos, 2011). This is particularly important in temperate regions, where seasonal fluctuations of biomass may differ from the seasonal occurrence of storms. For example, along the US Atlantic coast, the biomass of seagrass peaks in the summer (April–June) yet decreases in the fall (July–September) when storm events usually strike (Koch et al., 2009). In tropical areas, seagrass beds have relatively constant biomass throughout the year, so the coastal protection service is relatively unaffected by seasonal or temporal variability.

An analysis of the economic damages associated with 34 major hurricanes striking the US coast since 1980 found that coastal wetlands explained 60% of the variation in relative damages inflicted on coastal communities (Costanza et al., 2008). The additional storm protection value per unit area of coastal wetlands from a specific hurricane ranged from a minimum of US\$23 ha^{-1} for Hurricane Bill to a maximum of US\$463,730 ha^{-1} for Hurricane Opal, with a median value of just under US\$5000 ha^{-1}. However, for US Gulf Coast wetlands, the reliability of estimates of the value of wetlands for storm surge protection has been questioned, because the methods used have not taken into account that "the level of storm surge attenuation provided by wetlands depends on many factors including the location, type, extent, and condition of the wetlands and the properties of the storm itself" (Engle, 2011, p. 185).

Recent hydrodynamic storm surge models developed for southern Louisiana also show how the attenuation of surge by wetlands is affected by the bottom friction caused by vegetation, the surrounding coastal landscape, and the strength and duration of the storm forcing (Loder et al., 2009; Resio and Westerink, 2008; Wamsley et al., 2010). By incorporating such features into an economic valuation of simulated hurricane storm surges, Barbier and Enchelmeyer (2014) and Barbier et al. (2013) estimate that a marginal increase in the wetland-to-water ratio along a nearly 6 km storm transect would lower residential property flood damages in Southeast Louisiana by \$592,000–792,100, whereas the marginal increase in bottom friction caused by more wetland vegetation along the transect would reduce flood damages by \$141,000–258,000. Such marginal changes in wetland area and vegetation roughness along a single storm transect are equivalent to saving 3–5 and 1–2 properties/storm, respectively.

Marsh wetlands may also act as a buffer against the wind damages from hurricanes and other storms. Using historical storm frequencies for the Louisiana Gulf Coast, Faber (1987) estimates the expected wind damage to property from the loss of intervening marsh. The present value of the loss of a one-mile strip of wetlands amounts to between US\$1.1 and US\$3.7 million (1980 dollars). The increased cost to property damage amounted to between US\$7 and US\$23 acre^{-1}.

A different approach was taken to estimating the protective value of marsh as a sea defense in East Anglia, United Kingdom (King and Lester, 1995). In this region, existing marsh areas in front of constructed sea walls together provide protection against storms, and less marsh means that higher sea walls have to be built. The authors therefore estimate the value of marsh as sea defense by calculating the additional capital and maintenance costs that would be needed to build higher walls as the marsh disappears. Evaluation of an 80 m width of salt marsh in front of a seawall yields a value over the whole area of between £30 and £60 m^{-2}.

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) for a review). In a definitive study for one of the worst affected regions, Aceh, Indonesia, Laso Bayas et al. (2011) confirms 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 3–8%, as the trees appear to have slowed or diverted the waves. If these natural barriers were located behind the villages, casualties increased by 3–6%, because of the debris from the trees increased the risk of death.

A series of studies for Thailand also confirm the 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 1979–1996, 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 (2012) further shows how the type of declining wave attenuation function affects the mangrove conversion decision, including the optimal location of shrimp ponds in the mangrove ecosystem, as well as the risk of ecological collapse.

Despite the growing interest in and number of studies of the protective value of ECE systems, improving the methodology for estimating the benefits of storm surge protection and other values of wetlands is urgently needed. A survey of US Environmental Protection Agency wetland regulators revealed that that they rarely used monetary estimates of wetland values in their environmental decision making (Arnold, 2013). The survey respondents cited uncertainty about the scientific validity of estimates and subsequent concerns about the scientific and legal defensibility of estimate use as key reasons for ignoring wetland values. For example, past valuations of storm protection benefits have relied too much on the second-best valuation estimates, such as the replacement cost method, which involves estimating the protective value of ECEs with the cost of building human-made storm barriers. A promising alternative methodological approach to incorporate these factors is by using the expected damage function (EDF) method, which requires modeling the production of this protection service of ECEs and estimating its value in terms of reducing the expected damages or deaths avoided by coastal communities (Barbier, 2007; Barbier and Enchelmeyer, 2014). This article illustrates the EDF approach to value the storm protection service of ECEs, using the example of mangroves in Thailand to compare and contrast the EDF with the replacement cost approach to estimate the protective value of ECEs. In addition, the example of marshes in the US Gulf Coast is employed to show how the EDF approach can be combined with hydrodynamic analysis of simulated hurricane storm surges to determine the economic value of expected property damages reduced through the presence of marsh wetlands and their vegetation along a storm surge path.

2. Materials and methods

The above review of selective valuation studies suggests that an important development has occurred in the methods used to estimate the protective value of estuarine and coastal ecosystems (ECEs). Previously, many studies that have attempted to value the storm prevention and flood mitigation services of the "natural" storm barrier function of mangrove and other ECEs 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; King and Lester, 1995; Mangi et al., 2011; 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 sea walls, groins and other structures), and second, the human-built alternative is rarely the most cost-effective means of providing the service (Barbier, 2007; Ellis and Fisher, 1987; Freeman, 2003, Shabman and Batie, 1978).

Fig. 1 illustrates the limitation of using the replacement cost method to estimate the protective value of an ECE. 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, $0S_0$. 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 sea walls, 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. The true benefit of this ecosystem service is the demand curve, or total willingness to pay, for the service provided by S_0S_1 amount of wetlands less than the costs of providing protection. In Fig. 1, this net benefit corresponds to area S_0CDS_1. Thus, the replacement cost method overestimates the net benefits of the storm protection service by area ABCD.

As an alternative to the replacement cost method, some valuation studies of the protective value of estuarine and coastal ecosystems (ECEs) have used the expected damage function approach (Barbier, 2007; Barbier and Enchelmeyer, 2014). In such cases, the ECE 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).

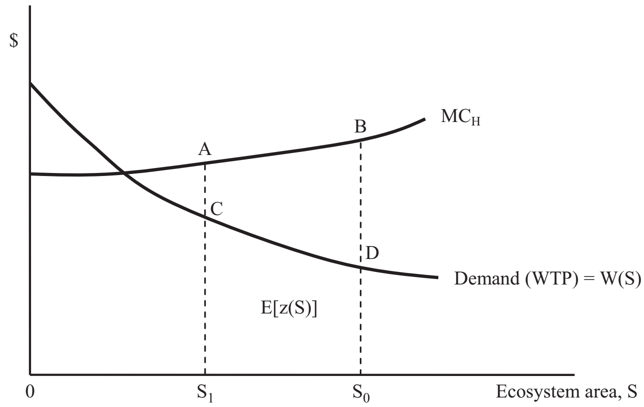

Fig. 1. Replacement cost versus expected damage function estimation of protective value.

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.

The following example, which is from Barbier and Enchelmeyer (2014), illustrates how the expected damage function (EDF) methodology can be applied to value the storm protection service provided by an ECE, such as a marsh or mangrove ecosystem. The starting point is the standard "compensating surplus" approach to value a quantity or quality change in a non-market environmental good or service. As the example illustrates, unlike the replacement cost method, the expected damage function approach can yield an exact measure of the willingness to pay for the loss or gain in wetland area that results in storm protection.

Assume that the preferences of all households in a coastal community are similar enough so that they can be represented by a single household. The household's property is threatened by damage from periodic storms, in particular storm-surge related flooding. Assume that the household receives utility from a composite consumption good $\mathbf{x}$ with corresponding price p_x, and has property assets A with initial level A_0. To keep the analysis simple, we also assume that, in the absence of surge damage, the household will not replace or make any repairs to its property.

If the household could allocate its income, M, at the end of period t, then the household's ex post utility if no storm surge occurs will be given by

$$\max_{\mathbf{x}} \; U^0(\mathbf{x}; A_{0t}) \quad \text{subject to} \quad M_t = p_{\mathbf{x}_t}\mathbf{x}. \tag{1}$$

However, if flood damage from a storm surge does occur, then the household's ex post utility is

$$\max_{\mathbf{x},R} \; U^L(\mathbf{x}, R; A_{Lt}) \quad \text{subject to} \quad M_t = p_{\mathbf{x}_t}\mathbf{x} + R \tag{2}$$

where, using asterisks to denote optimal values, $U^{0*} > U^{L*}$ and $A_L < A_0$ is the level of the household's assets when flood damage from a surge occurs and R denotes the expenditures on the repair or replacement of these damage assets undertaken by the household.

Suppose now that the household must choose a level of expenditure on R ex ante, as might be the case if the household purchased insurance, and that what remains will be used for the purchase of $\mathbf{x}$. Thus, at the start of any period t (i.e. before any storm has occurred), the household chooses $\mathbf{x}$ and R to minimize total expenditure on repairs or replacement and the composite good, while maintaining a desired level of expected utility. The ex ante problem is

$$\min_{\mathbf{x},R} M_t = p_{\mathbf{x}_t}\mathbf{x} + R \quad \text{subject to} \quad \pi_t U^0(\mathbf{x}; A_{0t}) + (1-\pi_t)E[U^L(\mathbf{x}, R; A_{Lt}) | Z_t > 0] = \overline{EU}_t \tag{3}$$

where π_t is the probability that no surge occurs during period t, Z_t is the number of storm surge flooding events affecting the household, and $\overline{EU}_t$ is the desired level of expected utility.[1]

Assume R is a perfect substitute for A such that, if the event losses occur, any replacements or repairs may be thought of as the proportion of the household's lost assets recovered.[2] Consequently, if the household knows with certainty that it will experience a loss in assets $L = (A_0 - A_L)$ from flood damage, then the level of replacement will be $R = qL$ where $q \le 1$. That is, if the loss L was known with certainty (as in the ex post problem denoted by (2)), the household's choice of R may be modeled instead as a choice of q, and thus L may be considered the unit cost of q (i.e. the cost of full recovery). From (2), it follows that the Marshallian demands of the household given certainty over losses are $q^M = q(p_{\mathbf{x}_t}, L, M_t)$ and $\mathbf{x}^M = \mathbf{x}(p_{\mathbf{x}_t}, L, M_t)$, respectively.

However, in (3) when the household is minimizing its expenditure ex ante, the actual level of L is uncertain. If the household is risk neutral, it will choose $\mathbf{x}$ and q using the expected loss as its assumed unit cost of q. Denoting the expected losses from flood damage as $E[L_t]$, and substituting for R in (3), the household's ex ante Hicksian demands and optimal expenditure are

$$q^H = q(p_{\mathbf{x}_t}, E[L_t], \overline{EU}_t) \quad \mathbf{x}^H = q(p_{\mathbf{x}_t}, E[L_t], \overline{EU}_t) \quad \text{and} \quad M^* = p_x\mathbf{x}^{H*} + E[L_t]q^{H*} = m^*(p_{\mathbf{x}_t}, E[L_t], \overline{EU}) \tag{4}$$

where the asterisks denote optimal values. For a rise in expected flood damage per storm from $E[L]^0$ to $E[L]^1$, the change in the optimal expenditure function in (4) provides an exact measure of the welfare loss, D_t, the household sustains per period. We can define this welfare loss as follows:

$$D_t(E[L_t]) = \left\{ \begin{array}{l} m^*(p_{\mathbf{x}_t}, E[L_t]^1, \overline{EU}) \\ -m^*(p_{\mathbf{x}_t}, E[L_t]^0, \overline{EU}) \end{array} \right\} = c(E[L_t]) \tag{5}$$

where $c(E[L_t])$ is the compensating surplus or the minimum increase in income the household needs to cover the expected cost of the increased damages. As expected utility is constant for both expenditure functions in (3), D_t is exactly equal to the *option price* measure of willingness to pay (WTP), which is defined as the change in income that results in the same level of expected utility as in the uncertain situation (Freeman, 2003).

Now suppose the presence of coastal wetlands mitigate the expected flood damages per storm. Because of this storm protection service, the area of coastal wetlands, S, may have a direct effect on reducing the "production" of flood events, in terms of their ability to inflict damages locally. Thus the "production function" for expected

[1] If the time period is sufficiently large (e.g., a hurricane season, year or longer), the household might experience more than one storm surge flooding event.

[2] Although we ignore any possible psychological effects due to property losses from storm damages (Merz et al., 2010), this is a standard assumption in a variety of approaches to modeling such damages (e.g., see Barbier, 2007; Bengtsson and Nilsson, 2007; Farber, 1987; Smith et al., 2006). As we approach the valuation problem from the standpoint of a household's ex ante decision making, it is impossible for the household to know in advance the likely psychological consequences of any storm damage to property.

flood damages per storm can be represented as

$$E[L_t] = z(S), \quad z' < 0, \; z'' > 0. \tag{6}$$

It follows from (5) and (6) that $\partial c(E[L_t])/\partial S = c'(E[L_t])z' < 0$. An increase in wetland area reduces expected flood damages per storm and therefore also reduces the minimum income compensation needed to maintain the household at its original expected utility level. Alternatively, a loss in wetland area would increase expected flood damages per storm and raises the minimum compensation required by the household to maintain its welfare. Thus, we can define the marginal willingness to pay, $W(S)$, for the protection services of the wetland in terms of the marginal impact of a change in wetland area on expected storm damages

$$W(S) = -\frac{\partial c(E[L_t])}{\partial S} = -c'(E[L_t])z', \; W' < 0. \tag{7}$$

The marginal valuation function, $W(S)$, is analogous to the Hicksian compensated demand function for marketed goods. The minus sign on the right-hand sign of (7) allows this "demand" function to be represented in the usual quadrant, and it has the normal downward-sloping property (see Fig. 1). Although an increase in S reduces z and thus enables the household to avoid expected flood damages from a storm, the additional value of this storm protection service to the household will fall as wetland area increases in size. This relationship should hold across all households in the coastal community. Consequently, as indicated in Fig. 1, the marginal willingness to pay by the community for more storm protection declines with S.

The value of a non-marginal change in wetland area, from S_0 to S_1, can be measured as

$$-\int_{S_0}^{S_1} W(S)dS = E[z(S)] = c(S). \tag{8}$$

If there is an increase in wetland area, 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. As indicated in (8), 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.

3. Results

A comparison of using an expected damage function approach and a 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 1. 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 ECEs and the storm protection service that they provide, it is a promising method of estimating the protective value of these ecosystems (Table 2).

4. Discussion

Given the growing interest in the protective value of estuarine and coastal ecosystems (ECEs), 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 value of ECEs.

Table 2
Valuation of storm protection service of mangroves, Thailand, 1996–2004.
Source: Adapted from Barbier (2007).

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

[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).

For example, recent storm surge models developed for southern Louisiana along the US Gulf Coast show how the attenuation of surge by wetlands is affected by the bottom friction caused by vegetation, the surrounding coastal landscape, and the strength and duration of the storm forcing (Loder et al, 2009; Resio and Westerink, 2008; Wamsley et al., 2010). Although existing studies of the protective value of Gulf Coast wetlands do not incorporate such factors (Costanza et al., 2008), more accurate determination of this value will require allowing for the hydrodynamic properties of storm surges as well as the effects of varying wetland landscape and vegetation across coastal systems. Similarly, 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.

As discussed in above, a growing number of field studies and experiments are showing that the wave attenuation function of ECEs, which is critical to their protective value, may vary spatially and temporally. For example, wave attenuation by coral reefs, seagrass beds, salt marshes, mangroves, and sand dunes provides protection against wind and wave damage caused by coastal storm and surge events, but the magnitude of protection will vary spatially across the extent of these habitats (Barbier et al., 2008; Gedan et al., 2011; Koch et al., 2009; Madin and Connolly, 2006; Shephard et al., 2012; Stockdon et al., 2007). Only recently are valuation studies taken into account of spatial and temporal variability of wave attenuation by ECEs in estimating their potential protective value (Barbier, 2012; Barbier et al., 2008; Koch et al., 2009).

Another unique feature of ECEs is that they occur at the interface between the coast, land, and watersheds. The location of these ECEs 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 ECE. 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. Similar cumulative effects of wave attenuation are noted for seascapes containing coral reefs, seagrasses, and marshes (Koch et al., 2009). For instance, evidence from the Seychelles documents how rising coral reef mortality and deterioration have increased significantly the wave energy reaching shores that are normally protected from erosion and storm surges by these reefs (Sheppard et al., 2005). 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, 2011).

5. Conclusion

As the world's estuarine and coastal ecosystems 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 ECEs may be one of the more significant benefits sacrificed when these habitats are lost or degraded. As we improve our understanding of how various ECEs 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 ECE 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 challenges lies in allowing for the connectivity across ECE 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 ECEs.

Although this paper has focused on the coastal protection service provided by ECEs, this benefit is only one of many services provided by these ecosystems. Estuarine and coastal habitats are also important maintenance of fisheries, nutrient cycling, tourism, recreation, education and research. A recent review of mangroves, marshes, near-shore coral reefs, seagrass beds and sand dunes indicates estimates of the key economic values arising from these myriad services, and discusses how the natural variability of ECEs impacts their benefits, the synergistic relationships of ECEs across seascapes, and management implications (Barbier et al., 2011). In assessing the overall value of these ECEs, 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 ECEs provide not just storm protection but multiple benefits give 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 ECE restoration either in combination with or as an alternative to human-made structures. For example, the 2012 Master Plan for the Louisiana Coast proposes to build 1412–2225 km^2 of new land, much of it restored marsh, over the next 50 years to provide storm protection and other ecosystem benefits (LCPRA, 2012). Dedicated dredging on the Barataria Basin Landbridge in Louisiana has already created 4.9 km^2 of intertidal marsh and nourished an additional 6.4 km^2 of marsh in 2010, at a total cost of $36.3 million (LCPRA, 2012). Arkema et al. (2013) make the case that substantial ECE restoration along the US coast could make a considerable difference in reducing the vulnerability of populations and property to future natural disasters, including the problems posed by rising sea levels. Improving the valuation of the protective service of ECES, as well as the other benefits provided by these critical habitats, may prove important in these future coastal management decisions.

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