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A practical framework of quantifying climate change-driven environmental losses (QuantiCEL) in coastal areas in developing countries

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ABSTRACT

Climate change impacts threaten the coastal environment and affect Coastal Ecosystem Services (CES) that are vital to human wellbeing. Quantifying the monetary value of climate change driven environmental losses is scarce, especially in coastal areas of developing countries that have low adaptive capacity to climate change impacts. To address this knowledge gap, we present a practical framework to Quantify Climate change driven Environmental Losses (QuantiCEL) that coherently assesses the likely physical impacts of climate change on CES, and pursues the valuation of their losses with primary data collection. The framework is applied to coastal areas in three developing countries, and may serve as a useful guide for practitioners. We quantify potential environmental losses due to relative sea level rise-induced coastal inundation in Indonesia and Bangladesh, and losses due to sea level rise and storm-induced coastline recession in Sri Lanka in the next 100 years. This study illustrates the applicability of the framework in different contexts in the data-scarce developing countries. Our findings suggest that the three case studies will experience the absolute loss value of CES by the end of the 21 st century, with food provision and tourism suffering the highest losses. Moreover, art, amenity, and tourism services are highly affected CES with respect to the percentage loss relative to the present-day value of these CES. The QuantiCEL framework and its application presented in this study could help researchers, policy makers, and coastal zone managers to get better insights into likely climate change driven environmental losses in coastal areas, contributing to the development of much needed environmental risk quantification methods, and sustainable management of coastal wetlands.

1. Introduction

Climate Change (CC) is already impacting the environment and causing considerable damages to the nature. For example, coastal hazards (e.g. flooding and coastal erosion) affected by the CC impacts, result in degradation or sometimes in disappearance of coastal wetlands which are among the most vulnerable habitats. Climate change impacts – including an increase in sea water temperature, Sea Level Rise (SLR), changes in the intensity/frequency of storms – exacerbate environmental risks and increase vulnerability of coastal wetlands in the future. Analysis of CC impacts on coastal wetlands is of great importance, considering that a large proportion of the World's population lives in coastal zones, and directly or indirectly benefits from the services provided by the coastal wetland ecosystems such as mangrove swamps, coral reefs, beach and dune systems, pelagic systems, etc. The climate change impacts will negatively affect flows of services provided by these habitats which are vital to human wellbeing. Yet, understanding the uncertainties associated with the physical CC impacts on coastal wetlands over centennial time spans has remained a challenge for both economists and ecologists.

In view of the above, achieving a sound understanding of potential CC driven variation in the health status of coastal wetlands is of great importance. A majority of CC impact assessment studies has focused on the first order CC impacts on coastal and marine areas such as changes in sea level, ocean conditions and biogeochemistry (Mohanty et al., 2010; Sumaila et al., 2011; Cheung et al., 2011; Sun et al., 2014; Lovelock et al., 2015; Henson et al., 2016; Idier et al., 2017; Dangendorf et al., 2018). However, less attention is given to the quantitative assessments of physical CC impacts on the wetland ecosystems and changes to the monetary value of services that these habitats provide

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(Cheung et al., 2011; Roebeling et al., 2013; Kuhfuss et al., 2016; Yoskowitz et al., 2017; Pavani et al., 2018). In addition, a vast majority of available literature has focused on the Present-day Value (PV) of Coastal Ecosystem Services (CES) (e.g. Brander et al., 2012; van Zanten and van Beukering, 2012; Schep et al., 2013; Castaño-Isaza et al., 2015; Czajkowski et al., 2015; Watson et al., 2016; Seenprachawong, 2016). Yet, this strand of literature does not offer a straightforward approach to quantifying the potential magnitude of the CC impacts on the present-day value of CES. Moreover, most studies were carried out in developed countries making it difficult to transfer valuations into the context of developing countries. Hence, this knowledge gap is especially prevalent in data-poor developing countries that are likely to suffer the most from CC, considering that their local communities are dependent on CES to make ends meet, while their adaptive capacity to CC impacts is low (Mehvar et al., 2018b).

To address this knowledge gap, this article introduces a practical framework that offers a scenario-based approach to Quantify potential Climate change driven Environmental Losses (QuantiCEL). The QuantiCEL framework which is adapted from the framework presented by Mehvar et al. (2018b) for a case study in coastal areas of Indonesia, is newly developed here, enabling it to be applicable for a range of similar applications. The QuantiCEL framework coherently assesses the likely physical impacts of climate change on CES, and pursues the valuation study with primary data collection and use of expert's opinions. In this study, the applicability of this framework is elaborated across the three case studies in coastal areas of developing countries for quantifying potential environmental losses due to relative sea level rise (RSLR)-induced coastal inundation (in Indonesia, and Bangladesh), and SLR and storm-induced coastline recession (in Sri Lanka) in the next 100 years.

The QuantiCEL framework links the potential impacts of CC induced coastal inundation and erosion on CES with economic concepts used in valuation studies (i.e. consumer and producer surpluses). Within this framework, (1) the present-day value of CES is quantified by using accepted economic valuation methods; (2) the potential impacts of CC driven hazards (e.g. erosion, inundation) on ecosystem services provided by mangrove swamps, beach, dune and pelagic systems are identified; and (3) these impacts are monetized by developing a scenario-based approach, grounded in expert's opinions and available primary and secondary data.

2. Case studies

The QuantiCEL framework was applied in three case studies: (1) Semarang coastal area in the Central Java province in Indonesia; (2) the Sundarbans region in the west coast of Bangladesh; and (3) the Trincomalee district in the east coast of Sri Lanka. Fig. 1 shows the locations of the case studies. In this study, four types of wetlands were considered: beach and dune system, pelagic system (marine area), mangrove swamp, and aquaculture land. In particular, Maron and Marina beaches, pelagic system (Java Sea) together with the Plumbon estuary including mangrove swamps were selected as the wetlands considered in the Semarang coastal area in Indonesia. The Sundarbans Mangrove Forest (SMF), pelagic system (Bay of Bengal) and aquaculture lands adjacent to the SMF were the wetlands considered in the Bangladesh case study. In addition, Trincomalee beaches together with the pelagic system were the wetlands selected in the Sri Lanka case study.

The choice of the study sites was driven by three main factors; (1) high importance of the coastal area in terms of the existing ecosystems and corresponding services provided (e.g. the SMF which is known as the richest natural forest and most economically valuable coastal wetland in Bangladesh); (2) high vulnerability of the coastal area to the CC driven hazards (e.g. Semarang as a low lying coastal region with high rate of future relative sea level rise); and (3) feasibility of data collection as done here by help of local professional teams such as CEGIS (Center for Environmental and Geographic Information Services) in Bangladesh and the CCD (Coastal Conservation Department) in Sri Lanka, and native language researchers in Indonesia.

Although the wetlands considered in this study provide a variety of ecosystem services (i.e. storm protection, erosion stabilisation, climate regulation, etc.), due to time/data limitations, here five ecosystem services were selected including tourism, food provision (fish and marine species), amenity, art, and provision of raw materials (timber and fuel wood).

3. Methodology

The QuantiCEL framework adapted from Mehvar et al. (2018b) is further generalized here to quantify the CC driven environmental damages/losses for a range of similar applications in coastal areas of developing countries. Fig. 2 illustrates the framework and the three methodological steps therein.

As shown in Fig. 2, the QuantiCEL framework constitutes three coherent steps including: (1) valuation of CES resulting in the present-day value provided, (2) identification of the CC driven impacts on CES, and (3) monetizing the impacts and quantifying the changes to the total CES value by linking the results of the previous two steps. A detailed description of the three methodological steps used for each case study; Indonesia, Bangladesh, and Sri Lanka is presented by Mehvar et al. (2018b, 2019a, 2019b), respectively. A summary of these three steps is presented below:

3.1. Step 1 – Valuation of CES (present status)

Wetland ecosystems provide services and goods that directly or indirectly contribute to human well-being. An overview of the economic valuation of ecosystem services and the available methods can be found in Tinch and Mathieu, 2011; Barbier (2013); Russi et al. (2013); Sukhdev et al. (2014); Champ et al. (2017); and Mehvar et al. (2018a). Applying the first step of the QuantiCEL framework for the three selected case studies, the present-day value of CES is estimated by using the standard economic valuation methods. Table 1 indicates the wetlands and ecosystem services considered as well as the corresponding economic valuation methods used for the three case studies.

According to the Table 1, pelagic system (marine area) is the type of wetland considered for all the three case studies, while mangrove swamp is the considered wetland for Bangladesh and Indonesia study sites. Additionally, aquiculture land adjacent to the Sundarbans mangrove swamp is considered only in Bangladesh case study, representing the only man-made coastal wetland in this study with the extent of 2300 km^2. With respect to the size of the other wetlands area considered for each study site, total beach area of 0.33 km^2 is considered for the Marina and Maron beaches in Indonesia, while size of the Trincomalee beach area in Sri Lanka is considered at approximately 30 km^2. Notably, size of the mangrove swamps considered in this study is remarkably different, since an area of 0.23 km^2 is the mangrove area of Plumbon estuary in Indonesia, while a total extent of 3778 km^2 mangrove forest is considered as the main wetland in the Bangladesh case study.

It should also be noted that there are some differences among the case studies while applying the QuantiCEL framework to each study site. For example, in data collection procedure, number of the interviews and surveys are dependent to the time of the field-data collection. Moreover, a total number of 210 visitors was interviewed in Indonesia beaches, while in the selected Trincomalee beaches, 70 visitors were interviewed. This difference is due to the fact that at the time of field-data collection, most of the visitors in Sri Lanka were foreigners plus a few number of Sri Lankans, while in Indonesia, Indonesians were mostly the group of visitors who were in the selected beach area. In addition, for the Bangladesh study site, a sample size of 80 fishermen was used for doing individual and group interview.

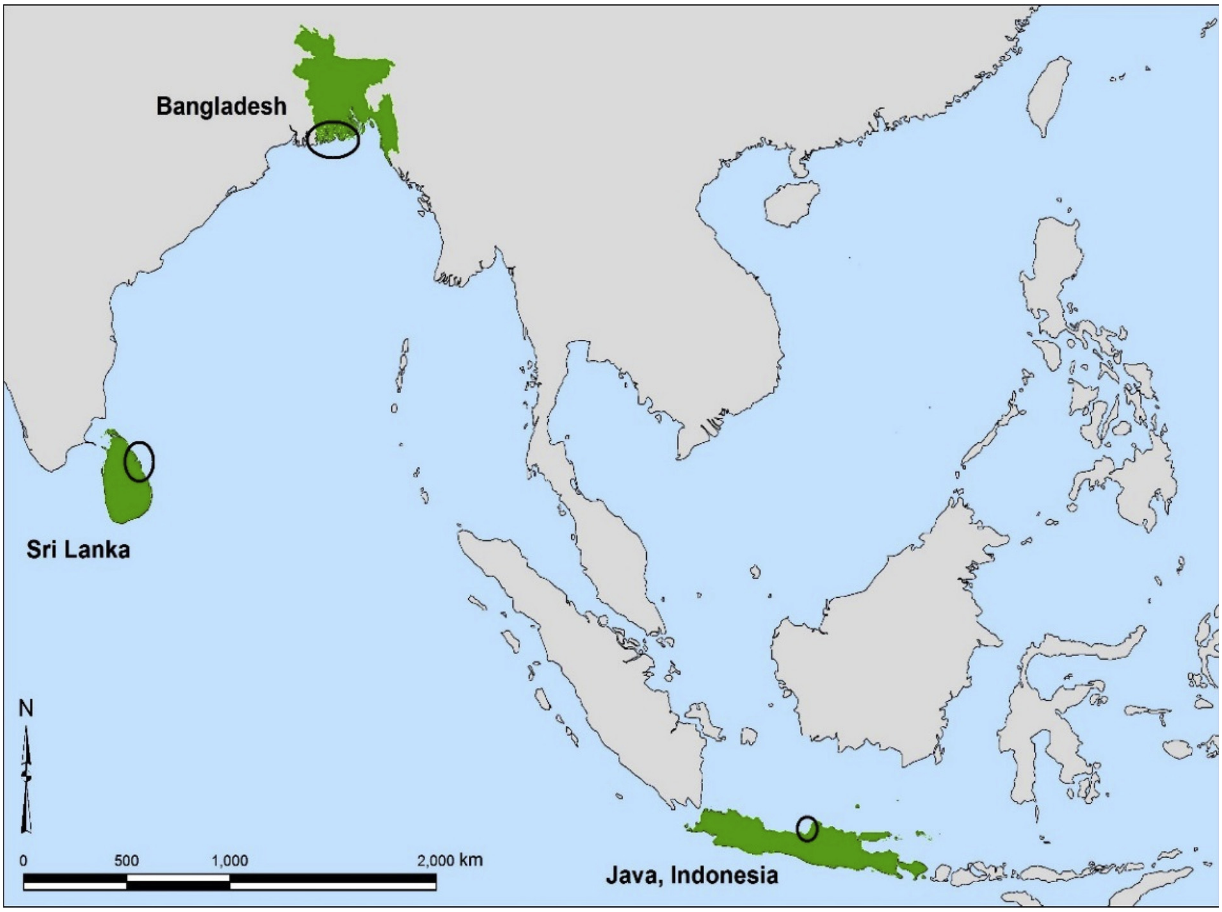

Fig. 1. Locations of the three case studies.

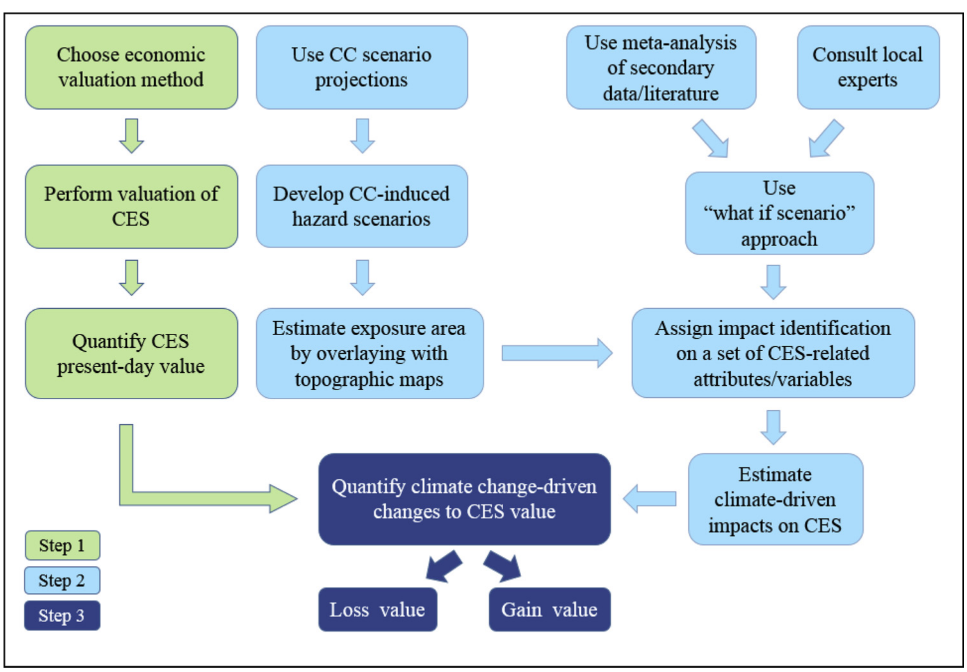

Fig. 2. Schematic representation of the generalized QuantiCEL framework, adapted from Mehvar et al. (2018b).

3.2. Step 2 – identifying the CC-driven impacts on CES

In the second step of the QuantiCEL framework, CC driven impacts on CES of the three case studies are identified by *firstly* determining the hazard and its associated scenarios in the future. *Secondly,* when the hazard scenarios are developed, the affected area is identified for each scenario by using the topographic map of the area (i.e. Digital Elevation Map "DEM") or satellite images. *Thirdly,* a scenario based approach

Table 1
Wetlands, and ecosystem services considered and the corresponding economic valuation techniques used in this study.

Case study	Wetland	Ecosystem service	Economic valuation methods
Indonesia	Beach area, pelagic system, mangrove swamp	Tourism	Contingent valuation, net factor income
		Food provision	Contingent valuation, net factor income
		Amenity	Hedonic price
		Art	Net factor income
Bangladesh	Mangrove swamp, pelagic system, aquiculture land	Tourism	Contingent valuation, net factor income
		Food provision	Contingent valuation, net factor income
		Art	Net factor income
		Provision of raw materials	Market price
Sri Lanka	Beach area, pelagic system	Tourism	Contingent valuation, net factor income
		Food provision	Contingent valuation, net factor income
		Amenity	Hedonic price

combined with secondary data and local expert opinions is used to identify the likely impacts of the hazard on wetland ecosystems and the services provided by these habitats.

3.2.1. Developing the CC-induced hazard scenarios and determining the affected area

In this framework, different CC-induced hazard scenarios need to be developed to investigate how the ecosystem services are likely to be affected by different hazard severity levels. Development of these scenarios are either based on the reported CC impact scenarios, or custom made projections for a given study area.

Following the second step above, here two CC-induced hazards were considered; (1) relative sea level rise (RSLR)-induced inundation in 2100 (in Indonesia and Bangladesh); and (2) sea level rise (SLR) and storm-induced coastline recession in 2110 (in Sri Lanka). In the Sri Lanka case study, the results of the study done by Dastgheib et al. (2018) were used, indicating that the Trincomalee beach area is likely to lose its total width, due to the combined effects of SLR and storm-induced erosion in 2110. For the two other case studies, the affected areas were determined by overlaying a DEM of the area with the map of RSLR induced inundation.

The type of hazards selected for the three case studies is rooted in the history of that particular hazard that has occurred therein. Therefore, in this study we intentionally focused the effects of a specific type of climate change induced hazard on CES of a selected study site. This enabled us to select a study area that has historically been vulnerable to a certain type of hazard such as coastal recession for the Sri Lanka case study, which is not historically so much prone to coastal inundation. Moreover, along the coastal area of Trincomalee, permanent inundation is part of the overall beach retreat (Mehvar et al., 2019b). In addition, RSLR-induced inundation is the considered hazard for the Indonesia and Bangladesh case studies, as SLR combined with considerable land subsidence rate (e.g. up to 4 cm per year in the Western coastal area of Semarang in Indonesia) is the main driver causing inundation in these two selected study sites.

Notably, the time horizon chosen in each case study is dependent on the hazard scenario considered. For example, for both Bangladesh and Indonesia, the RSLR-induced inundation scenario is developed based on the reported rates of RSLR in the literature, and thus these rates were used in calculating the likely RSLR by 2100 (assuming that the reported SLR (m) will be constantly occurred each year). In addition, the year 2110 is considered as the time horizon for the Sri Lanka case study, since the coastal recession scenario is derived from a previous study (Dastgheib et al., 2018) in which the coastal retreat due to SLR and storm was determined for the year 2110. Table 2 summarizes the hazard scenarios, and corresponding extents of the affected areas.

Considering the hazards and the affected areas, the potential impacts on CES are identified as follows:

3.2.2. Impacts of RSLR-induced inundation on CES

The potential impacts of RSLR-induced inundation on the CES considered are identified by using a novel scenario-based approach grounded in secondary data, field surveys, interviews, and expert opinions as described below:

- Impacts on tourism service

This analysis for the tourism (recreation) service is based on assessing how the considered hazard may potentially affect the consumer and producer surplus values associated with this service.

To identify the impacts on producer surplus value, *first,* different recreational attributes pertaining to the tourism service of CES are considered. These attributes are determined by the visitors in the interviews, representing their preferred recreational activities/aspects drawing them to the coastal areas which (depending on the case study and results of the interviews) include all or some of the following attributes: tranquility, shore water quality, diversity of birds and coastal species, natural landscape, welfare facilities for tourists, climate, and enjoying the beach area for relaxation. *Secondly*, depending on the attributes and the hazard scenarios considered, a certain percentage range of change is defined for each attribute by assigning positive or negative impact indications (+ or – sign). Assignation of these impact indications is based on a "what if scenario" approach, assuming a proportional range of change for each attribute relative to the extent of the inundation area.

The RSLR-induced inundation impacts on consumer surplus value are determined through the direct answers and WTP stated by the visitors in response to the damage related questions in the custom-designed questionnaire. For example, in the Indonesia case study, the visitors were asked to state their WTP to avoid losing 50% and 100% (corresponding to the Scenarios A, and B) of the beach area and considered tourism-related attributes.

- Impacts on food provision service (fish and marine species)

The potential impacts of RSLR-induced inundation on food provision service is analyzed (similar to the tourism service), on consumer and producer surplus values[1] . This analysis is relied on using secondary data to determine the fish/fishery related variables that can potentially be affected by climate change, and in particular by RSLR-induced inundation. For doing this, the following literature is used: Pörtner and Knust (2007); MAB (2009); Cochrane et al. (2009); Mohanty et al. (2010); Sumaila et al. (2011); Williams and Rota (2011). The variables considered in this analysis include the primary and secondary production, distribution or migration pattern, abundance, health status, food web, nursery habitat size, fish ponds and fishing communities.

[1] For the food provision service, consumer surplus value refers to the maximum amount the local community is willing to pay for each kilo of fish, subtracted from the actual market price. Producer surplus represents the net revenue generated by selling fish/marine species in the market.

Table 2
Hazard scenarios considered in this study.

Case study	Hazard scenario				Affected area
	RSLR-induced inundation in 2100			SLR & storm-induced recession in 2110	
	RSLR (m)				
	A	B	C	D	
Indonesia	1.10	4	–	–	50% and 100% inundated area due to the scenarios A and B, respectively
Bangladesh	0.25	1.18	1.77	–	2%, 7%, and 10% inundated area due to the scenarios A, B, and C, respectively
Sri Lanka	–			Varied probabilities	Total beach loss due to full beach retreat

After the variables were determined, the impact indications with different percentage range of change (as defined in tourism service analysis) are assigned to each variable by eliciting the fishery experts and local fishermen's opinions regarding the likely impacts of inundation on the pre-determined variables for the different inundation scenarios. For example, in the Bangladesh case study, since the inundation appears to occur mostly in the North of Sundarbans, where the aquaculture-ponds are located, a high (negative) impact indication was therefore assigned for the variable "fish ponds and fishing communities" upto 51%–60% for Scenario C. However, the fish abundance is likely to positively be affected in a range of 21%–30% for the same scenario in Bangladesh, which is expected to occur due to creation of larger water bodies and nursery areas with more nutrients provided due to inundation.

In this analysis, the changes to the affected value (consumer or producer surplus, or both) are identified by analyzing how the hazard impact on each attribute may potentially alter the catch volume, market price as well as fishing and adaptation costs. For example, the likely increase considered in the "fish abundance" attribute due to inundation is likely to increase the catch volume, resulting in a decrease in the market price. This would result in an increase in the consumer surplus value, since it refers to the difference between the WTP (assuming a constant value as stated) and the market price (which is likely to decreases). In addition, the producer surplus value (net revenue equal to gross revenue subtracted by the costs) is likely to have no change for this attribute, because of the opposite effects of catch volume and market price, as well as fishing cost and adaptation cost which neutralize each other's effects.

- Impacts on art, amenity, and provision of raw materials (timber and fuelwood) services

The identification of the impacts of RSLR-induced inundation on art service is based on a scenario-based approach, *first* by determining the art related attributes, and *second* by using the expert opinions (artwork sellers and artists) to present a range of scenarios of inundation impacts on the attributes depending on the severity of inundation scenarios considered. The art related attributes include marine and coastal landscape, and the flora and fauna of the coastal wetlands which are represented in the artworks sold such as paintings, posters, photos and etc.

Analysis of the impacts of RSLR-induced inundation on amenity service follows a scenario-based approach. This analysis is done by considering a range of impact indications to the average properties prices (contributed to the amenity value) to identify how different inundation scenarios are likely to affect the visual amenity of the coastal wetlands. With respect to the provision of raw materials service, the negative impacts of inundation on the value of timber and fuelwood (provided by the Sundarbans mangroves forest in this study) depend on the extent of inundated area and the level of soil and river salinity. This analysis is done by presenting a range of negative impact on this service, depending on the extent of inundation area in each scenario.

3.2.3. Impacts of SLR and storm-induced erosion on CES

Using the same approach for the inundation driven impacts, the resulting impacts of SLR and storm-induced erosion on CES are identified by considering a "what if scenario" approach consisting of determination of the related attributes, and assignation of the impact indication on each attribute. Applying the QuantiCEL framework for the Sri Lanka case study, we analyzed how coastal erosion and its resulting beach retreat in 2110 can damage the wetland ecosystems considered and the services provided by these habitats. However, here, coastal recession is the driver of complete beach loss in 2110 (resulted from Dastgheib et al., 2018), as opposed to different inundation scenarios in 2100 in the previous section. The different nature of the hazard considered here, results in different changes identified for some of the attributes considered (e.g. for the tourism service analysis, here no impact is identified on shore water quality due to the beach retreat considered).

Notably, the attributes considered for analysis of the potential impacts of recession on the food provision service (e.g. abundance, health status, etc.) and on the amenity service (e.g. ocean view and aesthetic value of beach and mangroves) are the same s as those considered for analyzing the inundation impacts in the previous section. For analyzing the coastline recession impacts on the tourism service, new attributes are added to the previously considered ones, which are derived from the interviews with visitors, including snorkeling, diving, hiking, and recreational fishery. As an example, for the Sri Lanka case study, a high range of negative impact (81%–100%) was assigned for the attribute "beach area for relaxation" due to the loss of entire beach area. However, lower negative impact was considered for the water sports (i.e. snorkeling, diving) for which the revenues earned are not much dependent on the beach retreat, since the tickets can be booked via websites and not necessarily by the recreational centers located in the beach area.

3.3. Step 3 – quantifying monetary value of the identified changes to CES

In the third step of the QuantiCEL framework, to quantify monetary value of the changes to CES, the impacts identified in the second step are linked to the monetary value of the services estimated in the first step. To achieve this, a contribution level of each attribute to the affected value (consumer or producer surplus values, or both) is considered. For the food provision service, the contribution level of each fish/fishery-related attribute is determined based on an approximate indication derived from consultation with local fishermen.

With respect to the tourism value, the contribution level is determined by the visitors through ranking the most enjoyed recreational attributes/aspects considered while visiting the wetland ecosystems. The result of this ranking as a percentage for each attribute/aspect is counted as the contribution of each attribute/aspect to the total tourism value. For the art service, an equal contribution level is considered for the two attributes, assuming both "flora and fauna" and "marine and coastal landscape" are equally contributed to the total estimated art value. For the amenity and provision of raw material services, no contribution level is considered, since there is only one attribute associated for each of these services. Changes to the CES value due to the considered CC-related hazards are ultimately calculated by multiplying “potential impact indications”, “contribution to the total value” (if applicable for the service), and “the affected value” together. The total change for each CES is quantified by summing the calculated changes of the affected values for each attribute.

4. Results and discussions

- Changes to the value of CES resulted for the three case studies

Application of the QuantiCEL framework for the three case studies has resulted in a number of findings. Here, we differentiate between (1) an overview of the identified impacts to the CES among the three applications, and (2) a summary of the estimated CES loss values, and the percentage of losses relative to the present-day value of CES. Identification of the potential CC driven hazards on CES considered in this study, shows positive, negative, and neutral impacts on different ecosystem related attributes/variables. The potential losses of CES depend on different factors such as type of ecosystem related attributes, extent of hazard exposure (scenarios considered in each study site), local expert opinions and secondary data used.

For the food provision service, results show that RSLR-induced inundation, and SLR and storm-induced erosion can potentially affect the fish-fishery related variables in different ways. For example, primary and secondary production, abundance, food web, and the extent of nursery habitat are likely to be positively affected by inundation (e.g. in a range of 21%–60% in the Indonesia study site), while the impacts on species distribution/migration pattern are unknown. In the Bangladesh study site, these positive impacts are less prominent (from 10% to 40%) due to the very low extent of inundation, and lower expectation of local fishermen of a considerable impact. In the Sri Lanka study site, the positive impact of (complete) coastal retreat on the fish-fishery related variables resulted in a range of 20%–40%, representing a relatively less positive impact of coastal erosion, compared to inundation impacts at the other two study sites. The results also show that health status and fish ponds can be considerably threatened by the impacts of inundation (e.g. 81%–100% damage in the extent of fish ponds due to full inundation scenario in the Indonesia case study).

For the art service, the negative impact of inundation was estimated in a range of 41%–100% for the Indonesia case study, while a lower impact on art value was computed (i.e. 31%–40%) for the Bangladesh coastal area. This is mainly due to the smaller inundation area, and lower expectation of the local experts for a severe impact of inundation on the art value of CES in the Sundarbans.

For the three other services (i.e. tourism, amenity, and provision of raw materials), the “what if scenario” approach used in this study shows a potentially medium-high range of negative impacts. For example, with respect to the tourism service, the negative impact of inundation was estimated between 41% and 100% for the Indonesia study site. However, this negative impact on tourism service was lower (31%–40%) in the Bangladesh study site, due to the very small extent of projected inundation area. In the Sri Lanka case study, the impact of complete erosion-induced beach retreat, resulted in a likely negative impact of 41%–100% for varied tourism related variables. In terms of the amenity service, a medium negative impact (41%–60%) was computed for the complete inundation scenario (in the Indonesia), and the complete beach recession scenario (in the Sri Lanka). With respect to the provision of raw materials service (timber and fuel wood) in the SMF in Bangladesh, a very low negative impact of inundation was estimated, mainly as a result of the small projected inundated area (about 5% of the SMF), and also due to the higher resilience of the forest to SLR which is expected as a result of interspecific facilitation. Fig. 3 summarizes the estimated CES loss values, and the percentage of losses relative to the present-day value of CES for the different hazard scenarios ranked from 1 (very low impact) to 4 (extreme impact) for the three case studies.

Fig. 4 provides a schematic representation of the above results including absolute loss values presented in million US$ in logarithmic scale (Fig. 4a), and percentages of CES loss values (relative to the PV) presented in linear scale (Fig. 4b) for the worst case hazard scenarios in the three case studies.

- Applicability of the QuantiCEL framework, and its limitations

The QuantiCEL framework presented in this article provides a practical method to quantify potential CC driven environmental losses in the coastal areas of developing countries. The application of this framework at three different study sites has illustrated its versatility in terms of its ability to be applied in each study site with different CES, and two different CC-induced hazards. This coherent framework can be used for a wide range of applications providing an approximate estimation of CC-driven impacts on CES value, especially in data-scarce developing countries in which it is not feasible to apply standard ecological and economic simulation methods.

Apart from the main use of the QuantiCEL framework, it can also be used to quantify the environmental risk due to CC-driven hazards, which is a poorly addressed issue in current literature. An example of this application was presented by Mehvar et al. (2019b), in which, the risk value of ecosystem related-tourism service, due to SLR and storm-induced coastline recession was quantified by using the QuantiCEL framework in the east coast of Sri Lanka for the year 2110.

The outcomes of this study show that there are some limitations in using the QuantiCEL framework. One of the largest uncertainties stem from the large CC related uncertainties, which add complexity to the quantitative assessment of CC driven environmental losses. The main limitation in valuation of CES is the incomplete estimation of values for only one or a few selected CES, which is often due to time limitation, complexity of translating the services to the monetary values, and costly process of data collection in a particular study site.

The findings of this study also show that valuation techniques may not be completely applicable for valuation of CES in a developing country context. For example, the concept of WTP was not well accepted in both Sri Lanka and Bangladesh study sites, because local communities were not willing to pay to conserve ecosystems, or to not lose the services provided by these habitats (see Mehvar et al., 2019a, 2019b). This would imply that there might be other factors (i.e. cultural issues, political issues, educational background, socio demographic factors, etc) affecting the WTP stated by the interviewees. Apart from the valuation itself, uncertainties associated with assessing the physical CC impacts on coastal wetlands over a very long time span present another challenge.

Adoption of the scenario-based approach for analyzing the hazards impacts on the three CES as art, amenity, and provision of raw materials, is due to the fact that the data/methodology for quantifying such losses are currently unavailable. Thus, these assessments of losses on the considered attributes (for the art and amenity services), and on the market price of timber and fuelwood could be considered as scenarios. In addition, the amenity service of wetland ecosystems is subjective in terms of the value that this service provides, and there is no accepted principle for a definitive quantitative assessment of inundation or coastline recession impacts on this service.

The main factors that add uncertainty to the estimation of CC driven environmental losses by using the QuantiCEL framework are: (1) diverse expert opinions and their expectations of CC driven impacts on CES; (2) present or future implementation of coastal protection structures; (3) economic discount rates; (4) land subsidence rate which is relatively high and uncertain in developing countries; (5) changes in tourist expenditure (associated with valuation of tourism service); (6) sample size; (7) market price of goods (associated with fish and marine species, and raw materials); and (8) social norms. In this study, the

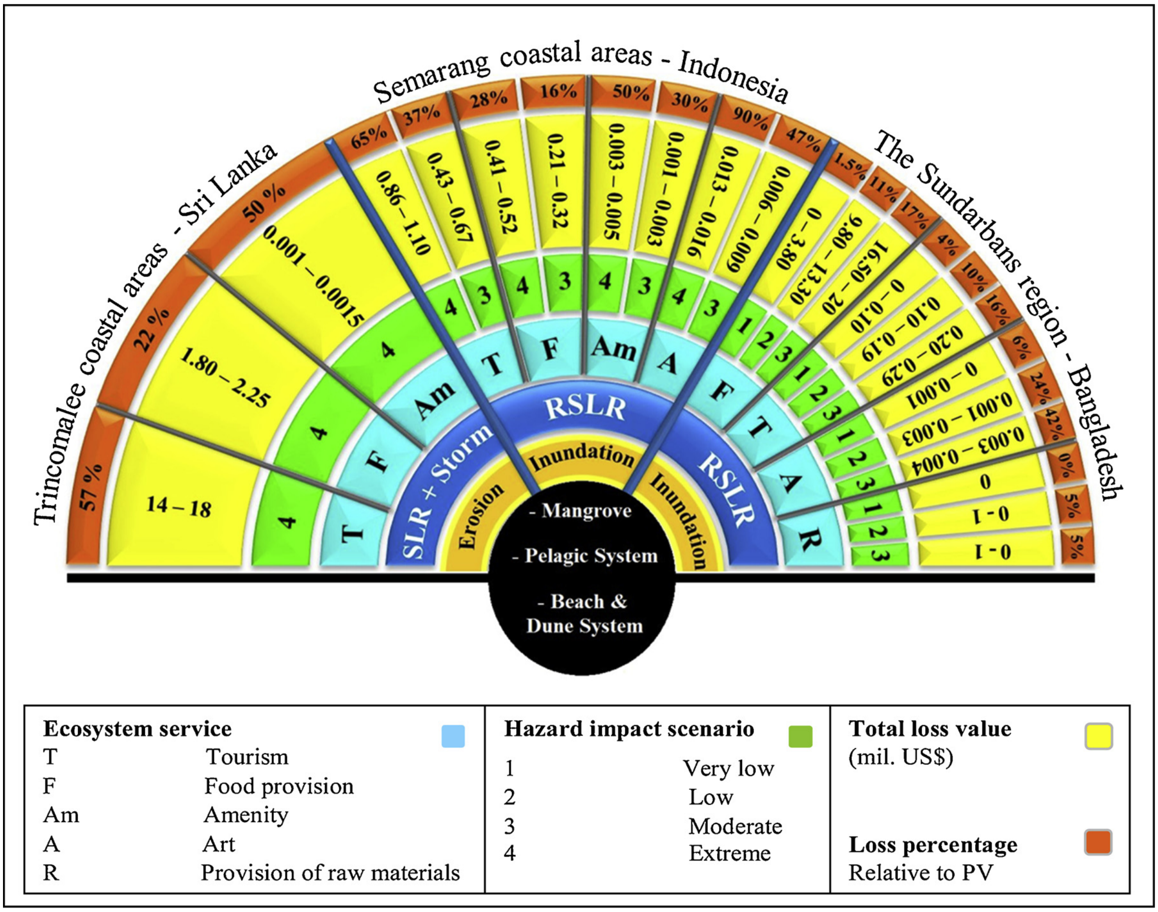

Fig. 3. Overview of the estimates of CES loss values (million US$), and the corresponding median percentage of losses (%), relative to the PV for the three study sites.

limitations and uncertainties mentioned above, resulted in estimating the losses of CES as a value range, and not as single deterministic values. It should be noted that the results of this study also depend on the identified impacts of the selected hazards on the CES-related attributes/variables considered. Therefore, the use of the QuantiCEL framework for other applications, may require the addition and consideration of different CES-related attributes.

It would be valuable to apply this framework at more study sites containing different types of coastal wetlands (services). This will provide better insight on whether the framework can be generically used for quantifying losses of any other types of coastal ecosystem services. Applying the QuantiCEL framework for the coastal areas in developed countries is also recommended, in order to explore whether the results (e.g. PV, loss values of CES, and WTP) are comparable with the results of study sites in developing countries. In addition, further research is required into the possible approaches to minimize the effect of CC related uncertainties on the quantification of the associated environmental losses.

5. Concluding remarks

This article introduces the QuantiCEL framework which is aimed at obtaining quantitative estimations of future CC-driven environmental losses caused by coastal inundation and erosion, and demonstrated its application in three data poor developing countries (i.e. Indonesia, Bangladesh and Sri Lanka). The QuantiCEL framework follows clear methodological steps grounded in the economic valuation techniques, expert opinions, secondary data and a novel scenario based approach.

The findings of this study showed that the QuantiCEL framework is a tool that can be applied for different case studies in developing countries. Application of this framework for three selected case studies showed that ecosystem services of different coastal areas are not likely to be similarly affected by different CC induced hazards (i.e. inundation and erosion). While, the general expectation is that climate change will exacerbate losses of services provided by coastal wetlands, this study showed that at some locations (i.e. Bangladesh study site) other factors (i.e. topography of the coastal area) can potentially decelerate degradation of wetlands ecosystems, and minimize the CC-driven losses of services provided by these habitats.

The outcomes of this study also showed that there are considerable variations in the estimates of loss value among the CES considered in the three study sites. Art service is the most sensitive service to the considered CC induced hazards, showing an estimated maximum loss of 90% relative to its PV (extreme scenario). Tourism is the second sensitive service to CC impacts, with an estimated reduction of its PV by nearly 65% for the considered extreme scenario, followed by amenity service with a decrease of upto 50%. The results also indicated that food provision service (fish and marine species) is likely to decrease by a maximum of about 30%. Provision of raw materials (timber and fuelwood) is the least affected service estimated to have about 5% loss of its PV, under a low inundation scenario.

In general, the application of this framework for the selected case studies showed that, where the absolute loss value of CES by the end of the 21 st century is concerned, food provision and tourism are the CES with higher loss values. However, art, amenity, and tourism are the highly affected CES where the percentage loss (by the end of the 21 st century) relative to the present-day value of CES is concerned. However, more studies of this nature are required to get better insight in the generic applicability of these observations.

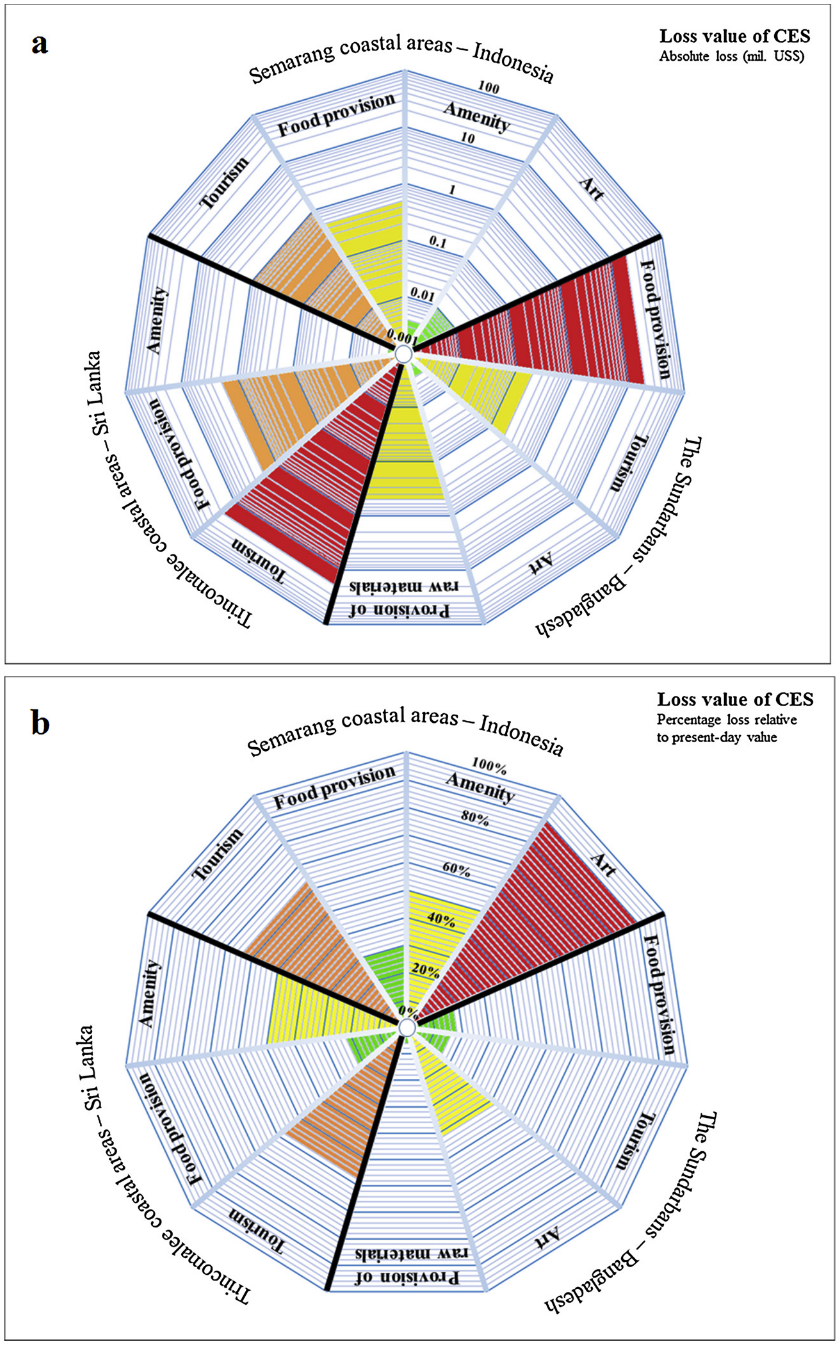

Fig. 4. Schematic representation of the absolute loss value of CES in logarithmic scale, in million US$ (a), and percentage of CES loss value relative to the PV in linear scale (b). Green (low value/impact); yellow (medium value/impact); orange (high value/impact); dark red (extreme value/impact). Both figures represent the worst case hazard scenarios in the three study sites.

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References

Barbier, E.B., 2013. Valuing ecosystem services for coastal wetland protection and restoration: progress and challenges. Resources 2, 213–230.

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

Castaño-Isaza, J., Newball, R., Roach, B., Lau, W.W., 2015. Valuing beaches to develop payment for ecosystem services schemes in colombia's seaflower marine protected area. Ecosyst. Serv. 11, 22–31.

Champ, P.A., Boyle, K.J., Brown, T.C., 2017. The Economics of Non-market Goods and Resources, a Primer on Nonmarket Valuation, second edition. Springer, pp. 13.

Cheung, W.W., Dunne, J., Sarmiento, J.L., Pauly, D., 2011. Integrating ecophysiology and plankton dynamics into projected maximum fisheries catch potential under climate change in the Northeast Atlantic. ICES J. Marine Sci 12.

Cochrane, K., De Young, C., Soto, D., Bahri, T., 2009. Climate Change Implications for Fisheries And Aquaculture. FAO Fisheries and Aquaculture technical paper, 530, 212. .

Czajkowski, M., Ahtiainen, H., Artell, J., Budziński, W., Hasler, B., Hasselström, L., Meyerhoff, J., Nõmmann, T., Semeniene, D., Söderqvist, T., 2015. Valuing the commons: an international study on the recreational benefits of the Baltic Sea. J. Environ. Manage. 156, 209–217.

Dangendorf, S., Marcos, M., Wöppelmann, G., Conrad, C., Frederikse, T., Riva, R., 2018. A reconciled estimate of 20th century global mean sea level rise. Sea Level Rise 16 (1), 6.

Dastgheib, A., Jongejan, R., Wickramanayake, M., Ranasinghe, R., 2018. Regional scale risk-informed land-use planning using probabilistic coastline recession modelling and economical optimisation, East Coast of Sri Lanka. J. Mar. Sci. Eng. 6, 120.

Henson, S.A., Beaulieu, C., Lampitt, R., 2016. Observing climate change trends in ocean biogeochemistry: when and where. Glob. Chang. Biol. 22 (4), 1561–1571.

Idier, D., Paris, F., Le Cozannet, G., Boulahya, F., Dumas, F., 2017. Sea-level rise impacts on the tides of the European Shelf. Cont. Shelf Res. 137, 56–71.

Kuhfuss, L., Rey-Valette, H., Sourisseau, E., Heurtefeux, H., Rufray, X., 2016. Evaluating the impacts of sea level rise on coastal wetlands in Languedoc-Roussillon, France. Environ. Sci. Policy 59, 26–34.

Lovelock, C.E., Cahoon, D.R., Friess, D.A., Guntenspergen, G.R., Krauss, K.W., Reef, R., Rogers, K., Saunders, M.L., Sidik, F., Swales, A., 2015. The vulnerability of Indo-Pacific mangrove forests to sea-level rise. Nature 526 (7574), 559–563.

MAB, 2009. Fisheries and aquaculture in a changing climate. Fao, Rome, Italy 6.

Mehvar, S., Filatova, T., Dastgheib, A., De Ruyter Van Steveninck, E.D., Ranasinghe, R., 2018a. Quantifying economic value of coastal ecosystem services, a review. J. Mar. Sci. Eng. 6 (1), 5.

Mehvar, S., Filatova, T., Syukri, I., Dastgheib, A., Ranasinghe, R., 2018b. Developing a framework to quantify potential Sea level rise-driven environmental losses: a case study in Semarang coastal area, Indonesia. Environ. Sci. Policy 89, 216–230.

Mehvar, S., Filatova, T., Sarker, M.H., Dastgheib, A., Ranasinghe, R., 2019a. Climate change-driven losses in ecosystem services of coastal wetlands: a case study in the West coast of Bangladesh. Ocean Coast. Manag. 169, 273–283.

Mehvar, S., Dastgheib, A., Bamunawala, J., Wickramanayake, M., Ranasinghe, R., 2019b. Quantitative assessment of the environmental risk due to climate change-driven coastline recession: a case study in Trincomalee coastal area, Sri Lanka. Clim. Risk Manag., 100192.

Mohanty, B., Mohanty, S., Sahoo, J., Sharma, A., 2010. Climate change: impacts on fisheries and aquaculture. Climate change and variability. InTech.

Pavani, B.F., Júnior, W.C.S., Inouye, C.E., Vieira, S.A., Mello, A.Y., 2018. Estimating and valuing the carbon release in scenarios of land-use and climate changes in a Brazilian coastal area. J. Environ. Manage. 226, 416–427.

Pörtner, H.O., Knust, R., 2007. Climate change affects marine fishes through the oxygen limitation of thermal tolerance. Science 315 (5808), 95–97.

Roebeling, P., Costa, L., Magalhães-Filho, L., Tekken, V., 2013. Ecosystem service value losses from coastal erosion in Europe: historical trends and future projections. J. Coast. Conserv. 17 (3), 389–395.

Russi, D., ten Brink, P., Farmer, A., Badura, T., Coates, D., Förster, J., Kumar, R., Davidson, N., 2013. The Economics of Ecosystems and Biodiversity for Water and Wetlands. IEEP, London and Brussels.

Schep, S., van Beukering, P., Brander, L., Wolfs, E., 2013. The Tourism Value of Nature on Bonaire Using Choice Modelling and Value Mapping. IVM Institute for Environmental Studies, Amsterdam.

Seenprachawong, U., 2016. An economic analysis of coral reefs in the andaman sea of Thailand. Marine and Coastal Ecosystem Valuation, Institutions, and Policy in Southeast Asia. Springer, pp. 31–45 2016.

Sukhdev, P., Wittmer, H., Miller, D., 2014. The economics of ecosystems and biodiversity (teeb): challenges and responses. Nature in the Balance: the Economics of Biodiversity. pp. 135–152.

Sumaila, U.R., Cheung, W.W., Lam, V.W., Pauly, D., Herrick, S., 2011. Climate change impacts on the biophysics and economics of world fisheries. Nat. Clim. Chang. 1 (9), 449–456.

Sun, Z.L., Lu, M., Nie, H., Huang, S.J., 2014. Impacts of climatological change on storm surge in Zhejiang coastal water. J. Zhejiang Univ. 41 (1), 90–94.

Tinch, R., Mathieu, L., 2011. Marine and Coastal Ecosystem Services: Valuation Methods and Their Practical Application. Biodiversity Series, UNEP-WCMC.

Van Zanten, B., van Beukering, P., 2012. Coastal Protection Services of Coral Reefs in Bonaire, Economic Values and Spatial Maps. IVM Institute for Environmental Studies, Amsterdam.

Watson, K.B., Ricketts, T., Galford, G., Polasky, S., O'Niel-Dunne, J., 2016. Quantifying flood mitigation services: the economic value of Otter Creek wetlands and floodplains to Middlebury. VT. Ecol. Eco. 130, 16–24.

Williams, L., Rota, A., 2011. Impact of Climate Change on Fisheries and Aquaculture in the Developing World and Opportunities for Adaptation. Fisheries Thematic paper.

Yoskowitz, D., Carollo, C., Pollack, J.B., Santos, C., Welder, K., 2017. Integrated eco-system services assessment: valuation of changes due to sea level rise in Galveston Bay, Texas, USA. Integrated Environ. Assess. Manag. 13 (2), 431–443.