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Economic valuation of coral reef ecosystem service of coastal protection: A pragmatic approach

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ABSTRACT

The identification and economic valuation of ecosystem services (ES) are becoming important components of coral reef management. In many contexts, protection of human assets against coastal floods is one of the most important ES provided by coral reefs. The methods utilized to characterize this ES should be able to accommodate situations with low data availability, without sacrificing robustness. In this paper, we suggest such an approach that utilizes expert opinion and does not require copious amounts of data. Our primary objective is to find a balance between simple and complex models that can be used in a data scarce environment, to produce an economic valuation of the coral reef ES of protection against coastal floods. The approach has three steps: (i) identify geographic zones and assets at risk, (ii) identify the contributing role of coral reefs in the protection of coasts and, (iii) value the annual repair costs of assets through the avoided damage cost approach. The proposed method seems appropriate for advocacy with policy makers, but appears to be less effective for small scale approaches, such as those required for Payment for ES negotiations or marine spatial planning.

1. Introduction

Economic valuations of coral reef ecosystem services (ES) have been undertaken to address several objectives, such as raising environmental awareness among decision-makers and the public, evaluating the costs and benefits gained from different levels of investment in coastal management, incorporating present and future values of both negative and positive impacts via a common metric and fine tuning economic instruments (Burke et al., 2008; Laurans et al., 2013). In addition, valuations can form part of monitoring routines which utilize quantitative indicators to inform management ("we manage better what we can measure") (Beukering et al., 2007; David et al., 2007; Pascal et al., 2012) and used in the implementation of tools such as 'Payment for ES' (PES) (Huwyler et al., 2014). To date, the most common use of economic valuations of marine ES has been for advocacy with policy makers (Waite et al., 2014). In these studies, the priority has been to transmit accurate information on the value of a large range of ES and their beneficiaries, without striving for the highest level of confidence ("science to inform policy"). For other studies, such as those focusing on monitoring or the design of a PES, the level of precision required is much higher (Sale et al., 2014).

Recent work on the economic valuation of coral reef ES shows that it is important to concentrate valuation efforts on three main ES, which under the Millennium Ecosystem Assessment's classification (MEA, 2003) fall under the headings of provisioning, cultural and regulating (Hilmi et al., 2014; Laurans et al., 2013). The first two ES (provisioning and cultural) refer to respectively: (i) fish biomass production; coral reef associated fisheries provide an important source of protein and a basis for livelihoods and (ii) scenic beauty for recreational tourism; coastal recreation and tourism activities generate significant economic value depending on the quality and availability of specific marine ecosystem attributes. This article will focus on coastal protection provided by coral reefs, which falls under the third heading of regulating services.

Coral reefs form barriers which buffer coastal zones from severe weather events and in so doing, protect human lives, coastal properties and economic activities (Barbier et al., 2011). Several

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studies show that reefs reduce ocean swells, which results in wave transformations and rapid attenuation of wave energy (Brander et al., 2004; Kench and Brander, 2009; Lugo-Fernandez et al., 1998). The fringing reef can absorb a large part of this force (Brander et al., 2004; Roberts et al., 1992) up to 90% at low tide (Lugo-Fernandez et al., 1998). Given the expected increase of extreme climatic event occurrences, as well as sea level rise due to climate change (IPCC, 2013), it becomes increasingly important to better understand, communicate and manage this ecosystem service of coral reefs.

Another service related to coastal protection, is the contribution of reefs to the regulation of erosion and sedimentation, which are critical to maintaining beaches and coastlines. Coastlines where coral reefs are located receive coral or algal derived sediments from this ecosystem via various hydrodynamic processes (waves, currents, tides). Accumulation on the coastline of those sediments (sedimentation) is the source of beach formation (Huang et al., 2007).

The ES of coastal protection is therefore relevant both for the protection of human lives and economic activities associated with beaches. Economic valuation of shoreline protection provided by coral reefs is a useful tool in highlighting the importance of this service to decision-makers (Sale et al., 2014).

Characterization (with or without economic valuation) of the coastal protection ES however is extremely challenging, especially in a data scarce environment. Over 64% of coral reef ecosystems lay in developing countries (Bryant et al., 2011) which are often characterised by high population densities in the nearshore and limited government resources for coastal management. The development of ES valuation methodologies adapted to these contexts is a requirement if the full potential of ES valuations is to be realized.

Many factors contribute to make the valuation of coastal protection ES complex. The typology of the reef, its depth and the type of wave that impact it, result in great variability in the assessment of coastal protection (Kench and Brander, 2009). In addition, the role of coral reefs in coastal protection is mixed with other factors which drive the process, such as: bathymetry, currents, geomorphology, and biological cover (Burke, 2004). Some of these factors (e.g. biotic components such as live coral coverage) require complex methods and add another layer of difficulty (Barbier et al., 2008; Cooper et al., 2009; Ferrario et al., 2014; Gourlay and Colleter, 2005; Van Zanten et al., 2014; Yee et al., 2014) This might explain why, to our knowledge, relatively few economic valuation studies (Laurans et al., 2013; Van Zanten et al., 2014) have focused on isolating the role that reefs play in coastal protection. However, taking into consideration the importance of their role for advocacy for policy makers, it is important to improve these valuations, in order to transmit the most accurate values of this ES.

The aim of this article is to propose a relatively easy methodology that will allow for an assessment of the value of coastal protection provided by coral reefs, within a data scarce environment. The methodology has been designed primarily for policy advocacy.

We will discuss if improved characterization of the ES (with or without valuation) can contribute to better management of the coastal ecosystems, as well as being the initial step of a payment scheme with beneficiaries of the ES as suggested by Engel et al. (2008).

2. Material and methods

To fulfill the objective of this paper, five studies were used to illustrate the valuation of coastal protection provided by coral reefs (Table 1). Chosen study areas have many similarities: (i) insular

Table 1
Main characteristics of case studies – ADC stands for Avoided Damage Costs method and RC stands for Replacement Cost method.

Ocean/Regional Seas	Country/Island or specific area Island or specific area	Objectives of the study	Scale of the study	Valuing method	Method particularities	Sources
North West Pacific Ocean/Philippines Sea	Northern Mariana/Is. Saipan	Valuation of total value of ecosystem services provided by coral reefs	Island	ADC	Comparison of damages inflicted by marine flooding based on a reference situation (current geomorphology of reefs) and an hypothetic one (absence of reefs).	Beukering et al. (2006)
North West Pacific Ocean/Philippines Sea	Philippines/Marine Bohol Triangle	Economic valuation of ecosystem services provided by four marine ecosystems (coral reefs, mangroves, beaches or intertidal areas, and marine waters)	Specific area	RC	Only mangroves are considered as acting for coastal protection (the role of reefs is not accounted)	Samonte-Tan et al. (2007)
North West Atlantic Ocean/South East Caribbean Sea	Trinidad&Tobago, Belize, St. Lucia	Economic valuation of coral reefs in the area	Island	ADC	Use of Coastal Protection Index	Burke et al. (2008), Cooper et al. (2009)
South West Pacific Ocean	New-Caledonia	Economic valuation of ecosystem services of coral reefs at the scale of the area	Island	ADC	Method applied in a low-data context	Pascal (2010)
North West Atlantic Ocean/North East Caribbean Sea	Virgin Islands/Saint-Croix	Comparison of existing methods for quantifying shoreline protection at island scale	Island	N/A	Measurement of relative contribution of different habitat types to wave energy attenuation. Use of bio-physical features of the reef for characterization of the coastal protection	Van Zanten et al. (2014); Yee et al. (2014)

territories (entire single islands such as Tobago, New-Caledonia), Saint-Croix (Virgin Islands), Saipan (Northern Mariana Islands) or a set of several islands such as Marine Bohol Triangle (Philippines) and, (ii) a GDP superior to the world average[1] (excluding the Bohol Marine Triangle, located in Philippines) (Central Intelligence Agency, 2014). They were chosen to reflect the diversity of existing methodological approaches, and provide an optimal background for supporting our choices presented in the Results section.

In the majority of case studies analyzed, methodologies used to value coastal protection were based on three primary steps: (i) determination of areas and assets exposed to risk, (ii) quantification of reef contribution to coastal protection and (iii) economic valuation. These three steps can be implemented independently of each other, producing important heterogeneity in methodological approaches.

In the next section, we will present the three methodological steps, including a case study that is highly data (and time) demanding and another which is less data dependent.

2.1. First step: determination of areas and assets exposed to risk

The area at risk is defined as the shoreline located under the maximum wave height. To identify such on the island of Saipan (Commonwealth of the Northern Marina Islands) (Beukering et al., 2006) the authors used a comparison of two models predicting maximum average wave height during an extreme climatic event along the entire shoreline. One model utilized the existing situation, with reef, while in the other hypothetical case, the reef was excluded. After determining the zone at risk for flooding, both in the presence and absence of reef, the authors then determined the infrastructure and buildings that might be impacted. A similar approach was used in Cooper et al. (2009).

In other studies, only the scenario with existing reef coverage was used (Burke et al., 2008; Pascal, 2010; Van Zanten et al., 2014) and simpler historical data on 'average wave height' during extreme climate events were utilized instead of predictive models to determine the zones at risk. Van Zanten et al. (2014) incorporated local oceanographic data for assessing the maximum average height of waves, while Burke (2008) used local data based on observations from a storm atlas (online source from Organization of American States) and Pascal (2010) an average regional maximum height calculated for tropical environments by meteorological departments (online sources from Meteo France and NOAA).

2.2. Second step: quantifying the role of coral reefs in coastal protection

Reefs can dissipate wave energy either by waves breaking on the physical structure or via reef friction (biophysical) (Van Zanten et al., 2014; Yee et al., 2014). The physical function has been well documented (Hardy et al., 1990; Hearn, 1999; Massel and Brinkman, 1999; Roberts et al., 1992; Young, 1989), but less emphasis has been placed on the friction or biophysical aspects (Beaumont et al., 2007; Done et al., 1996; Duarte, 2000). Both processes have been utilized in methods to assess the value of the coral reef to coastal protection.

Yee et al. (2014) and Van Zanten et al. (2014) used the biophysical approach to demonstrate the role of coral reefs in decreasing wave heights, and dissipating wave energy. These studies showed the importance of friction which is linked to percentages of living coral coverage. A wave model taking into account coral cover, wave characteristics, water depth and storm characteristics, was applied by Van Zanten et al. (2014). The wave model was used to determine the amount of energy dissipated via four reef types (shallow high density, shallow low density, deep high density and deep low density reefs). It was then possible to assess the contribution of reefs to the coastal protection service.

Yee et al. (2014) confirmed that models including friction are better at explaining wave energy dissipation over the reef. Sheppard et al. (2002), introduced a method to measure attenuation percentage in wave energy and wave height due to the presence of the reef. The spatial scale was a critical aspect. In this case, the studied area was divided into 10×10 meter-cell grids to reflect the complexity of the shoreline (coral cover, reef depth etc). The scale and data required by the biophysical models however, makes them difficult to establish for large areas of tens of kilometers (as might be the case for the valuation of an island or sub-national areas).

Burke et al. (2008), Cooper et al. (2009) and Pascal (2010) developed a coastal protection index (CPI), which incorporates the contribution of the reef to coastal protection (the reef-contributing factor). This index is the sum of scores, attributed to several factors that contribute to coastal protection and represents the 'degree of protection' to the shoreline, which includes the contributory role of the reef. The number of factors required to calculate the CPI were intentionally limited to 6 in order to avoid extensive data collection and they partially reflect the complexity of the coastal protection service. The calibration of the factors is a critical component in the determination of the CPI.

In Van Beukering et al.'s (2006) study, the contributory role of the reef was assessed by comparing the values of avoided damages cost with and without the presence of the coral reef. This method relied heavily on the application of a theoretical model, where the quality of results was directly linked to the availability of the input data.

2.3. Third step: economic valuation of the ES

The literature provides two main methods for the economic valuation of the coastal protection service: avoided damages and replacement costs.

Van Zanten et al. (2014) used economic data from an existing land use valuation methodology estimating "the maximum damage for flood events per land use class per hectare in the Netherlands". The Dutch values were then translated from euro to dollar[2] and adapted to the USVI context. Then, the percentages of wave energy dissipation and friction established from the previous step were applied to the four types of reef.

Burke et al. (2008) and Pascal (2010) used average property values (derived from real estate market prices and construction costs), prorated by the reef-contributing factor previously calculated. While Cooper et al. (2009) used location-specific average property values, adjusted by settlement and proximity to the coast. The avoided damages costs method used in Beukering et al.'s (2006) study considered the mean value of property at risk, and then estimated a percentage of 'flooding damage' to the property (in that case, 5% of the entire property value was impacted by flooding). Burke et al. (2008) and Cooper et al. (2009) used the share of coastal protection ascribed to the coral reefs as a prorating factor.

For replacement costs, (Samonte-Tan et al., 2007) used replacement costs of the construction and maintenance of an artificial breakwater (seawall or dyke) to assess the value of coastal protection provided by mangroves in the Bohol Marine Triangle (BMT). Although the method is applied in this case for the

[1] This material highlights the difficulty in finding case studies from developing countries.

[2] The exchange rate used is: €1 = \$1.32 (2007, source: www.xe.com).

mangroves, it behaves similarly for coral reefs (Brander et al., 2012). The average value of constructing protective seawalls or dykes in the area was estimated at $352/Ha. This approach did not take into account the potential differences of construction and maintenance costs between different types of seawalls and a wide range of seawalls exists, varying in material and orientation.

2.4. Summary of economic values

Results of economic valuations have been summarised (see Table 3) for informative and comparative purposes.

3. Results

3.1. General model

The model proposed hereafter is based on those developed by Burke et al. (2008) and Pascal (2010). Both served as a starting point and elements of each have been utilized in developing this new method. The general model is divided in four main steps: (i) Identify coastal areas potentially at risk during coastal flooding events, (ii) determine the CPI and the contribution of coral reefs to coastal protection and, (iii) quantify and value the avoided damages, including repair costs and loss of use through two substeps: (a) characterization of the assets exposed to risk (three main categories), (b) valuation of the total repair costs of direct and indirect tangible damages and, the last step (iv) estimation of the annual probability of flood event per impact category.

3.2. Step 1: zones at risk mapping

Identifying assets under flood risk is the first step of the economic valuation. The main challenge is to clearly identify the areas at risk, using low precision maps and satellite data. We proposed that areas at risk be designated as the coastal lands between 0 and 6 m above the high tide sea level (as storm surge will have maximum impact if it coincides with high tide). This level comes from models of extreme wave height, such as Slosh (Sea, Lake and Overland Surges from Hurricanes) as well as from data on historic maximum heights of non-tsunami waves during the last 25 years (main sources: NOAA, Météo France and Vanuatu Meteorological Office), showing that the maximum wave height surging on shorelines rarely exceeds 6 m.

A projection of this height to determine the potential impacts of flood events can be made easily with GIS topographic data. Several databases might be used, such as Aerial photography: PlanetObserver (satellite images), Google Earth plug-in layer on Qgis software, and/or GIS data from Pacific Catastrophe Risk Assessment and Financing (PCRAFI, 2011). The areas vulnerable to the flood impacts has been limited to 1 km inland following the experiences developed by Cooper et al. (2009), Das and Vincent (2009), Kench and Brander (2009).

3.3. Step 2: Coastal Protection Index (CPI)

The Institute of Marine Affairs (IMA) the World Resources Institute (WRI) and the University Of New Caledonia (UNC) developed a Coastal Protection Index (CPI), based on a set of geomorphological and physical factors. This CPI showed in numerical form, the level of protection provided from intense wave action (Burke et al., 2008) as well as the contribution of coral reef to this protection.

The decision was made to divide the study zone into shoreline segments of 10s-100 km depending on the similarity of one or several of the first 3 factors of the Table 2 (i.e. geomorphology, coastal exposure and reef morphology).

For each segment of the coastline, the CPI incorporates up to seven factors (Table 2) depending on available data. For each factor, a number between 1 (no protection provided) and 5 (maximum protection) is assessed. The average of all factors is then calculated to produce a unique index value, the CPI. The relative contribution of reefs to the CPI can then be calculated.

3.4. Step 3: economic valuation

For the valuation of avoided damages costs, it is necessary to determine the different categories of damages from flood events (Messner et al., 2007). Due to the difficulty of assigning an economic value to intangible damages (loss of life, increased vulnerability of survivors), we chose to focus the analysis on tangible damages. For those that are direct and tangible (i.e. damage on physical assets), three categories of land use are distinguished: (i) buildings (ii) infrastructure and (iii) crops. For those that are indirect (i.e. loss of industrial production, traffic disruption and emergency costs), emergency costs is the most appropriate choice in terms of availability of data. Other indirect tangible damages such as loss of industrial and agricultural production, as well as loss of tourism revenue due to the temporary closure of hotels are very important, but precise data are generally difficult to find.

Following the methodology developed in several reports (Bolt et al., 2005; Messner et al., 2007; Pagiola, 2004; PCRAFI, 2011), we assess the total repair costs of damages based on average construction (and/or crop appraisal values as well as standard

Table 2
Coastal Protection Index.

	Very strong	Strong	Medium	Low	None
	5	4	3	2	1
Geomorphology	Rocky shore	Mix of rocks/sediments/ mangroves	Mangroves	Sediments	Beaches
Coastal exposure	Protected bay	Semi-protected bay	Artificial reefs	Low protected bay or coast	No protection
Reef morphology, area and distance to the coast	Continuous barrier (> 80%) close to the coast (< 1 km)	Continuous barrier (> 50%), patch reef, close to the coast (< 1 km)	Fringing reefs (width > 100 m)	Coral formation discontinuous	No reefs
Inner slope, crest width	Very favorable conditions (gentle slope, large crest width)	Favorable conditions (slope, large crest width)	Favorable conditions (at least one component)	Reduced favorable conditions (strong slope, reduced crest width)	None
Platform slope	6–10%	2.5–6%	1.1–2.5%	0.4–1.1%	< 0.4%
Main depth (1 km away from the coast)	< 2 m	< 5 m	> 5 m	> 10 m	> 30 m
Presence of other ecosystems	Mangroves, seagrass > 75% shoreline	Mangroves, seagrass 50–75% shoreline	Mangroves, seagrass 25–50% shoreline	Mangroves, seagrass < 25% shoreline	None

emergency costs), and then apply a standard depth-damage function to determine the value of damages. The standard was established to determine the value of damages, assessing the average percentage of destruction of the total asset during a high flooding event (> 5 m high). This standard percentage represents destruction of 65% of the total asset, which corresponds to the average of several studies (California Natural Resources Agency, 2012).

3.5. Other aspects

3.5.1. Assets at risk

Assets might be residential, commercial, public infrastructure (such as airports, ports, power plants, dams, major roads, and bridges), rural and industrial buildings and crops. A database containing a description of the assets with the number of residential houses, the floor area of residential, commercial and public infrastructure and simplified structural characteristics has to be created for each segment. When detailed data are available, information on single properties (also called object-oriented data) will allow for a property-by-property approach (Penning-Rowsell et al., 2003). In other cases, properties will have to be aggregated in areas that are fairly homogeneous (also called aggregated land use data). Land use data might be available from secondary sources (e.g. urban planning). Data can be completed with a GIS-based population database to identify the population at risk in each segment. Data field verification, if planned, will have to be located in areas that have more variety in building type and usage.

3.5.2. Repairing costs

The direct damages for all assets (except crops) are valued through estimates of benchmark costs needed to repair or replace the damaged assets. The values (generally expressed in $US per m^2 of building floor area) are collected from a variety of sources, including construction companies, government reports, interviews with local real estate experts, and historical disaster reports. In tropical areas, three types of structures should be considered to reflect costs of different structures: single-story timber, masonry/concrete, and traditional-style buildings. For crops, the damages are derived from loss in annual gross profit. Data might come from local governments or from official annual rental values of croplands.

3.6. Step 4: probability of the hazard event

The final step consists of calculating the annual probability of the hazard event (storm, cyclones) to determine valuation of the ES on a yearly basis. Tropical cyclone activity and intensity are variable on the intraseasonal, interannual, interdecadal and multidecadal timescales (CSIRO and Australian Bureau of Meteorology, 2007). The probability of events is calculated from existing models for the study region. Tracks of historical tropical cyclones are analyzed from a catalog of historical storms assembled from the dataset of the International Best Tracks Archive for Climate Stewardship project, the NOAA Historical Hurricane Tracks, the Joint Typhoon Warning Center (JTWC), the Australia Bureau of Meteorology (BoM), the France Météo and other country Meteorological Service.

3.7. Formula

(Fig. 1).

3.8. Approach of uncertainties

The model is based on an important number of factors, with uncertainties. Estimates of the minimum and maximum values for the reef contributive index, the areas at risk (e.g. number of residential houses) and the repair costs are proposed to show the range in which the "real" value most likely lies.

3.9. Summary of economic valuations

The valuation outputs in international dollars reflect the variability of coral reefs and the economic context of the sites. This variability is very clear both in absolute values and in values per km^2 ranging from 14 to 12,250 US$/ha. In terms of values per capita, results seem less variable, from 14 to 615 US$/capita (Table 3).

4. Discussion

The proposed methodology aims to be adaptable for a wide range of contexts, in particular low-data availability settings. As highlighted previously, other methods are more precise, but are also more data demanding and require calibration of complex models. Our method is appropriate for many situations, using local parameters that are easily available in most countries. It is being implemented so far in very different geographical contexts (Colombia, French Polynesia, Fiji, Honduras, Martinique, Mayotte, New Caledonia and Vanuatu) bringing concrete experiences of field data collection and communication to decision-makers. As usual the "one size fits all" model does not exist and it is important to determine the pros and cons of the proposed model and identify the best method of utilization. It is also important to note that this method includes only those factors that can be monetized, while policy makers rely on a range of information types and analyses in

$$\boxed{C = \left(\Sigma_{ie}\, uw_i * f_i * rc_{ie}\right) * p \qquad uw_i < \text{max. } h}$$

With :

C: costs of avoided damages

uw_i : coastal area under wave originated flood risk per zone (i)

$Max.\ h$: maximum height of waves (historical average)

f_i : Contributing factor of ecosystems in the coastal protection index (CPI) per zone (i)

rc_{ie} : building, infrastructure, crops repair costs estimated per zone (i) (damage function).

P: probability of hazard event

Fig. 1. Formula to assess the value of coral reefs in terms of coastal protection, method of avoided damages costs.

Table 3
Summary of economic valuation from the selected studies. Original results are converted into international Dollar (2011) based on the Power Parity Purchase (PPP) data (Heston et al., 2011) for all countries except Marianas Islands based on The World Fact book (Central Intelligence Agency, 2014). Results are presented in value per km^2 of coral reef and value per capita based on total population of the study site.

Study Site, sources	*Annual value of coastal protection provided by coral reefs or associated ecosystems*			*Area (Hectares)*	*Inhabitants (year of census)*
	in Int. Dollar (PPP factor used)	*in Int. Dollar Per Capita*	*in Int. Dollar Per hectare*	*CR: Coral reefs M: Mangrove*	
Saipan, Beukering et al. (2006)	8 442,000 (1.05)	173	2 723	3 100 (CR)	48,430 (2012)
Marine Bohol Triangle, Samonte-Tan (2007)	405,800 (23.06)	14	1610	252 (M)	28,280 (2010)
Tobago, *Burke et al. (2008)*	38,250,000 (3.76)	615	12,750	3 000 (CR)	62,219 (2014)
New Caledonia, *Pascal, 2010*	41,650,000 (0.71)	159	90	460,700 (CR)	262,000 (2013)
Sainte-Croix, *Van Zanten et al. (2014)*, *Yee et al. (2014)*	No economic valuation. Measurement of relative contribution of different habitat types to wave energy attenuation				

order to determine the best course of action. One very important element, not captured here is the social element: the importance of coastal ecosystems to human lives for example, and such information should be incorporated as well.

4.1. Interpretation and communication of economic values

As indicated by the high range of valuation outputs, most of the results are very specific to the site and reflect differences in methodologies, ecosystem geomorphology, climate regimes, storm characteristics, coastal exposure and economic development. Experience has shown us that these characteristics can be very variable at the scale of km and this makes difficult any comparison between sites. In this context, the correct use of transfer benefit approaches as defined by (Wilson and Hoehn, 2006) is a complex exercise with, to our knowledge, a limited track record with coral reef ecosystems (Burke, 2004; Pérez-Maqueo et al., 2007; Waite et al., 2014).

Regarding presentation of results, the absolute annual economic values, when compared to per hectare or per capita ratios seem to provide clearer indicators of the importance of the ES. Both ratios can suffer bias with a large coral reef area (e.g. New Caledonia) or large, unprotected coastal populations (e.g. Colombia) that would diminish the importance of the ES.

Additionally, we propose to clearly identify the beneficiaries (e.g. the number of households or area size of tourism infrastructure protected) that will aid in communicating the results to decision-makers. This information is extremely useful at the policy level (Pascal et al., 2014; Waite et al., 2014).

In terms of communication with policy makers and other stakeholders, the method is designed to produce preliminary information that can be of great value for general advocacy. At the scale of 10 s to 100 km (e.g. national or sub-national scale), the results reflect the importance of coral reefs for the local society and can complete the valuation of other ES (e.g. biomass production for fishery, scenic beauty for tourism). It can also assist with the identification of the beneficiaries and generate additional arguments for reef importance. From a conservation point of view, this is extremely positive, as it will help advocate for better management of coral reefs ecosystems.

However, some caution has to be employed, as the method relies on a number of assumptions, which should always be mentioned when communicating the results.

Our approach is not recommended for small-scale processes (1–10 km) or for communication with small-scale stakeholders (e.g. municipal or provincial level) who have specific information needs (Hein et al., 2006). Small scale processes such as the development of management plans for many Marine Protected Areas (MPAs) or provincial Marine Spatial Planning (MSP) require more accurate information on the role of the coral reef, than can be provided with this methodology (Sale et al., 2014).

This method is also not recommended for the design of instruments such as Payment for Ecosystem Services (PES). To our knowledge, the role of economic valuation of marine ES is not extensively described for this instrument. Recent field experiences have revealed that most marine PES are designed for small scales (1–10 km) either for a bundle of services or for a unique service (Clua and Pascal, 2014; REECS, 2014; The Katoomba Group and Marketplace, 2010). Take for example the case of a beneficiary who wishes to pay for the ES of shoreline protection. As this requires a precise characterization of the ES, at a small scale and a clear identification of the role of live coral (Agardy et al., 2014), our method would be inappropriate.

4.2. Biological and physical role of coral reefs

Our approach is based on the wave breaking function of coral reefs in coastal protection. It is clear that friction with coral also plays a role in dissipation of wave energy (Burke, 2004; Gourlay and Colleter, 2005; Sheppard et al., 2002; Van Zanten et al., 2014). According to Thornton and Guza (1982), the relative amount of wave energy dissipation of coral reefs in St. Croix is around 75–85%. In the absence of corals on the reef crest (i.e. friction) the wave energy dissipation function would be 57–66%. The relatively small contributive value of live coral to wave energy dissipation, while important, would be lost in our broad scale methodology proposed. In addition, in spite of the friction factors developed by Sheppard et al (2005) which denote the relative wave energy dissipation for reef types and health and range between 0.1 (coral pavement) to 0.2 (75–100% live coral) this is still considered relatively data demanding and therefore not appropriate for our model. Finally, the scale required by the biophysical models makes them difficult to establish for large areas, such as the tens of kilometers that would be required for the valuation of an island or sub-national areas.

There is also natural coral mortality that should be taken into consideration. The coastal protection service provided by the reef structure (wave-breaking function) is expected to slowly decrease at the rate of natural erosion (10′s to 100′s of years). This is an aspect that should be reflected in ES valuation studies, through the use of long term projections and discounted rates(Van Zanten et al., 2014). Then, the importance of live coral on the reef is highlighted and valued.

4.3. Specific role of the coral reef in coastal protection

One other important component of the approach is the assessment of the contributive role of coral reefs to coastal protection. It is important that this value avoids an over-estimation of the role and value of the coral reef ecosystem service, especially when using the avoided damages costs method. As presented with the CPI calculations, many inter-related factors contribute to the coastal protection service. Linking avoided damages only to the presence of coral reefs does not reflect the role of these other factors. Our proposed method relies on expert opinion to provide information on the relative importance of each of the different factors. As highlighted by different studies (Curtis, 2004; Wilson and Hoehn, 2006) methods of reducing errors associated with the expert approach are supposed to: (1) define a clear and simple quantitative range of values (2) set up a limited number of factors and (3) segment the valuation as much as possible. In this way, the proposed method is based on a quantitative approach, utilizing a maximum of seven different factors.

4.4. Choice between avoided damages and replacement costs approaches

This choice depends on several context variables such as the presence or absence of reef, which might affect the technical feasibility of setting up coastal engineering works, the fetch (distance over water that the wind blows in the same direction) and the economic activities in the zone. Usually, governments, in their strategy against erosion, prefer to concentrate on high priority areas (e.g. with tourism or residential infrastructure) rather than to establish defenses across large areas, which would lead to unrealistic implementation costs. A comparison of the avoided damages costs approach and the replacement cost method shows that the replacement cost method tends to produce extremely high estimates, up to 10 times greater than the lower-bound estimate, calculated using the damage approach (Barbier et al., 2011; Sathirathai and Barbier., 2001; Tri et al., 1996). This suggests that the replacement cost method should be used with caution, in the context of small scales and specific zones. The avoided damage cost approach appears to be better adapted to scales of km and 10 s of km.

4.5. Repair costs calculations

Although Torterotot (1993) gave us a strong basis for the use of damages functions in the economic valuation method, we chose to use a simplified form of damage functions in our methodology in order to adapt it to available data. We assigned to each kind of building, a standard damage percentage for a given inundation depth. The benefit of such an approach is that it eliminates the requirement of collecting parameters required for the calibration of the damage function (e.g. velocity of inundation, duration of immersion, building materials and age) by using a level of damage, dependent on inundation depth and basic type of buildings (e.g. one-level/two-level houses, hospital, school, hotel, restaurant, shops etc). Only average local construction costs per square meter and building type (data which is easy to obtain) have to be collected. The chosen approach via repair costs, allows one also to avoid fluctuations in the real estate market price. The damage function by structure type (wood, concrete etc) is an important element to include in the future. This information is helpful especially in a tropical context, where there is a higher proportion of houses made with wood or local materials, that are more likely to experience severe damage, compared to concrete houses.

4.6. Damages to be valued

Our valuation has been applied to two types of damages only: direct tangible damages (impacts on buildings, infrastructures and crops), and one kind of indirect tangible damages (emergency costs). The development of damage functions for other specific damages is also important and would complete the valuation. For impacts on humans, other models (PCRAFI, 2011) done in the South Pacific have estimated the casualty number as a function of the total economic losses, which are used as a proxy for the number of damaged buildings.

Another aspect for investigation is the integration of indirect tangible damages, such as loss of industrial production or tourism loss of earnings. For example, regarding impacts on tourism facilities, loss of benefits due to temporal closures of the hotel complex and lower occupancy rates, in addition to the construction replacement costs should provide a better overview of economic benefits of coastal protection provided by coral reefs. Delays in the reopening of hotels due to repairs for example, and the loss of earnings that ensue, are strong arguments for decision-makers and investors, in light of the important contribution of tourism to the GDP of many coral reef countries.

4.7. Climate change

Finally, in an environment where climate change issues are becoming increasingly prominent, leading to their inclusion in environmental policies, it is critical to incorporate this element. In particular, the expected changes in the frequency of extreme climatic events should be considered in the valuation of the coastal protection service (Bender et al., 2010; Van Zanten et al., 2014). There is substantial evidence from theory and model experiments that the large-scale environment in which tropical cyclones form and evolve is changing as a result of climate change (PWA and SAIC, 2009) and that increases in hurricane frequencies are expected (IPCC, 2013). With our model, the probability of extreme events is easily incorporated in the valuation through adapting the annual frequency of occurrence of the events (referred as P, “probability of the hazard event”, in the Fig. 1, formula to assess the value of coral reefs in terms of coastal protection).

5. Conclusion

The result is the design of a 3-step logical method that responds to different socio-ecological contexts, and based on local, publicly available data sources. In addition, we suggested several elements that should be further investigated in order to improve this method, such as extending the categories of repair costs, reflecting the friction role of reefs and including climate change impacts. Most of the methodological choices made have been driven by limited scientific knowledge and the desire for a pragmatic approach, in a data poor environment.

The proposed method demonstrates some promising elements, albeit with clear limitations. Results reflect the relative importance of coral reefs in coastal protection at national or sub-national scales (i.e. at a scale of 10 s to 100 km) and can therefore complete the valuation of other ES (e.g. biomass production for fishery, scenic beauty for tourism). They can also assist in identifying beneficiaries and so contribute required information to policy and decision makers. This sort of information could prompt decision makers to allocate resources for the conservation of coral reefs. The method however appears to be less effective for small scale approaches (km), such as those required for the design of a PES scheme or a process of marine spatial planning.

It is hoped that this paper will assist researchers interested in improving the valuation of the ES of coastal protection provided by coral reefs and other ecosystems (e.g. mangroves, seagrass beds). It further highlights the importance of improved collaboration with other disciplines such as ecologists, geologists, oceanographers, social scientists and those involved in management and policy.

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References

Agardy, T., Pascal, N., Brathwaite, A., 2014. Innovative financial mechanisms for coastal management in the Pacific: a state of the art. Technical Report - SPC/ RESCCUE , Marine Ecosystem Services (MARES) Program, p. 59.

Barbier, E.B., Hacker, S.D., Kennedy, C., Koch, E.W., Stier, A.C., Silliman, B.R., 2011. The value of estuarine and coastal ecosystem services. Ecol. Monogr. 81 (2), 169–193.

Barbier, E.B., Koch, E.W., Silliman, B.R., Hacker, S.D., Wolanski, E., Primavera, J., Granek, E.F., Polasky, S., Aswani, S., Cramer, L.A., Stoms, D.M., Kennedy, C.J., Bael, D., Kappel, C.V., Perillo, G.M.E., Reed, D.J., 2008. Coastal ecosystem–based management with nonlinear ecological functions and values. Science 319, 89–98.

Beaumont, N.J., Austen, M.C., Atkins, J.P., Burdon, D., Degraer, S., Dentinho, T.P., Derous, S., Holm, P., Horton, T., van Ierland, E., Marboe, A.H., Starkey, D.J., Townsend, M., Zarzycki, T., 2007. Identification, definition and quantification of goods and services provided by marine biodiversity: implications for the ecosystem approach. Mar. Pollut. Bull. 54, 253–265.

Bender, M.A., Knutson, T.R., Tuleya, R.E., Sirutis, J.J., Vecchi, G.A., Garner, S.T., Held, I. M., 2010. Modeled impact of anthropogenic warming on the frequency of intense Atlantic hurricanes. Science 327, 454–458.

Beukering, P.v., Brander, L., Tompkins, E., McKenzie, E., 2007. Valuing the Environment in Small Islands, in: Joint Nature Conservation Committee, P.P.J.U.T.r., p. 128. June 2007 (Ed.), Available at: 〈http://www.jncc.gov.uk/page-4065〉.

Beukering, P.v., Haider, W., Wolfs, E., Liu, Y., Leeuw, K.v.d., Longland, M., Sablan, J., Beardmore, B., Prima, S.d., Massey, E., Cesar, H., Hausfather, Z., 2006. The Economic Value of the Coral Reefs of Saipan, Commonwealth of the Northern Mariana Islands. Department of Interior, NOAA - Technical report, 99 pp.

Bolt, K., Ruta, G., Sarraf, M., 2005. Estimating the Cost of Environmental Degradation: A Training Manual. The World Bank: Environment Department Papers.

Brander, L., Wagtendonk, A.J., Hussain, S.S., McVittie, A., Verburg, P.H., Groot, R.Sd, Ploeg, Svd, 2012. Ecosystem service values for mangroves in Southeast Asia: a meta-analysis and value transfer application. Ecosyst. Serv. 1 (2012), 62–69.

Brander, R.W., Kench, P.S., Hart, D., 2004. Spatial and temporal variations in wave characteristics across a reef platform, Warraber Island, Torres Strait, Australia. Mar. Geol. 207, 169–184.

Bryant, D., Burke, L., Mcmanus, J., Spalding, M., 2011. Reefs at risk: A Map-Based Indicator of Threats to the World's Coral Reefs. World Resources Institute (WRI), International Center for Living Aquatic Resources Management (ICLARM), World Conservation Monitoring Centre (WCMC). United Nations Environment Programme (UNEP).

Burke, L., 2004. Reef at risk in the Caribean: Economic Valuation Methodology. Working Paper. Washington, DC: World Resources Institute. Available online at 〈http://www.wri.org/ coastal-capital〉.

Burke, L., Suzie Greenhalgh, Prager, D., Cooper, E., 2008. Coastal Capital – Economic Valuation of Coral Reefs in Tobago and St. Lucia. Working Paper. Washington, DC: World Resources Institute. Available online at: 〈http://www.wri.org/ coastal-capital〉.

California Natural Resources Agency, 2012. 2012 Central Valley Flood Protection Plan, A Path for Improving Public Safety, Environmental Stewardship, and Long-Term Economic Stability. Central Valley Flood Protection Board Pursuant to the California Central Valley Flood Protection Act of 2008.

Central Intelligence Agency, 2014. The World Factbook 2013–2014. 2016. Central Intelligence Agency,, Washington, DC 〈http://www.indexmundi.com〉.

Clua, E., Pascal, N., 2014. Shark-watching ecotourism in the Pacific islands: A move towards "payments for ecosystem services"? SPC Fisheries Newsletter #144 - May–August 2014.

Cooper, E., Burke, L., Bood, N., 2009. Coastal Capital: Belize. The Economic Contribution of Belize's Coral Reefs and Mangroves. WRI Working Paper. Washington, DC: World Resources Institute. 2009. 〈http://pdf.wri.org/working_papers/coastal_capital_belize_wp.pdf〉.

CSIRO, Australian Bureau of Meteorology, 2007. Climate Change in Australia – CSIRO and Bureau of Meteorology - Technical Report 2007. Chapter 5: Regional climate change projections. Chapter 5.9.1 Severe weather: Tropical cyclones.

Curtis, I.A., 2004. Valuing ecosystem goods and services: a new approach using a surrogate market and the combination of a multiple criteria analysis and a Delphi panel to assign weights to the attributes. Ecol. Econ. 50, 163–194.

Das, S., Vincent, J.R., 2009. Mangroves protected villages and reduced death toll during Indian super cyclone. Proc. Natl. Acad. Sci. 106 (18).

David, G., Herrenschmidt, J.B., Mirault, E., 2007. Valeur sociale et economique des recifs coralliens du pacifique insulaire. Rapport technique - CRISP Projet 1A4 - 40 pp.

Done, T.J., Ogden, J.C., Wiebe, W.J., Rosen, B.R., 1996. Biodiversity and ecosystem function of Coral Reef. Book: Functional roles of biodiversity: a global perspective.

Duarte, C.M., 2000. Marine biodiversity and ecosystem services: an elusive link. J. Exp. Mar. Biol. Ecol. 250, 117–131.

Engel, S., Pagiola, S., Wunder, S., 2008. Designing payments for environmental services in theory and practice: an overview of the issues. Ecol. Econ. 65 (2008), 663–674.

Ferrario, F., Beck, M.W., Storlazzi, C.D., Micheli, F., Shepard, C.C., Airoldi, L., 2014. The effectiveness of coral reefs for coastal hazard risk reduction and adaptation. Nat. Commun. 5, Article number: 3794.

Gourlay, M.R., Colleter, G., 2005. Wave-generated flow on coral reefs - an analysis for two-dimensional horizontal reef-tops with steep faces. Coast. Eng. 52, 353–387.

Hardy, T.A., Young, I.R., Nelson, R.C., Gourlay, M.R., 1990. Wave attenuation on an offshore coral reef. In Proceedings of the 22nd Coastal Energy Conference. Delft 1, 330–344.

Hearn, C.J., 1999. Wave-breaking hydrodynamics within coral reef systems and the effect of changing sea level. J. Geophys. Res. 104, 30007–30019.

Hein, L., Koppen, Kv, Groot, R.Sd, Ierland, E.Cv, 2006. Spatial scales, stakeholders and the valuation of ecosystem services. Ecol. Econ. 57, 209–228.

Heston, A., Summers, R., Aten, B., 2011. Penn World Table Version 7.0, Center for International Comparisons of Production, Income and Prices. University Of Pennsylvania, June 2011.

Hilmi, N., Bambridge, T., Claudet, J., David, G., Failler, P., Feral, F.o., Léopold, M., Pascal, N., Safa, A., 2014. Préserver la biodiversité des récifs coralliens: l'évaluation économique comme outil d'une gouvernance multi-échelle. Les sciences humaines et sociales dans le Pacifique Sud – Cahiers du Credo – 2014 Chapitre 14.

Huang, J., Huang, J.-C., Poor, P.J., Zhao, M.Q., 2007. Economic valuation of beach erosion control. Mar. Resour. Econ. 32 (2007), 221–238.

Huwyler, F., Käppeli, J.r., Serafimova, K., Eric, S., Swanson, Tobin, J., 2014. Conservation Finance. Moving beyond donor funding toward an investor-driven approach. Technical report. WWF and Credit Suisse Group AG and McKinsey & Company. 32 pages.

IPCC, 2013. Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V., Midgley, P.M. (Eds.), Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, p. 1535.

Kench, P.S., Brander, R.W., 2009. Wave processes on coral reef flats: implications for reef geomorphology using Australian case studies. J. Coast. Res. 22, 209–221.

Laurans, Y., Pascal, N., Binet, T., Brander, L., Clua, E., David, G., Rojat, D., Seidl, A., 2013. Economic valuation of ecosystem services from coral reefs in the South Pacific: taking stock of recent experience. J. Environ. Manag. 116 (2013), 135–144.

Lugo-Fernandez, A., Roberts, H.H., Wiseman, W.J., J, 1998. Tide Effects on Wave Attenuation and Wave Set-up on a Caribbean Coral Reef. Estuar. Coast. Shelf Sci. 47, 385–393.

Massel, S.R., Brinkman, R.M., 1999. Saxena, N.K. (Ed.), Measurement and modelling of wave propagation and breaking at steep coral reefs. Recent advances in marine science and technology '98. PACON Int., Honolulu, pp. 27–36.

MEA, 2003. Ecosystems and Human Well-being. millennium Ecosystem Assessment - Synthesis. Island Press, Washington, DC, p. 47.

Messner, F., Penning-Rowsell, E., Green, C., Meyer, V., Tunstall, S., Veen, A.v.d., 2007. Evaluating flood damages: guidance and recommendations on principles and methods. FLOODsite Project Deliverable D9.1; Integrated Flood Risk Analysis and Management Methodologies - 156 pp.

Pagiola, S., 2004. Assessing the economic value of ecosystem conservation. The World bank - Technical report: 75 pp.

Pascal, N., 2010. Ecosystèmes coralliens de Nouvelle-Calédonie, valeur économique des services écosystémiques Partie I: Valeur financière. IFRECOR (Initiative Française pour les Récifs Coralliens) Nouvelle-Calédonie, Nouméa, Avril 2010, 155 pp. +12 planches.

Pascal, N., Brander, L., Clua, E., David, G., Laurans, Y., Seidl, A., 2012. What impacts to expect from economic valuation of coral reefs? Proceedings of the 12th International Coral Reef Symposium, Cairns, Australia, 9–13 July 2012 22D Economic valuation and market-based conservation.

Pascal, N., Brander, L., Crossman, N., Dang, T., 2014. Regional research to inform the high level panel on global assessment of resources for implementing the strategic plan for biodiversity 2011–2020. Final report for Australasia and Pacific region. CBD technical report, 35 p. .

PCRAFI, 2011. Pacific Catastrophe Risk Assessment and Financing Initiative. World Bank, Asian Development Bank And SPC/SOPAC, p. 18.

Penning-Rowsell, E., Johnson, C., Tunstall, S., 2003. The benefits of flood and coastal defence: techniques and data for 2003 (al, e.). Flood Hazard Research Centre, Middlesex University, UK.

Pérez-Maqueo, O., Intralawana, A., Martíneza, M.L., 2007. Coastal disasters from the perspective of ecological economics. Ecol. Econ. 63, 273–284.

PWA, SAIC, 2009. Greenhouse Gas Mitigation Typology Issues Philip Williams & Associates and Science Applications International Corporation for California Climate Action Registry PWA REF. 1957.

REECS, 2014. Sustainable Financing for Protected Areas. Protected Areas and Wildlife Bureau - Department of Environment and Natural Resources - The World Bank by Resources, Environment, and Economics Center for Studies, Inc (REECS). Technical report. 276 pages.

Roberts, H.H., Wilson, P.A., Lugo-Fernandez, A., 1992. Biologic and geologic responses to physical processes: Examples from modern reef systems of the Caribbean-Atlantic region. Cont. Shelf Res. 12, 809–834.
Sale, P.F., Agardy, T., Ainsworth, C.H., Feist, B.E., Bell, J.D., Christie, P., Hoegh-Guldberg, Ove, M., Peter, J.,F., David, A.,S., Megan, I.,D., Tim, M., Foale, S.J., Levin, P.S., Lindeman, K.C., Lorenzen, K., Pomeroy, R.S., Allison, E.H., Bradbury, R.H., Corrin, J., Edwards, A.J., Obura, D.O., Sadovy de Mitcheson, Y.J., Samoilys, M.A., Sheppard, C., 2014. Transforming management of tropical coastal seas to cope with challenges of the 21st century. Mar. Pollut. Bull. 85 (1), 8–23, ISSN 0025-326X.
Samonte-Tan, G.P.B., White, A.T., Tercero, M.A., Diviva, J., Tabara, E., Caballes, C., 2007. Economic valuation of coastal and marine resources: bohol marine triangle, Philippines. Coast. Manag. 35, 319–338.
Sathirathai, S., Barbier, E.B., 2001. Valuing mangrove conservation in Southern Thailand. Contemp. Econ. Policy 19 (2), 109–122.
Sheppard, C., Dixon, D.J., Gourlay, M., Sheppard, A., Payet, R., 2005. Coral mortality increases wave energy reaching shores protected by reef flats: Examples from the Seychelles. Estuar. Coast. Shelf Sci. 64 (2005), 223e234.
Sheppard, C.R.C., Spalding, M., Bradshawa, C., Wilson, S., 2002. Erosion vs. Recovery of Coral Reefs after 1998 El Niño: Chagos Reefs, Indian Ocean. J. Hum. Environ. 31 (1), 40–48, 2002.
The Katoomba Group, Marketplace, E., 2010. Paying Poseidon: Financing the Protection of Valuable Ecosystem Services. Technical Report, Forest Trends, The Katoomba Group, and UNEP IISBN: 978–1-932928–42-6, 80 pp.
Thornton, E.B., Guza, R.T., 1982. Energy saturation and phase speeds measured on a natural beach (1978–2012). J. Geophys. Res.: Ocean. 87 (C12).
Torterotot, J.P., 1993. Le coût des dommages dus aux inondations : Estimation et analyse des incertitudes. Mémoire présenté pour l'obtention du titre de Docteur de l'Ecole Nationale des Ponts et Chaussées (06/10/1993), Pierre-Alain Roche (Dir.).
Tri, N.H., Adger, N., Kelly, M., Granich, S., Nimh, N.H., 1996. The Role of Natural Resource Management in Mitigating Climate Impacts: Mangrove Restoration in Vietnam. CSERGE (Centre for Social and Economic Research on the Global Environment) Working Paper GEC 96–06.
Van Zanten, B.T., Wagtendonk, A., Beukering, P.J.H.V., 2014. Coastal protection by coral reefs: A framework for spatial assessment and economic valuation. Ocean & Coastal Management, August 2014.
Waite, R., Burke, L., Gray, E., 2014. Coastal Capital: Economic Valuation for Decision-Making in the Caribbean 2014. World Resources Institute, Washington, DC ⟨http://www.wri.org/publication/coastal-capital-guidebook⟩.
Wilson, M.A., Hoehn, J.P., 2006. Valuing environmental goods and services using benefit transfer: the state-of-the art and science. Ecol. Econ. 60, 335–343.
Yee, S.H., Dittmar, J., Oliver, L., 2014. Comparison of methods for quantifying reef ecosystem services: a case study mapping services for St. Croix, USVI. Ecosyst. Serv. 8, 1–15.
Young, I.R., 1989. Wave transformation over coral reefs. J. Geophys. Res. 94, 9779–9789.