Mapping the Benefits of Tropical Coastal Ecosystems:

Economic Value and Qualitative Insights for Socio-Economic Cost-Benefit Analyses

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CE BSc Thesis Report

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Table of Contents

Abbreviations

BCE - Blue Carbon Ecosystems
BCR - Benefit-cost Ratio
C - Carbon
CAPEX - Capital Expenditures
CBA - Cost Benefit Analysis
CE - Coastal Ecosystems
CES - Coastal Ecosystem Services
CICES - Common International Classification of Ecosystem Services
CMS - Coral reefs, Mangroves and Seagrasses
CT - Carbon Tax
CVM - Contingent Valuation Method
DR - Discount rate
ES - Ecosystem Services
ETS - Emission trading system
GHG - Green House Gases
IDR - Indonesian Rupiah
INR - Indian Rupees
IRR - Internal Rate of Return
MEA - Millenium Ecosystem Assessment
NBS - Nature-Based Solutions
NPV - Net Present Value
OPEX - Operating Expenses
SCC - Social Costs of Carbon
SCBA - Socio-Economic Cost-Benefit Analysis
SGD - Singapore Dollar
TEEB - The Economics of Ecosystems and Biodiversity
USD - United States Dollars
WTP – Willingness-To-Pay
ZAR - South African Rand

Summary

This report offers an overview of the ecosystem services provided by tropical coastal ecosystems in Eastern Africa, including the Indian Ocean islands along its coast, and Southeast Asia. It focuses on mangroves and coral reefs, categorising, quantifying, and, where feasible, monetising their ecosystem services, which are summarised in an inventory table.

The methodology employed combines a thorough literature review with expert elicitation, emphasising the application of Socio-economic Cost-Benefit Analysis (SCBA) to determine relevant parameters for assessing the economic values of these services. The research utilised benefit value transfer techniques to complete the quantification and monetisation of identified benefits based on existing studies.

Key findings reveal significant economic impacts: for instance, mangroves and coral reefs collectively prevent approximately US $1 billion annually in flood damages. In Southeast Asia, coral reefs contribute an estimated US $2.4 billion annually of fishery revenues.

Furthermore, the study highlights gaps in the valuation of certain services, particularly cultural services. These services provide essential human welfare benefits, including mental and physical well-being for communities residing near these ecosystems. Cultural services encompass symbolic and inspirational values, recreational opportunities, visual amenities, and educational resources, which also serve as sources of entertainment.

1. Introduction

There are at least 100 countries and island nations worldwide that host tropical coastal ecosystems. Coastal areas worldwide are increasingly vulnerable to natural disasters, due to climate change, unregulated development, and nature loss from anthropogenic activities. With these changes, there are societal challenges arising from them that need to be addressed. Nature Based Solutions (NbS) that focus on the restoration, conservation and preservation of ecosystems can offer strategies to reduce this vulnerability while simultaneously providing other ecosystem services, such as carbon sequestration or fishing revenues that bring about human welfare.

However, investments in NbS are still insufficient, and often 'grey engineering solutions' are chosen over NbS. This can be explained by the limited understanding of the additional potential benefits that NbS provide to society. The long-term resilience of NbS is an additional benefit on top of what grey engineering solutions can offer. More insight into the societal benefits of NbS, such as an increase in fishing revenues and recreational opportunities, quantified through a socio-economic cost-benefit analysis, would help decision-makers understand the impacts of NbS and justify their investments in NbS.

This literature research conducted in the regions of Eastern Africa and Southeast Asia aims to fill the gaps in understanding the full range of benefits offered by NbS for coastal management through coral reefs and mangroves, within an elaborated socio-economic cost-benefit analysis. An inventory of all benefits of tropical coastal ecosystems will be curated, to guide and facilitate objective decision-making. This will provide decision-makers and stakeholders with valuable information about the feasibility and market potential of NbS.

2. Context

2.1 Coastal Ecosystems

Marine ecosystems are dynamic aquatic environments where diverse organisms interact, thrive, and generate valuable services that are advantageous to both the ecosystem and its surroundings. Unlike other ecosystems, marine ecosystems and more specifically ones found in tropical climates, are ecologically bountiful and are regarded as an "exclusive reservoir" of the majority of the world's biodiversity (Wood et al., 2019). Coral reefs, mangroves, and seagrass meadows (CMS) are such tropical marine ecosystems (Image 2.1). A quarter of all known marine species are hosted by coral reefs alone (McAllister, 2015 & Plaisance et al., 2011). They are also known for their high economic value to many of their host countries (Kathiresan & Alikunhi, 2011).

These marine ecosystems can be classified into two categories: open ocean systems (also referred to as pelagic systems) and coastal ecosystems (CE) (Mehvar et al., 2018). Mangroves, seagrass or algae beds, and coral reefs are some of the main types of tropical CE (Costanza et al., 1997). Figure 2.1 shows a cross-section of the location of these ecosystems above and below water.

Image 2.1: Coral reefs, mangroves, and seagrass bed along Turneffe Atoll in Belize. Photo by Ethan Daniels/Shutterstock.

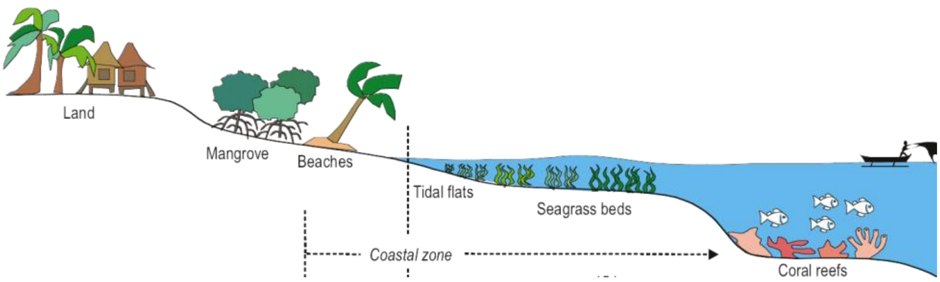

Figure 2.1: Cross-section of where mangroves, seagrass beds and coral reefs are located. Retrieved from (Peace Corps CRM, 2017).

2.1.1 Mangroves: Dynamics, Processes and Distribution

Mangroves are clusters of trees and shrubs found in coastal intertidal zones of tropical and subtropical regions (Figure 2.2), covering approximately 150,000 square kilometres (km²) of sheltered coastlines worldwide (Michel, 2014). These trees can grow either continuously over an area or in patches. With about 70 known species worldwide, mangroves exhibit unique adaptations, providing shelter and habitat for a diverse range of animals (Polidoro et al., 2010 & Connolly & Lee, 2007).

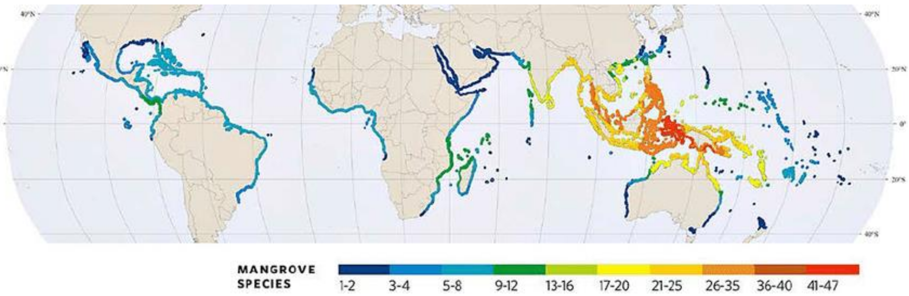

Figure 2.2: Global distribution of the amount of mangrove species. Retrieved from (Michel, 2014).

Due to various ecological and biophysical processes, mangroves perform numerous functions that are vital to both nature and humans. Their above-ground biomass and aerial root system (Image 2.2) dampen the energy of incoming waves, induced by drag forces exerted by their roots, leaves, and trunks, resulting in energy losses (Gijsman et al., 2021). Moreover, their complex roots induce local turbulence within the mangroves, further contributing to energy dissipation, as well as providing the ideal environment for the nursery of juvenile fish, adult shrimp and other high-value fish, serving as biodiversity hotspots (Gijsman et al., 2021). Within their foliage and root structures, various mammals, including monkeys and tigers in India and Bangladesh, as well as amphibians, reptiles, insects, and distinctive plant species can be found (Susilo et al., 2017 & Marois & Mitsch, 2015).

Image 2.2: Mangrove forest in Cavite, Philippines. Retrieved from (Hello From The Philippines, 2017).

2.1.2 Coral Reefs: Dynamics, Processes and Distribution

Coral reefs are sea animals that act as the ocean's "rainforest". Several nations were formed due to coral reefs, and others depend on them to sustain their populations through nutrition as seen in Image 2.3. These intricately detailed calcareous animals grow in shallow, sunlit warm-water oceans in tropical and subtropical regions (Sheppard et al., 2018). Their structures allow for habitat provision and protection of about 25% of known marine species despite only occupying 0.1% of the ocean floor (Hoegh-Guldberg et al., 2017).

Image 2.3: School in great numbers at Rapture Reef, French Frigate Shoals, Papahānaumokuākea National Marine Monument. (Image by James Watt).

Coral reefs come in various structures, ranging from continental reefs which are connected to continental shelves and oceanic reefs which are connected to oceanic island complexes (Figure 2.3). They are distributed worldwide, with a high concentration of coral reefs found in the seas between Southeast Asia and Australia (Figure 2.4).

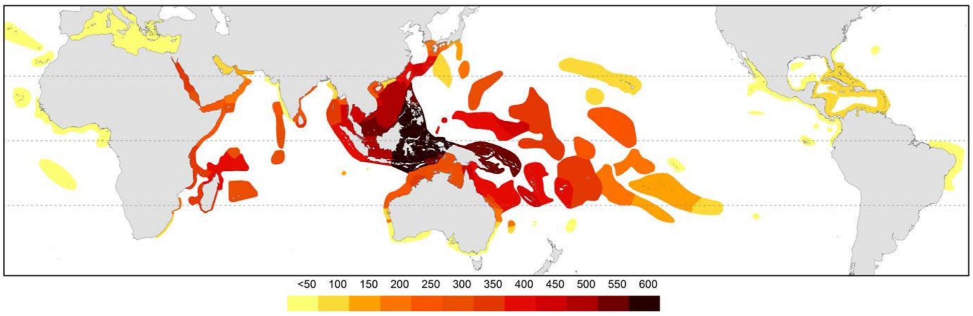

Figure 2.3: Global distribution of coral reef diversity. Retrieved from (Corals of the World, 2014).

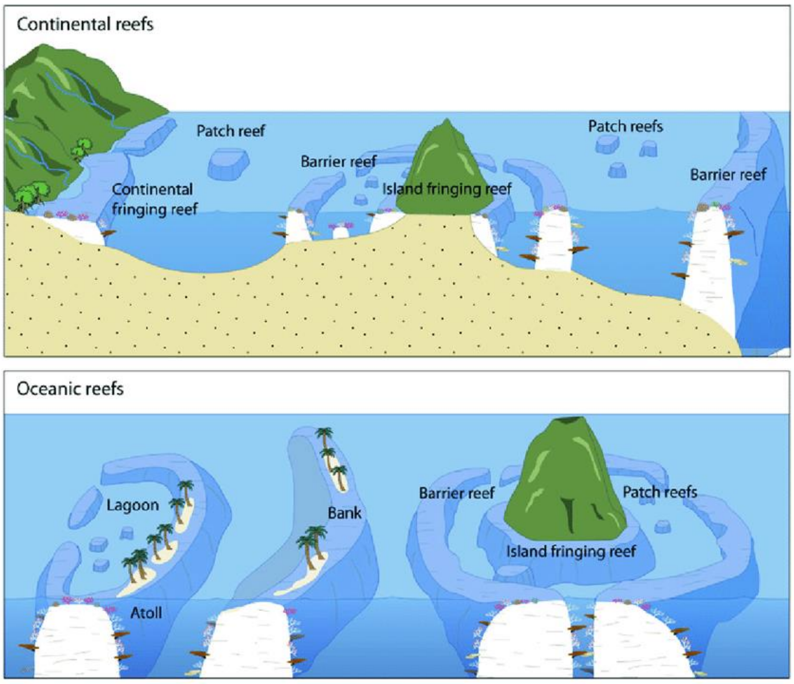

Figure 2.4: Different types of coral reef structures and where they occur. Retrieved from (Hoegh-Guldberg et al., 2011).

Through their multiple functions, coral reefs interact with and create the ideal conditions for other ecosystems nearby through their provision of nutrients and organic matter. The intricate structure of coral reefs provides adequate dampening of incoming wave energy. They can dissipate up to 97% of wave energy and help protect its adjacent coast against storm surges and swell waves (Woodhead et al., 2019).

2.2 Natural Capital, Ecosystem Services & Human Well-Being

Coastal ecosystems sustain themselves through the flow of energy from biological interactions that constitute the food web. This energy and material traverses from microbes to predators, including humans, and circles back to decomposed and detritus matter (Doney et al., 2012). Furthermore, their overall dynamics and processes with the external environment, including hydrodynamics, and morphological and ecological factors, collectively give rise to various ecosystem functions (Gijsman et al., 2021). These ecosystem functions create ecosystem services leading to the production of use and non-use benefits also known as natural capital. For clarity and consistency, the term 'benefits' will be used throughout this report rather than 'natural capital,' as both terms describe the same concept. Ecosystem benefits support, provide for and enhance human life, i.e. human well-being. Humans can make use of these benefits directly or by simply appreciating them without a direct material gain (Nieuwkamer, 2008). A logic chain showing the causal relationship between CE eventually leading to benefits for human welfare is shown in Figure 2.5.

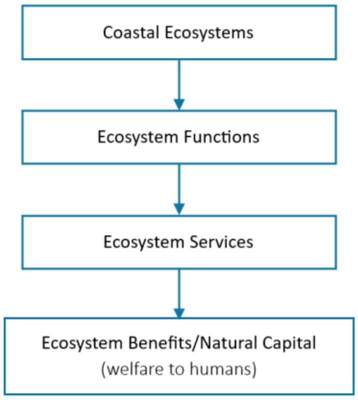

Figure 2.5: The logic chain from coastal ecosystems to the generation of ecosystem benefits. Adapted from Nieuwkamer (2008).

Below, the logic chain from CE to ecosystem benefits is applied to mangroves to better understand how one factor enables another. Figure 2.6 shows the filled-out components with the logic chain used as a reference.

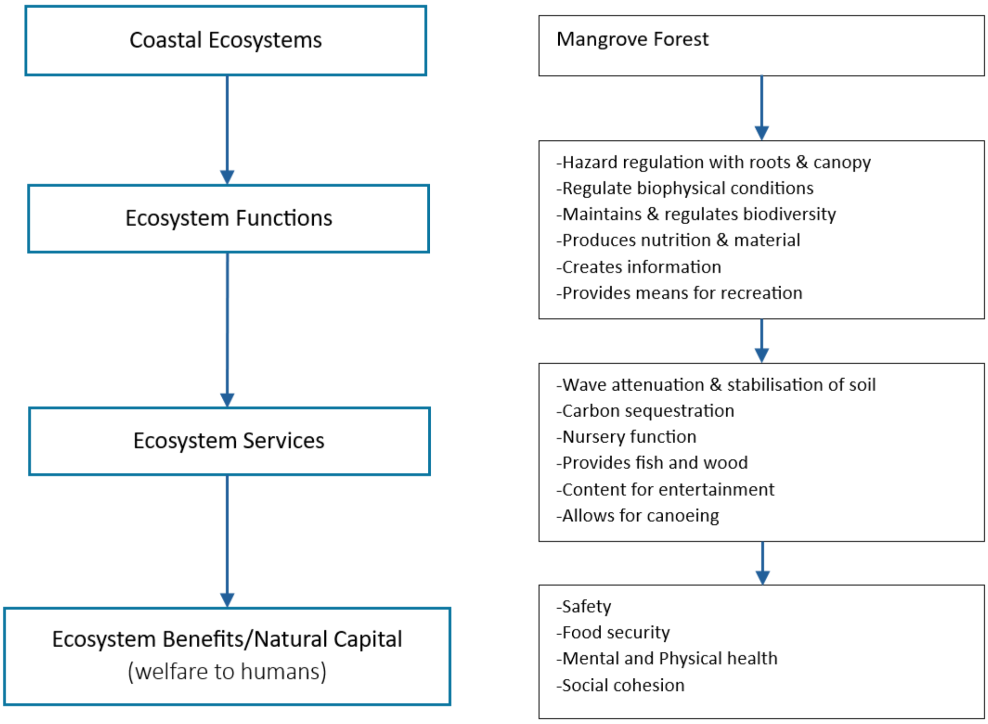

Figure 2.6: Logic chain of coastal ecosystems to the generation of ecosystem benefits with the example of a mangrove forest.

2.2.1 Ecosystem Services

The dependency of society on these natural benefits requires that CE be used sustainably to continue providing for us for years to come. Some of these benefits are drinking water, wood, and fertile soil produced through several ecosystem services. Authors van Egmond & Ruijs (2016) categorise these services into three groups linking and relying on one another: regulatory, production and cultural services.

First, the **regulatory services**. Ecosystems can regulate natural phenomena such as air quality, water runoff, soil erosion, and wave attenuation, among others. The flora and fauna regulate air and water quality by filtering and degrading toxic pollutants (waste assimilation) (Burke et al., 2001); living organisms like bacteria decompose detritus matter into nutrients; the roots and leaves of the plants create friction and disperse wave energy and the roots of the plants help bind the soil to prevent excessive erosion (Gijsman et al., 2021). Together, these processes create a healthy, sustainable, and functional ecosystem.

Next**, production services** are the direct benefits that ecosystems provide to humans, including food, like fish and shellfish. Due to the nature of regulating services, drinking water can also be provided. Moreover, timber, fuel wood, medicinal benefits from plants, and oils can be gained as well. Often overlooked, supporting services are also included within production services. With this, ecosystems provide access to an environment that includes fundamental natural processes including the water cycle, soil formation, photosynthesis, and nutrient cycling (*National Wildlife Federation, 2024).*

Lastly, **cultural services** indirectly enhance the socio-economic status of ecosystems' locations namely our cultural, intellectual, and social development. Furthermore, creativity, flourishment of local, national, and global cultures, ecotourism (Pueyo-Ros, 2018) and recreation opportunities are all different ways in which the ecosystems provide non-material benefits to us. In some countries, for instance, Tanzania, mangroves are regarded as 'sacred forests' as these forest patches preserve the historical value and significance of the past through biodiversity, culture, and religious and ethnic heritage (Mangora & Shalli, 2014). Additionally, cultural services include the "remote experience" of ecosystems through entertainment such as films, books, and photos (United Nations et al., 2021). An overview of the many services of ecosystems is shown in Figure 2.7.

Figure 2.7: Types of ecosystem services (PBL, 2016).

2.2.2 Ecosystem Services and Human Well-being

Not only are the relations between coral reefs, mangroves and seagrasses useful in protecting the coasts, but the services they provide also have a significant influence on people's quality of life and general well-being. According to MEA (2005), ecosystem services have a notable role in all aspects of human well-being. Below, is a list of ecosystem services and their associated contribution to human well-being.

Regulatory services:

- Security: safety from disasters and secure resource access.
- Good health: access to clean air and water.

Production service:

- Basic goods: food, material for shelter, and adequate livelihoods.

Cultural service:

- Social relations: social cohesion, respect, being inspired, and the ability to help others.
- Freedom of choice and action: the ability of an individual to achieve their values and desires despite changes in socio-economic conditions.

2.3 Drivers of Change and Threats to Ecosystems

Due to the dependency on these benefits, even slight changes to ecosystems can affect human well-being (MEA, 2005). Direct and indirect factors can alter ecosystem services, such as declining productivity due to health issues, homogeneity in species reducing cultural services, and land cover changes decreasing regulatory services (MEA, 2005). Human well-being here includes poverty reduction as part of the quality of life.

Direct drivers of change are events or actions impacting ecosystem services, such as climate change, natural hazards, and the high concentration of coastal inhabitants leading to land cover changes and increased demand on ecosystems (Dayton et al., 2005). The introduction or removal of plant or animal species through deforestation or unintentional import of foreign species, also serves as a direct driver, with invasive species threatening local ones and affecting production services. Technological advances have benefited humans through better ecosystem management and understanding (MEA, 2005). External inputs like fertilisers, pest control substances, and polluted irrigation water can also cause biological and chemical changes, leading to nutrient excess and algae blooms (eutrophication) that contaminate fish (Dayton et al., 2005). Human harvest and resource consumption trends also directly impact ecosystem recovery or succession (MEA, 2005).

Indirect drivers, namely demographics, and sociopolitical, cultural, and religious factors primarily influence direct drivers. Changes in these indirect drivers can lead to changes in ecosystem services. The MEA (2005) summarised these interactions on a local scale, grouping drivers with grey arrows illustrating how changes in direct and indirect drivers impact ecosystems and, consequently, human well-being (Figure 2.8). This framework thus emphasises the importance of the preservation and maintenance of natural ecosystems that are essential to human livelihoods.

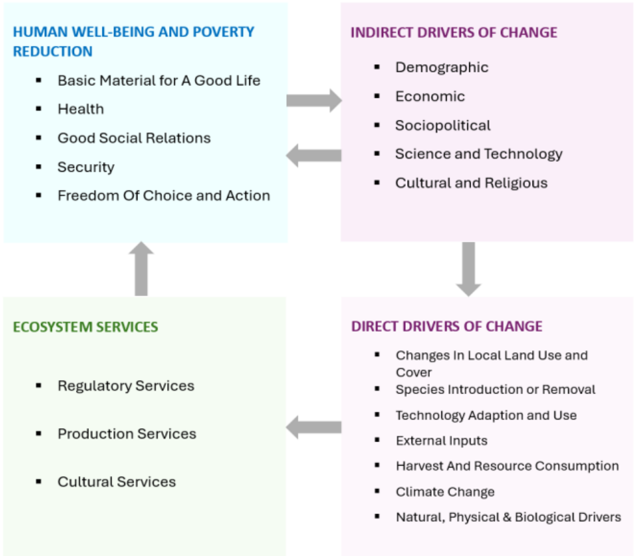

Figure 2.8: Conceptual framework of the direct and indirect drivers of change to ecosystem services and thus human well-being. Adapted from (MEA, 2005).

2.4 Nature-Based Solutions (NbS)

In attempts to protect the coast from various threats, different solutions can be put into place. The different types explored here are the traditional grey engineering solutions and NbS.

2.4.1 Grey Engineering Solutions

Grey engineering structures, more commonly known as hard engineering structures comprise seawalls, groynes, piers, revetments, dams, dikes, and embankments (Phillips & Jones, 2006). They are hydraulic constructions that alter the natural physical processes and systems of water and/or absorb wave energy to prevent or mitigate the potential damage caused by the water (van der Brugge et al., 2005). Grey engineering solutions are implemented for their structural integrity designed based on safety codes and sustaining extreme conditions, among other reasons. During their design lifetime, different failure probabilities are taken into account such as the probability of breaching, erosion, and instability (Schoonees et al., 2019).

2.4.2 Nature-Based Solutions

The IUCN (2020) defines NbS as “Actions to protect, sustainably use, manage and restore natural or modified ecosystems, which address societal challenges, effectively and adaptively, providing human well-being and biodiversity benefits.” Originating from a paradigm shift in the civil engineering world, the approach of working with nature rather than against it is more advantageous for both humans and the natural environment (Wilms, 2024). NbS are designed strategies to tackle pressing societal challenges. These societal challenges greatly affect coastal areas with large populations, especially small island nations. The IUCN defines and categorises these issues into seven societal challenges that NbS should attempt to solve.

Figure 2.9: The seven societal challenges according to the IUCN (2020).

This implies that addressing these challenges must involve the preservation, conservation, and restoration of CE. Given that CE provides the natural capital that humans highly depend on, their sustainable use should be a priority. NbS must be clearly defined and understood to ensure effective implementation in policies and projects. Without this clarity, the incorporation of NbS could result in inconsistent and ineffective outcomes (IUCN, 2020).

The United Nations set Goals 14 and 15 focusing on “Life below water” and “Life on land” for the 2023 Sustainable Development Goals (United Nations, 2023). These two goals support continued progress towards NbS, which provides climate-adaptable and natural defences to lessen the damaging effects of anthropogenic activities and climate change on coastal communities and can address the seven societal challenges stated by the IUCN (2020) (Roberta et al., 2022). Specifically, NbS for coastal areas is crucial in mitigating possible threats and damages, generating benefits, and enhancing biodiversity. Wave attenuation is one of NbS’s immediate contributions to reducing the direct threats of flooding. Moreover, if well maintained, NbS can contribute to the long-term stability and resilience of the coastal environment.

Despite their benefits, NbS are still less frequently chosen due to concerns regarding their reliability, adaptability and cost-effectiveness compared to grey engineering alternatives (Gijsman et al., 2021). Ecosystems' rate of recovery after an extreme event is dependent on their sensitivity and adaptive capacity (Seddon et al., 2020).

Nevertheless, studies indicate that, for example, mangroves outperform grey structures in their adaptive qualities over extended periods (i.e., several decades), because they possess the ability to regenerate and adapt to environmental changes, such as sea level rise (Gijsman et al., 2021).

Functionality and Persistence of Mangroves

The functionality of mangroves is defined by their capacity to attenuate hydrodynamic energy, through their biophysical characteristics, including aerial roots, forest width, species diversity, stem density, diameter, and height, all of which interact with the hydrodynamic processes such as sea level rise, wave height, and wave speed. They also have sediment-trapping capacities and stabilising effects of the coastline from their roots which help reduce erosion. Additionally, mangroves demonstrate persistence through bio-geomorphic dynamics influenced by various intertidal zone processes. These include hydrodynamic processes; morphological processes related to the structural features of the land, such as topography and land subsidence; and ecological processes that pertain to the characteristics of the mangroves themselves, such as their tree growth. Through these mechanisms, mangroves adapt to long-term environmental changes like sea level rise and alterations in the spatial dimensions of forests (Gijsman et al., 2021). Figure 2.10 illustrates how these different factors influence the functionality and persistence of mangroves. They play crucial roles in attenuating waves, and stabilising coastlines through sediment accretion and erosion reduction, thereby enhancing coastal protection.

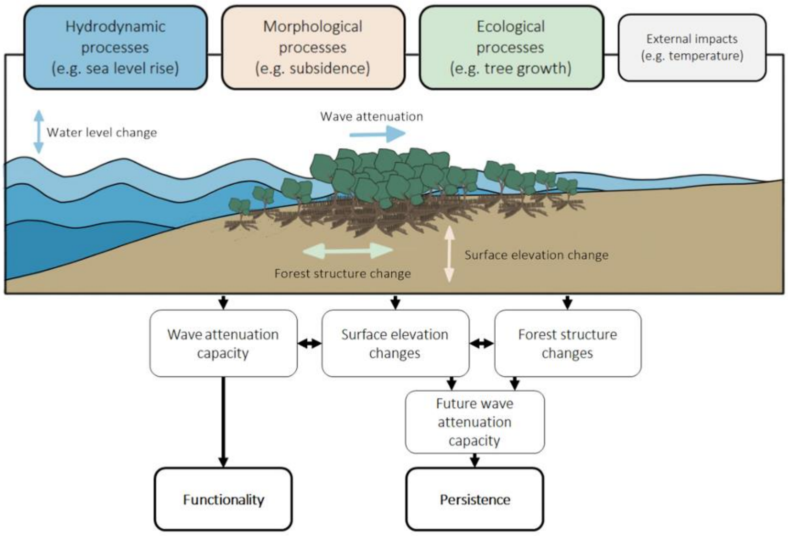

Figure 2.10: Hydrodynamic, morphological, and ecological factors determining the functionality and persistence of mangroves. Retrieved from (Gijsman et al., 2021).

To objectively compare the performance of hard-engineering structures and NbS ecosystems such as mangroves, an assessment was carried out to compare the variability and uncertainty in their functionality and persistence (Figure 2.11).

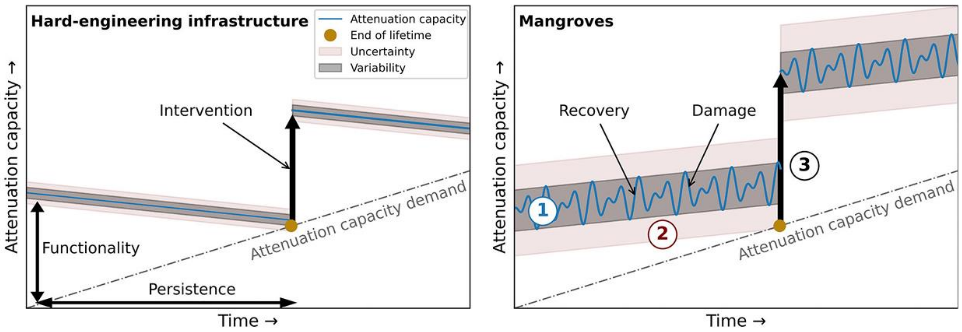

Figure 2.11: Hard engineering infrastructure and Mangroves variability and uncertainty in reducing flood risks. Retrieved from (Gijsman et al., 2021).

Due to the nature of the material, hard structures deteriorate over time, decreasing their attenuation capacity. Therefore, hard engineering structures can not adapt to the increased demand for attenuation capacity due to the expected increase in flood risks, resulting in the need for structural maintenance and upgrades (Gijsman et al., 2021). Comparatively, mangroves' attenuation capacity can increase over time thanks to their ecological properties allowing them to adapt to the changes in their environment. These findings conclude that CE like mangroves, are suitable nature-based alternatives in mitigating coastal flood risks.

2.5 Challenges of NbS

NbS have many benefits but remain limited and uncertain, which is why many decision-makers question them. A significant challenge is that many ecosystem benefits lack a market value (Hudson et al., 2023). This leads to reluctance among financiers to invest in NbS. Consequently, during the decision-making process of NbS alternatives, trade-offs may emerge among the beneficiaries and investors. These trade-offs often involve the balance between the biodiversity level and ecosystem benefits attributed to the respective stakeholders (Seddon et al., 2020 & Zanten et al., 2023).

3. Study Scope

In this research, the services of mangroves and coral reefs will be the main focus as they not only provide direct material gains (e.g. fish, fuel wood, and clean water) but also indirect, non-material gains (e.g. carbon sequestration, coastal protection, and cultural and spiritual value).

Hence, the scope of this study will be on regions of tropical climates, where the physical (regulatory and production) services and social (cultural) services of mangroves, coral reefs (and seagrasses) will be assessed to explore the additional benefits that they provide alongside coastal protection. The regions chosen to be explored in this study are Southeast Asia and Eastern Africa, including the Indian Ocean islands on the coast of Africa, see Figure 3.1. Case studies of countries from these regions will be used for reference when needed.

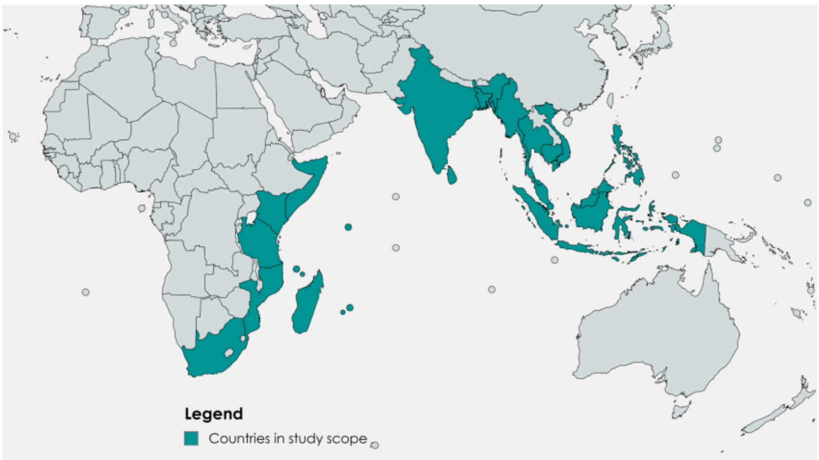

Figure 3.1: Map of tropical regions of focus: Southeast Asia, and Eastern Africa.

3.1 Problem Statement

In this section, the problem statement is introduced. Additionally, the research objective is provided which provides a clear and specific statement outlining the goals and aims of the research study.

Problem statement:

Monetising the benefits of NbS (ecosystems) is often deemed unmanageable, leading to a lack of fair comparison with grey infrastructure. A significant gap in research and knowledge on ecosystem services stems from an inadequate understanding of the short-term (functionality) and long-term (persistence) benefits of NbS. Additionally, regulatory, and cultural benefits, such as coastal protection, ecological benefits, and aesthetics, are often considered 'intangible' and difficult to value

(Costanza et al., 1997). However, many benefits can be directly and indirectly reaped from the ecosystems in coastal zones, and these often have high and significant value for the development of the area and the quality of human life. Therefore, valuing these benefits is worth exploring, especially in coastal management, where NbS are becoming more popular. This would not only help investors make informed decisions but also aid engineers in understanding and working with these systems.

3.2 Research Objective & Questions

Research objective:

The objective of this study is to provide input for SCBA that includes an inventory of the monetised regulatory, production, and cultural services of mangroves and coral reefs. This research aims to guide the quantification of the socio-economic benefits of NbS for coastal protection and identify gaps in the valuation of these services.

Following the research objective, four main questions can be formulated. Each research question can be further broken down into sub-questions to effectively conduct the research needed to achieve the objective.

1. **What are the ecosystem services of mangroves and coral reefs?**

- What are the regulating, production, and cultural services that mangroves provide?
- What are the regulating, production, and cultural services that coral reefs provide?

2. **What are the socio-economic benefits, in monetary value where possible, of mangrove and coral reef ecosystems?**

- What are the socio-economic benefits of regulatory services of mangroves and coral reefs?
- What are the socio-economic benefits of production services of mangroves and coral reefs?
- What are the socio-economic benefits of cultural services of mangroves and coral reefs?

3. **Who are the beneficiaries (stakeholders)?**

- Who are the beneficiaries of each benefit from each ecosystem?

4. **How can the monetised socio-economic benefits of mangrove and coral reef ecosystems be integrated into a socio-economic cost-benefit analysis (SBCA)?**

- How to integrate the inventory of all the benefits of coral reefs and mangroves in a socio-economic cost-benefit analysis (SCBA)?

4. Methodology

4.1 Socio-Economic Cost-Benefit Analysis (SCBA)

For this research, the inputs will be curated to fit a socio-economic cost-benefit analysis (SBCA). SCBAs are meticulous approaches used to evaluate the economic efficiency and social welfare implications of policy interventions, investments, or projects. They provide clear overviews of all costs and benefits of an intervention including their positive and negative impacts, welfare gains and losses, and help decision-makers identify who will benefit or be disadvantaged. This involves stakeholders—beneficiaries and investors, including communities and organisations. A SCBA must be analysed in both spatial and temporal dimensions to understand geographical impacts in the short- and long-term, encouraging "holistic thinking" regarding the goals and impacts on different stakeholders (Atkinson et al., 2018).

In the context of NbS, a SCBA estimates all costs and benefits, including ecosystem services in monetary terms, and aids in comparing NbS with grey engineering solutions. An SCBA analyses whether the socio-economic benefits, quantified in monetary value, outweigh the costs relative to a baseline or "business-as-usual" scenario (Dongen, 2023). If the benefits outweigh the costs, the investment is socio-economically sound (Nieuwkamer, 2008). Negative benefits, or costs, are adverse effects associated with a project. Examples of negative benefits of NbS projects include health impacts from CE, species invasion, and cultural disservices like noise or smells from wildlife (Friess et al., 2020).

Author Nieuwkamer (2008) developed a simple flowchart that shows the steps to be taken by the analysts performing a SCBA (Figure 4.1). Starting with a full description of the baseline, which is the current situation without any intervention yet, followed by the relevant features of the proposed project alternatives. This leads to calculating all the costs of the project, i.e. Capital Expenditures (CAPEX) which are the construction and planning costs and Operating Expenses (OPEX) which are the operating costs of a project solution. Then, identifying and assessing the physical impacts that bring about benefits depending on the physical impacts and environmental quality during the life cycle of the project. From there, the impacts that lead to human welfare are quantified and monetised. Furthermore, financial metrics are used to make all welfare impacts and costs comparable with the same quantification and valuation units. Finally, a sensitivity analysis is performed to observe trends and patterns in the performance of the project with changing variables over time.

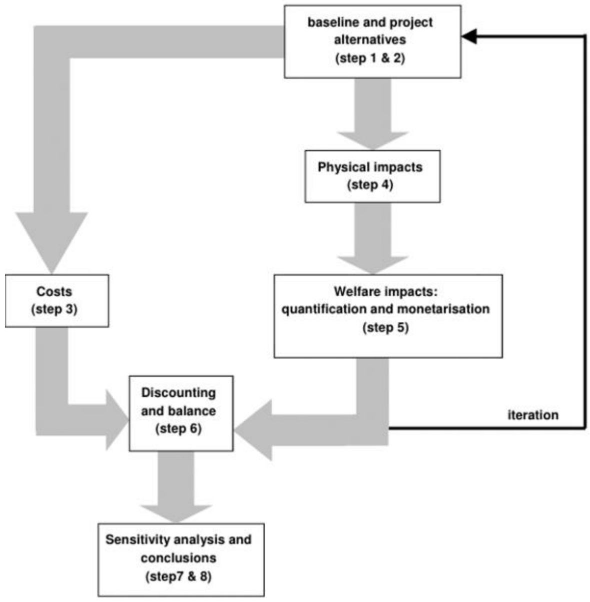

Figure 4.1: Steps in a SCBA retrieved from (Nieuwkamer, 2008).

Since the SCBA's data is gathered at various points in time, it is essential to transform the values into "present values" using a discount rate (DR) to account for people's time preferences and the opportunity cost of capital. This allows monetary values to be made comparable (Zanten et al. 2023). Three different interlinked financial metrics can be used to evaluate the performance of an intervention or policy over time; see Table 4.1.

Table 4.1: Interlinked financial metrics used in a cost-benefit analysis (CBA).

Net Present Value (NPV)	The difference between present-value benefits and present-value costs (Zanten et al. 2023). —If NPV > 0, then the NbS is worth investing in since over time, the benefits and revenue will be greater than CAPEX and OPEX (OECD, 2018).
Benefit-cost Ratio (BCR)	The ratio of benefits to costs at present value. —When a project's benefits outweigh its costs, its BCR is greater than one (Zanten et al. 2023).
Internal Rate of Return (IRR)	The DR at which the net present value (NPV) of a project drops to zero. —If an IRR exceeds the DR, then investing in the ecosystem will yield a rate of return higher than it would if investments were made in an alternative solution (Zanten et al. 2023).

4.2 Valuation of Ecosystem Services

Researcher Nieuwkamer (2008), explains that nature has three values shown in Figure 4.2:

1. **Financial value**: Income for citizens, business owners, investors, governments etc; cash flows from the benefits of ecosystems.

2. **Economic value**: Welfare for humans through the use (material gains) and non-use (non-material gains) of goods and services from the ecosystems.

3. **Intrinsic value**: Welfare for plants and animals; human welfare obtained through the ecosystems is a form of non-use (nonmaterial-gain) value.

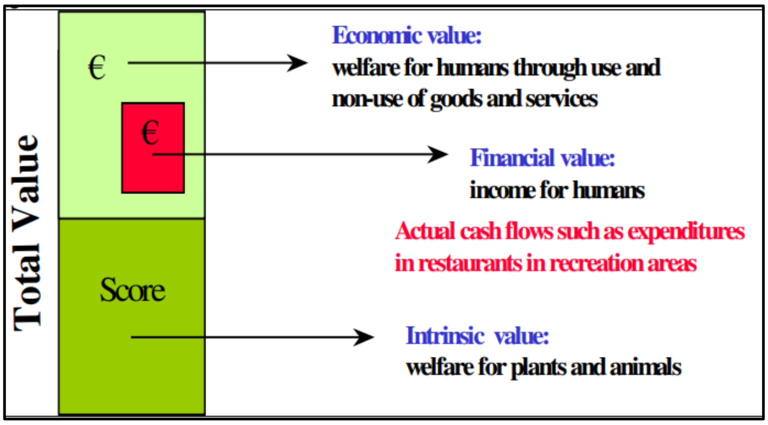

Figure 4.2: The three values of nature. Retrieved from Ruijgrok et al. (2007) and Nieuwkamer, (2008).

To facilitate valuation, quantification, and monetisation, all identified benefits of mangroves and coral reefs have to be characterised into these three different groups of nature values. It will aid in determining the benefits that can and can not be directly valued by employing different valuation methods. An overview of several valuation methods is presented in Figure 4.3 by Zanten et al. (2023). The use of each valuation method is dependent on the available ecosystem benefits.

	Valuation method					
NBS benefit	Market prices	Net factor income	Avoided damages	Replacement cost	Stated preferences	Value transfer
	NBS benefits that are directly observed in markets	Revenue from a marketed good with an NBS benefit input minus the cost of other inputs	Damage costs avoided due to NBS	Estimate the cost of replacing an NBS with an engineered solution	Ask people to state their WTP for an NBS benefit through surveys	Use results from existing valuation studies for similar NBS and socioeconomic contexts
Food and raw materials	✓	✓				✓
Tourism and recreation		✓			✓	✓
Climate regulation	✓		✓			✓
Biodiversity	✓				✓	✓
Water quality			✓	✓		✓
Health					✓	✓

Figure 4.3: Valuation methods of different ecosystem NbS benefits. Retrieved from Zanten et al. (2023).

Once all the benefits of these ecosystems have been identified, they are aggregated into use and non-use value, this eases the determination of valuation methods based on the use and indirect use of the goods and services. Figure 4.4 displays a flow diagram with examples of how to reach the determination of the valuation method per good and service.

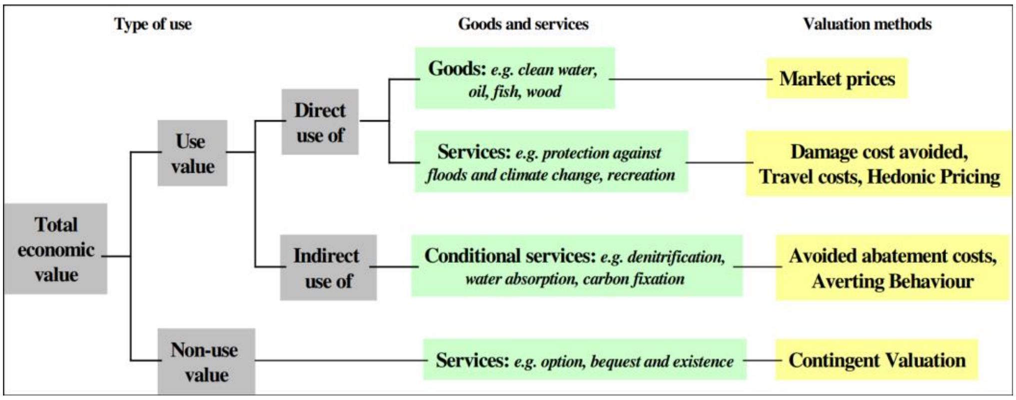

Figure 4.4: Different use types, linking goods and services with their valuation methods. Retrieved from Nieuwkamer, (2008).

Intrinsic values are the welfare of living organisms thanks to the existence, and health of ecosystems, hence why it is not considered a value that brings welfare to humans and can not be expressed in monetary value. Instead, they can be assessed using a scoring system related to the 'bequest value,' which reflects the indirect benefits humans derive from preserving ecosystems for future generations. This concept will not be expanded further in this study.

4.2.1 Valuation Methods

Market prices: Valuing a benefit based on current market prices reflects the actual monetary value of products received from the ecosystems, such as food, drinking water, oil and wood. This valuation method most accurately represents the economic/financial value of these benefits.

Avoided damages: Owing to certain ecosystem functions, many future damages and costs can be avoided. To calculate the value of a function and its benefits, particularly regulatory functions, the costs of an alternative to NbS performing the same role are considered. Another form of avoided damage is the cost incurred if for example an asset or infrastructure were damaged. The monetary value of this benefit is equivalent to the cost of implementing an alternative intervention to NbS. This "avoided" cost represents the value of that function.

Travel cost Method: This valuation method considers the travel costs that individuals are willing to incur to visit an ecosystem. The expenditures made reflect the welfare derived from the ecosystem services, translating into economic value to better understand the significance of these services.

Contingent Valuation method (CVM)/Willingness-to-Pay (WTP): This valuation method is used for bequest values, or intangible benefits that cannot be directly assessed. Services that commonly require CVM and/or WTP for quantification and valuation, are cultural services. It is done through surveys, where people state their willingness to pay for the preservation, conservation, and restoration of nature, either for personal enjoyment or the enjoyment of others and future generations.

Hedonic Pricing: A valuation method often used to assess the ecosystem services contributing to visual amenities is known as the hedonic pricing method. This approach uses property prices to represent the value of these amenities by examining the price differences between properties with views of the visual amenities and those without.

4.3 Data Collection

4.3.1 Values for Valuation

For this study on the ecosystem services of mangroves and coral reefs, ecosystem values are retrieved through value/benefit transfer, also known as reference values. The literature review conducted, gathered reference values from case studies and average values of studies conducted on the mean value of ecosystem benefits globally per service.

4.3.2 Classification of Services

To classify the services provided by mangroves and coral reefs, the Common International Classification of Ecosystem Services (CICES version 5.1) is used (Haines-Young & Potschin, 2018). This classification system is widely recognised in different literature for valuing ecosystem services, ensuring consistency throughout research, and facilitating future use. From the comprehensive list of ecosystem services, those relevant to marine ecosystems (MARINE CICES Relevance = 1) were selected for this classification.

Furthermore, the Millenium Ecosystem Assessment (MEA, 2005), which is a detailed study done on the consequences of ecosystem changes in relation to human well-being and The Economics of Ecosystems and Biodiversity (TEEB; Kumar, 2012) is an initiative focused on providing economic values of biodiversity and ecosystem services to promote the integration of ecological alternatives in decision-making. These two classification systems were utilised in combination with the CICES classification to correlate the services along with their end benefits. These additional classifications are simplified versions that correspond to the CICES framework. The two were merged to make a column of ecosystem functions named '*Reference Class*' (see Excel table).

4.4 Links and Double Counting in the (Eco)System

Due to the nature of the categories of ecosystem services, i.e. regulatory, production and cultural services, there can be some overlap when assigning values to them. This overlap arises because the functions of CE enable and lead to the goods and services received by humans. To avoid double counting in the valuation process, the functions of the ecosystems are linked to the goods and services they provide. Subsequently, the goods and services that directly generate welfare are valued.

To better understand the links between ecosystem functions and services, a systems diagram is created to simplify the complexity of an ecosystem (Figure 4.5 & 4.6). While this diagram has been specifically developed for mangroves, it can also serve as a template for other marine ecosystems due to their similar functions and services.

Legend	
Solid lines	System Functions
Dotted lines	Valued Services
Bold solid lines	End Benefits
Light grey	Ecosystem Services
Grey	Intermediate Impacts
Dark grey	Policy

Figure 4.5: Legend of systems diagram of the mangrove ecosystem.

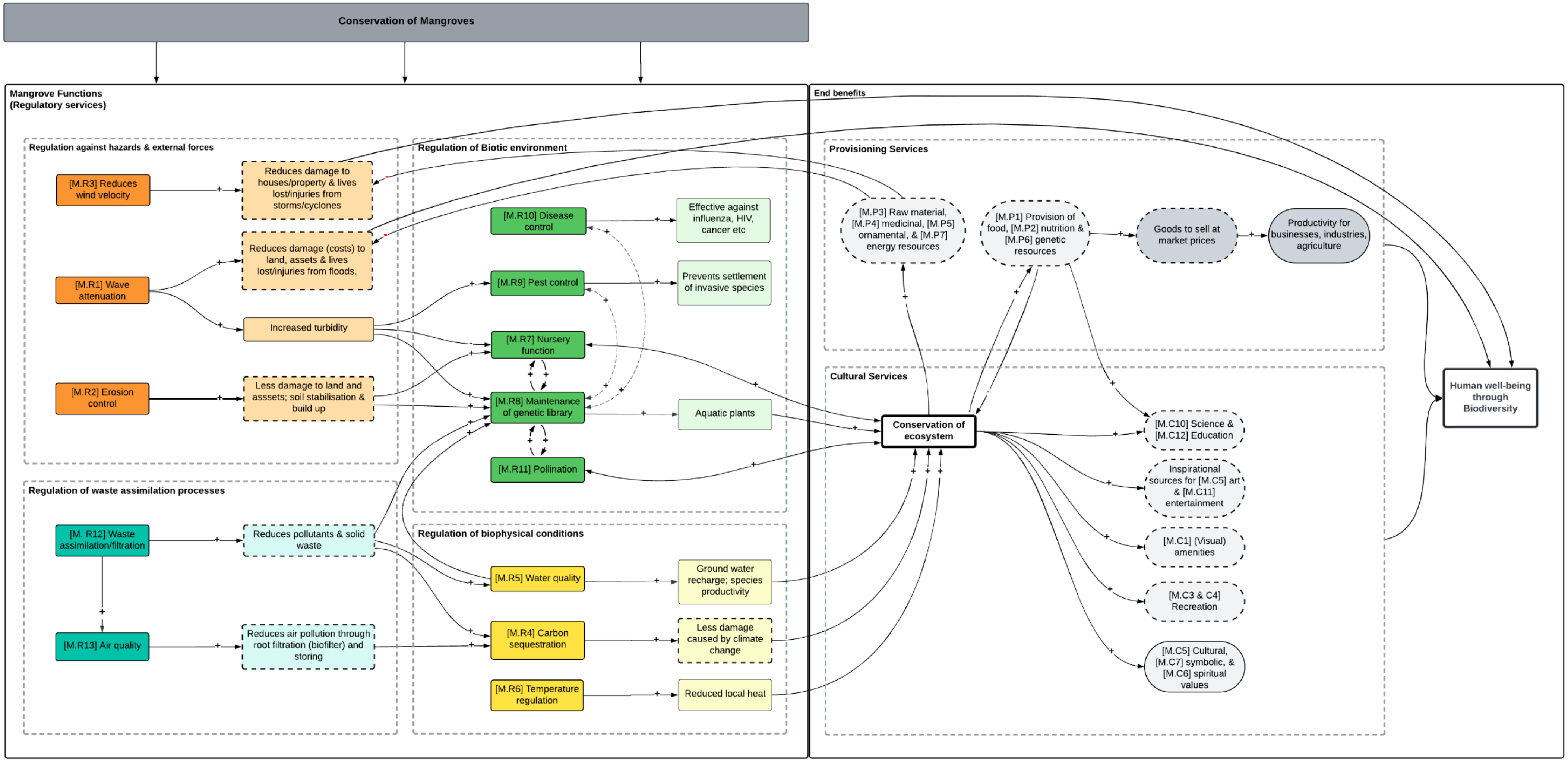

Figure 4.6: Systems diagram of the mangrove ecosystem.

4.4.1 Link 1

Mangroves, positioned in intertidal zones, play a critical role in **[M.R2] erosion control,** which in turn supports their **[M.R7] nursery function** and the **[M.R8] maintenance of a genetic library.** These ecosystems receive sediment from both terrestrial and marine sources, and the roots of mangroves effectively trap this sediment, preventing it from entering the ocean. This action protects nearby ecosystems, such as coral reefs and seagrass beds, which require clear, shallow waters for optimal sunlight penetration (Akram et al., 2023). By maintaining water clarity, mangroves create ideal conditions for the nursery habitats of various species, which supports biodiversity and preserves genetic diversity.

4.4.2 Link 2

[M.R7] Nursery function, [M.R8] maintenance of a genetic library and **[M.R11] pollination** contribute significantly to the production and provision of all the production services **[M.P1 - M.P8]** which are subsequently sold at market prices. Thus, the end benefit lies in the production of goods which are the quantifiable and valued outcome of these ecosystem functions. The beneficiaries of these functions are ultimately the businesses, industries and people that make use of or sell the goods retrieved.

4.4.3 Link 3

[M.R12] Waste assimilation removes and filters waste, pollutants, and heavy metals, which also results in better **[M.R13] air quality** surrounding the ecosystem. Additionally, this process includes **[M.R4] carbon sequestration**, which contributes to the maintenance of **[M.R5] water quality**. These combined effects help the **[M.R8] maintenance of the genetic library** and support biodiversity. This means there can be double counting because one function can lead to another. However, the easiest way to value these services and prevent overlap is by focusing on the end benefit of fish catch, which can be quantified and valued at market prices.

4.5 Stakeholder Analysis

It is imperative to consider the stakeholders when starting a project; this is no different for NbS projects. Identifying the relevant stakeholders helps in understanding the needs and requirements of each, with respect to the ecosystem services that will benefit them. Establishing a list of stakeholders and their requirements helps in distinguishing between beneficiaries who benefit from the NbS but do not pay for it, and investors/initiators who pay for the NbS's costs (CAPEX and OPEX) but do not exclusively receive the benefits, such as clean air, clean water, or increased biodiversity.

Concerning CE, the principal stakeholders will be those that will be directly impacted by or contributors to the NbS on the coast. Some examples of these stakeholders include (Dongen, 2023):

- Local communities, aquaculture, fishermen, agriculture
- Ministry of marine affairs and fisheries, ministry of public work and housing
- Business owners
- Hotel or resort owners and clients

Based on this, along with the results of an SCBA, on a stakeholder level, the distribution of costs and benefits between the beneficiaries and investors can be evaluated to determine whether certain trade-offs are needed and whether compensation is warranted (Dongen, 2023).

4.6 Inventory List

The inventory list compiled in an Excel file (s2829401 E.Louange - CE BSc Thesis - Ecosystem Services Inventory - July 2024) contains detailed information on ecosystem services and their valuation. The excel file contains two sheets: 'Mangrove – ES Inventory' and 'Coral Reef – ES Inventory'. The columns included are as follows:

1. **ID**: An identifier for each entry.
2. **Ecosystem Functions**: Describes the natural processes and interactions within ecosystems.
3. **Ecosystem Services from 'Reference Class' and 'CICES Class'**: Lists the ecosystem services categorised by both the reference and CICES classifications.
4. **Benefits**: The end benefits derived from the ecosystem services.
5. **Short Description**: A brief explanation of each ecosystem benefit.
6. **Direct or Indirect Use**: Specifies whether the benefits are used directly or indirectly.
7. **Monetised**: Indicates if the services can be monetised.
8. **Valuation Methods**: The methods used to determine the monetary value of the ecosystem services.
9. **Unit Quantification**: The units used to measure the quantity of the ecosystem services.
10. **Unit Monetisation**: The units used to measure the monetary value of the services.
11. **Quantity**: The measured amount of the ecosystem service.
12. **Price**: The monetary value assigned to the service.
13. **Price Year**: The year the price data was collected or calculated.
14. **Source:** The country or region of the data or the ecosystem service.
15. **Beneficiaries**: The individuals or groups benefiting from the ecosystem services.
16. **Literature**: References to the academic or research sources supporting the data.

5. Valued Ecosystem Benefits (Results)

The descriptions in this chapter, correspond to the inventory table of ES can be found in the separate excel file.

5.1 Ecosystem Benefits of Mangroves

5.1.1 [M.R1] Wave Attenuation

Mangroves provide wave attenuation services through the drag forces exerted by their roots, stems and canopies on water dynamics. This reduces damage and inundation from flooding caused by storm surges and cyclones to coastal and inland areas on the leeward side of the mangroves. Consequently, damage to infrastructure, houses, properties, crops, green spaces, and other assets is minimised or prevented. Additionally, this flood regulation decreases the risk of injuries and loss of human lives. The damages endured vary strongly depending on the type of hazardous event, location, land use, and characteristics of the event.

Quantification and Valuation:

To quantify and value the damage caused by floods, avoided costs of damage of different land use types and locations based on varying flood depths were retrieved from the publication of the European Union. Available data from different countries were made into global flood-depth damage functions (Huizinga et al., 2017). Based on the scope of this study, only the resulting damage curves of the relevant countries from Southeast Asia and Eastern Africa were retrieved. Huizinga et al., simulated damage curves based on the following land use classes:

- Residential buildings
- Commerce
- Industry
- Transport
- Infrastructure
- Agriculture

The damage curves per land-use class of both continents (Asia and Africa) with damage in Euro per meter square (Euro/m^2) per flood-depth of 0 to 6 m are presented in Appendix A. The average maximum damage value per country, relevant to this study can be found in Table 5.1. These values can be used to estimate the avoided damage costs with the implementation per m^2 of mangroves.

*Table 5.1: Average maximum damage value per country [Euro/*m² *- 2010]. Adapted from (Huizinga et al.,2017).*

Damage class:	Residential	Commerce	Industry	Transport	Infrastructure	Agriculture
Africa						
Mozambique	283.00	n.a.	n.a.	n.a.	267.00	0.10
South Africa	765.00	n.a.	120	n.a.	n.a.	0.18
Asia						
Cambodia	24.00	n.a.	n.a.	n.a.	n.a.	0.01
Bangladesh	25.00	144.00	92.00	n.a.	2.50	0.05
India	n.a.	n.a.	n.a.	n.a.	n.a.	0.01
Indonesia	6.00	29.00	27.00	4.00	n.a.	8.00
Thailand	1.00	n.a.	245.00	n.a.	n.a.	0.02
Vietnam	7.00	15.00	n.a.	n.a.	0.25	0.10

Note: Some land use classes in certain countries are not available to develop a damage function which indicates that further research must be done in these sectors.

Another study conducted in the Philippines by Menéndez et al., (2018), showed that mangroves reduce flooding to 613,000 people annually and save up to **US $1.7 billion** in damages to residential, industrial stock and infrastructure from 1/50-year flood occurrence. On average, The Philippines' mangroves provide flood reduction benefits of more than **US $3200/ha/yr**. The research on the spatial variation of the damage reduction benefits of mangroves can be utilised in other countries to identify the areas needing mangrove conservation and restoration to provide coastal protection (Menéndez et al., 2018).

5.1.2 [M.R2] Erosion control

The roots of mangroves help trap sediment, making the soil more resistant to erosion and encouraging sediment build-up around the trees, stabilising the shoreline.

Quantification and Valuation:

The valuation of erosion control can be assessed through avoided costs, representing a direct benefit. Although it can not be directly measured based on erosion rates, the avoided costs of the reduced need to nourish the coast and the maintenance of hard structures. The value transfer method taken from a case study done in Vietnam gives a representative value of the avoided costs of maintenance on sea dykes with the presence of mangroves of **US $7.3 million** annually (Wittmer & Gundimeda, 2010).

5.1.3 [M.R3] Wind Velocity

The foliage of mangrove trees and shrubs helps buffer wind velocities during cyclones. The maximum wind velocity occurs in the eye wall region, which is a few kilometres surrounding the eye of the storm, with tangential winds varying with radial distance from the eye. On land, factors such as soil conditions, such as soil moisture (since cyclones thrive from surface moisture), topography, and vegetated land cover cause the wind speed of cyclones to decrease exponentially once they make landfall (Das & Crépin, 2013). Consequently, mangroves have the potential to reduce wind speeds as the tangential winds reach the coastline and move further inland.

A study conducted in India assessed the ability of mangroves to attenuate wind and protect villages by reducing wind-related damages (Das & Crépin, 2013). The findings showed that villages without mangroves experienced greater wind-related damage compared to those sheltered by mangroves, even under the same level of storm impact. Mangroves provide optimal protection when they grow in large, continuous clusters. It is important to note that damage varies based on the materials used for structures: non-engineered structures made of mud (*kutcha*) are more vulnerable to being swept away by storm surges, while engineered structures are more likely to suffer damage or fully collapse from strong winds. Figure 5.1 shows a simplified version of a cyclone path and its dynamics.

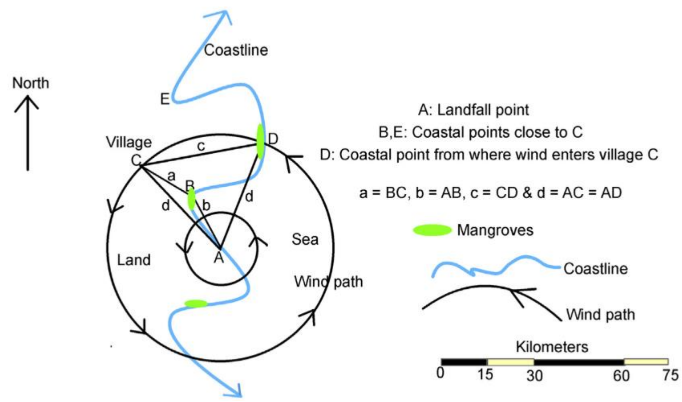

Figure 5.1: Model of storm path and characteristics. Retrieved from (Das & Crépin, 2013).

The study demonstrated that villages within 10 km of the coast, protected by mangroves, experienced reductions in damage at varying distances from the cyclone's landfall. Specifically, for mangrove widths averaging 2.61 km, 0.44 km, and 1.86 km, damages were reduced by 17%, 10.6%, and 9.9%, respectively, at bandwidths of 30-35 km, 50-60 km, and 60-80 km from the landfall. A figure showing the different locations of villages and mangroves along the coast and further inland in the Odisha region of India, along with the percentage of damaged houses per distance to the coast can be found in Appendix B.

Quantification and Valuation:

The damage was quantified based on housing units and families affected, where the number of workers and male heads was used as proxies to determine the number of families in each village due to a lack of demographic information about households and families. Using the construction costs, led to a conclusion that the wind attenuation value for mangroves came to INR969 or **US $23** (1999 exchange rate) per family. Aggregating families for all the housing units leads to the value of **US $177** per hectare of mangroves (1999 prices).

These findings are, however, case-specific and would require further research in different locations with different storm/cyclone conditions to fully understand the total damage that mangroves can reduce by attenuating wind speeds.

5.1.4 [M.R4] Carbon sequestration

An essential function that mangroves possess is carbon sequestration, whereby they absorb carbon dioxide from the atmosphere through photosynthesis and store carbon in both the biomass and the soil beneath (Burke et al., 2001 & Chatting et al., 2022). They can sequester proportionally more carbon (up to 5 times more) below ground compared to carbon stored above ground by terrestrial trees (Alongi, 2012). Along with coral reefs, they are good carbon sinks known as "blue carbon" ecosystems (BCE).

A study published in 2022 by authors Chatting et al., found that mangroves store an estimated average of 472.7 ± 56.4 metric tons of carbon (mean ± standard error). Southeast Asia has been shown to have the highest stocks of Carbon (C) per hectare, especially in Indonesia and the Philippines (Chatting et al., 2022).

Quantification and Valuation:

Carbon sequestration offers numerous benefits, including improved air quality for human respiration, enhanced health of animals and plants, and mitigation of the global warming effects of greenhouse gases (GHGs), thereby reducing the impacts of climate change. However, these benefits are often difficult to quantify and value directly. Therefore, a value transfer method can be used to quantify and value carbon sequestration (Mehvar et al., 2018). Carbon emission prices are measured through estimates of social costs of carbon (SCC) based on the global damages per ton of CO_2 emitted [tCO_2e], serving as a proxy to value the service of carbon sequestration (Mehvar et al., 2018 & World Bank, 2023). Only 26% of priced emitted carbon is accounted for globally. To attain the 2030 goals of the Paris Agreement, carbon prices must remain high, therefore the World Bank (2023) stated that prices should remain between **US $40-80 tCO_2e.**

There are two main types of carbon pricing mechanisms: Emissions Trading Systems (ETS) and Carbon Taxes (CT) (World Bank, 2023).

- Emissions Trading Systems (ETS): an approach used to reduce emissions through a "cap-and-trade" system. Capping sets a limit on the total level of GHG emissions allowed within an area or industry and these industries can trade with one another by buying and selling allowances to each other depending on the amount they emit. ETS sets a market price for carbon (GHG) emissions.
- Carbon Taxes (CT): a tax rate placed upon the carbon content of fossil fuel which directly sets a price on carbon emissions.

The carbon emission prices are from Singapore, Indonesia, and South Africa, representing the Southeast Asian and Eastern African regions, respectively.

Singapore implemented the CT approach as the first to establish a carbon pricing scheme in Southeast Asia in January 2019, with CT expected to increase between SGD $50-80$tCO_2e$ by 2030 (NCCS, 2019).

South Africa is the largest emitter of GHG in Africa and the only one so far to have a carbon mechanism of CT implemented, which started in June 2019 (IMF Asia and Pacific Dept, 2022).

Indonesia is another Southeast Asian country that has a carbon pricing mechanism in place, however, they implemented the ETS in April 2022 for coal-fired power plants, with tax rates lower than other countries with CT adopted (IMF African Dept., 2023).

Prices:

- Singapore: **SGD 25/tCO_2e** *carbon tax* (approx. 18 USD) (price year 2024) (NCCS, 2019)
- Indonesia: **IDR 30,000/tCO_2e** *emission trading system* (approx. 2 USD) (price year 2022) (IMF Asia and Pacific Dept, 2022)
- South Africa: **ZAR 120/tCO_2e** *carbon tax* (approx. 7 USD) (price year 2019) (IMF African Dept., 2023)

5.1.5 [M.R5] Water quality

Like other ecosystems, mangroves maintain water quality through waste assimilation and the nutrients they provide from litterfall that maintain the ecological balance within the ecosystem. They also provide clear and clean water by trapping particles from flowing into other coastal ecosystems like seagrass beds and coral reefs which require clear surface waters to thrive (Kathiresan, 2021).

Quantification and Valuation:

Once again, valuing this service overlaps with waste assimilation services. However, if a project prioritises water quality through NbS, this can be valued by quantifying the avoided costs of treating cubic metres (m^3) of water per hectare of mangrove per year. This approach ensures a focused and relevant valuation for water quality improvement.

5.1.6 [M.R6] Temperature regulation (local)

Like many forests and foliage, mangrove forests can reduce local temperatures in the surrounding areas through the process of evapotranspiration from their leaves. This cooling effect provides a more comfortable environment for both animals and humans who inhabit or pass through the mangroves, benefiting activities such as fishing and recreation by reducing heat stress.

Quantification and Valuation:

However, the quantification and valuation of this benefit have not yet been thoroughly studied. Further research is needed to better understand and measure the socio-economic benefits of this cooling service provided by mangroves.

5.1.7 [M.R7] Nursery function & [MR.8] Maintenance of genetic library

Mangroves provide the ideal environment for nursery functions as well as breeding and nesting grounds for various species including water birds like white herons, reddish egrets, roseate spoonbills and many more. The water conditions surrounding mangroves allow for the nursing of juvenile fish and other water species that thrive on coasts.

Quantification and Valuation:

As resulting from the systems diagram (Figure 4.6) mangrove and coral reef nursery functions have multiple intermediate benefits and overlap with other functions and services such as the maintenance of the genetic library which consequently maintains/increases biodiversity. This then leads to provisioning services for an increase in fish/crustaceans catch and raw materials. Additionally, an increase in biodiversity is an input physical impact for the cultural services as it 'allows' for the continuous existence of biodiversity. Therefore, visual amenities, recreation, cultural values, inspirational services, conservation and bequest value and information services are all linked to nursery function in one way or another.

5.1.8 [M.R9] Pest control

Mangrove species can prevent the settlement of invasive species by providing habitats for predatory species that regulate the invasion of species harmful to plants, animals, and humans. Additionally, mangroves maintain water quality, which helps keep away pests and vector-borne diseases, thereby preserving biodiversity and ecological balance.

Although this service is not yet quantifiable due to the difficulty in directly linking its benefits to human welfare, it indirectly contributes to maintaining the productivity of agriculture in the area (United Nations et al., 2021).

5.1.9 [M.R10] Disease control and [M.P5] Medicinal resources:

Mangroves have certain properties that can provide disease control services. Their leaf, flower and trunk extracts, have antibacterial activities, antioxidant properties, and antimicrobial activities that inhibit bacterial growth. These properties are both beneficial to humans and animals that feed on the biomass of mangroves, such as the lignin extracted from a type of mangrove plant called *Ceriops decendra* is reported to protect mice from lethal infections of E.coli (Kathiresan, 2021).

However, this is all still an early investigation and can not yet be officially used as medical resources. It requires further studies to confirm the effectiveness and safety of mangrove-based medication. Therefore, these services can not yet be quantified or valued.

5.1.10 [M.R11] Pollination

Pollination is a crucial function in an ecosystem, as it leads to many services and benefits, creating a constant natural feedback loop. Pollination can occur through various agents such as bees, birds, wind, and insects. The systems diagram (Figure 4.6) illustrates the resulting intermediate impacts of pollination. From this, Figure 5.2 was drawn up to closely depict the feedback loop inherent in the process of pollination.

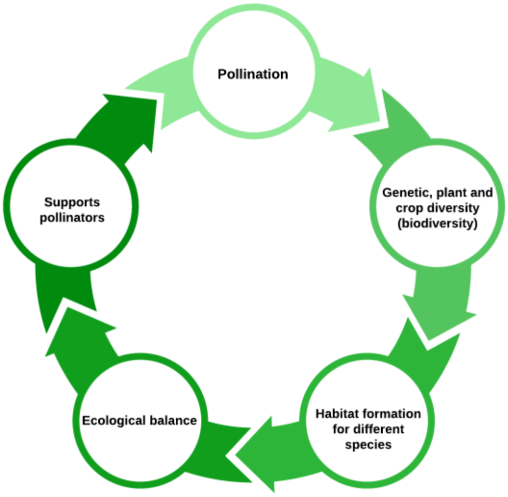

Figure 5.2: Pollination cycle and resulting chain of benefits as a feedback loop.

Although mangroves themselves do not actively contribute to their own pollination, the surrounding ecosystem supports pollination through various agents. Pollination by animals, insects, and wind facilitates the reproduction of many plant species and enables cross-pollination, both of which are crucial for maintaining and increasing the genetic diversity of plants. Plant reproduction creates habitats, shelters, and nurseries for animal species, fostering an ecological balance between flora and fauna. This balance, in turn, supports more pollinators and enhances human well-being through increased and sustained biodiversity. Thus, while mangroves play a significant role in providing nursery habitats, their contribution to the ecosystem includes supporting the broader processes of pollination and biodiversity maintenance.

5.1.11 [M.R12] Waste Assimilation

Ecosystems such as mangroves can maintain the health of the biotic (living organisms within an ecosystem) and abiotic (non-living components such as water and soil) environment through assimilation. Waste assimilation is the filtering and absorbing of toxins, pollutants, heavy metals and solid waste without causing harm to the ecosystem itself and those who use it. The soil, algae, microbes, and physical processes of mangroves absorb the organic and heavy metal pollutants by trapping them in the soil, thus preventing the pollution from reaching other CE. (Kathiresan, 2021).

Additionally, mangroves can recycle different nutrients such as carbon and nitrogen, making them accessible to other living organisms that depend on them (Kathiresan, 2021). Furthermore, mangrove roots can also filter solid waste from anthropogenic activities by trapping the waste and preventing it from entering the open ocean. This however requires waste management strategies that state that the solid waste must be cleaned up to not further harm the mangroves themselves (Kathiresan, 2021).

Quantification and Valuation:
The waste assimilation services of an ecosystem can be valued through the cost of pollutants released into the environment based on surrounding land use and solid waste, and through the avoided costs (replacement costs) of establishing waste treatment plants to purify wastewater.

While it can be complex to find a general value to represent the economic value of this service, project analysts must seek location-specific prices for wastewater treatments. These prices can vary significantly depending on factors such as the amount of waste discharged, the characteristics of the affected ecosystems, and the various land use purposes that generate wastewater. This means that the unit quantification will differ depending on the component of waste or pollutant that is being valued. This tailored approach ensures a more accurate and relevant valuation of the ecosystem's waste assimilation services.

As an example, a case study in Western Cape, South Africa quantified the removal of pollutants per hectare of wetlands (including mangroves) and estimated the equivalent cost of doing this treatment through treatment facilities. This amounted to **US $12,385/ha/yr** (Wittmer & Gundimeda, 2010).

5.1.12 [M.R13] Air quality

Mangroves maintain air quality by sequestering and filtering pollutants from the atmosphere. They absorb and filter air through their roots and leaves and release bioactive compounds that help regulate air quality in surrounding areas (Rusmayadi et al., 2024).

Air pollution is a significant source of health problems in humans, so preserving, conserving, and restoring ecosystems provide natural processes to filter and improve air quality. Carbon sequestration is one aspect of maintaining air quality; however, in the context of a SCBA for a NbS, this can lead to double counting. To determine the economic value of the air quality regulation services provided by mangroves, one can consider the avoided costs of air purification treatments, or the avoided medical costs related to human health. Improved air quality also enhances productivity in local agricultural sectors and overall worker productivity by reducing sickness (Wittmer & Gundimeda, 2010).

5.1.13 [M.P1] Provision of Nutrition

Mangroves are great sources of different types of nutrition, like fish, shrimp, prawns, crab, mussels, fruits, wax, and honey (with the presence of bee colonies). In India, about 2000 people employed partake in extracting 111 tons of honey annually (Bandaranayake, 1998). Mangroves also provide a cod surplus to produce cod liver oil supplements (Haines-Young & Potschin, 2018).

A meta-analysis done in the Sundarbans mangrove area in Bangladesh and India summarised (Table 5.2) the economic values of some of the provisioning benefits of mangroves in USD per hectare per year (Kanan et al., 2024).

Table 5.2: Estimated economic value of Sundarbans ES (US$/ha/yr)

Provisioning	Bangladesh Sundarbans	Indian Sundarbans	Entire Sundarbans (10,277m²)
Fish	420.00	108.00	295.00
Shrimp	110.00	35.00	80.00
Shrimp fry	78.00	27.00	58.00
Crab	106.00	50.00	84.00
Honey	44.00	38.00	41.00

Thatching material	18.00	6.00	13.00
Fodder	28.00	18.00	23.00

Note: Values were rounded up for simplicity and clarity

5.1.14 [M.P3 - M.P6] Raw Materials

- **[M.P3] Materials & [M.P7] Energy resources:**

Mangroves can be harvested for wood or timber for construction purposes. However, to use this ecosystem as a NbS, the harvesting of these trees must be done sustainably. Cutting down mangroves will disable other services that bring monetary benefits, such as wave attenuation, fish catch, and carbon sequestration. Therefore, the conditions and state of the project, as well as its spatial considerations (area of the project), must be considered when choosing which valued benefit to use in the SCBA to avoid double counting.

Mangroves can be harvested to use as fuelwood and charcoal as a source of energy especially in developing countries, where coastal inhabitants depend on the wood for cooking and heating in Southeast Asia. Up until 1998, 90% of the fuel used in Vietnam came from mangroves (Bandaranayake, 1998). They are also sold at market prices which provides employment and income for the citizens who rely on them.

Quantification and Valuation:

A meta-analysis conducted on the economic value of mangroves showed that they produce an average of **5976kg/ha/yr** of timber and **5140kg/ha/yr** of fuelwood and charcoal (Salem & Mercer, 2012). A case study conducted in Vietnam concluded that farmers and citizens spend about **US $300/yr** and **US $800/yr** on fuelwood and timber respectively (Vo et al., 2015). This would differ per location based on the market prices of the wood.

- **[M.P6] Genetic resources:**

Genetic resources are the genetics of the different species of mangroves and corals that can be studied and used as plant seeds, spore or gamete production, which are the reproduction agents in all biota. Genetic resources can also be used to restore the ecosystem and reproduce or mimic the processes of nature within for instance bioengineering and biomedical sectors (United Nations et al., 2021).

Quantification and Valuation:

It would be too complex to value the use of genetic resources in science, however, the value of seeds can be estimated through a proxy of approximation of mangrove restoration costs. Globally, the median costs of restoring mangroves amount to **US $1000-9000/ha.** A case study done in Indonesia showed an average restoration cost of **US $3,900/ha** (The World Bank et al., 2022).

- **[M.P5] Ornamental resources**:

Ornamental resources refer to parts of mangroves harvested for decorative purposes, such as flowers, leaves, and branches. This practice typically occurs on a small scale and is usually done by mangrove dwellers for personal use rather than for sale at market prices. While the economic value of these resources is minimal, they contribute to the traditional and symbolic value of mangroves, enhancing the mental well-being of those who use and appreciate these ecosystems (Bandaranayake, 1998).

5.1.15 [M.C1-M.C4 & M.C8-M.C9] Cultural services

Both mangroves and coral reefs offer significant visual amenities and recreational opportunities through activities like ecotourism, tours, excursions, kayaking, exploring, snorkelling, and fishing. These activities generate revenue for local areas through payments for hotels, resorts, tour tickets, and activity fees. They enhance the mental and physical well-being of visitors and create job opportunities for locals and foreigners who work in or run these businesses. In small island nations like the Seychelles, most recreational and tourism amenities are owned by locals and are typically small-scale operations, which sustain the community economically and support their overall welfare. Additionally, the conservation of these natural ecosystems and their bequest value contribute to the long-term ecological and economic benefits for future generations.

Quantification and Valuation:

The valuation of these services varies significantly based on the specific activity and location. Recreational activities are often quantified and valued using market prices for hotels, entrance tickets, and activity fees. Expenses in local restaurants for food can also contribute to the overall valuation. The travel cost method can be used to estimate the value of visual amenities by calculating the amount it would cost to travel to the location of the ecosystem or through hedonic pricing. Additionally, services without specific market values can be estimated using the CVM or WTP methods to determine how much individuals are willing to spend for the experience of these natural resources or their bequest value. Table 5.3 provides a few examples of the economic values of recreational and aesthetic services in the relevant countries of Eastern Africa and Southeast Asia (Mehvar et al., 2018).

In summary, the economic valuation of coral reefs and mangroves encompasses various factors, including direct market transactions and indirect benefits, ensuring a comprehensive assessment of their contributions to human well-being and local economies.

Table 5.3: The estimated economic value of recreation and tourism from coral reefs

Country	Ecosystem goods/service	Valuation method	Estimated value [US $]
Seychelles	Tourism and recreation	CVM	88,000.00 (whole area per year)
Indian Ocean	Aesthetics	Hedonic pricing	174.00 (per hectare)
Andaman Sea of Thailand	Recreation	Travel costs and CVM	205.41 million (per year)

5.1.16 [M.C5 - M.C7 & M.C10 - M.C12] Cultural values and Information

Inspirational sources provided by ecosystems offer diverse content for art, entertainment, photography, films, education, and books, among others. These services enhance human mental well-being and support livelihoods and income for those who utilise these mediums. However, quantifying these benefits can be challenging and they have not yet received the proper recognition needed for thorough research and valuation.

Promoting these ecosystems educates and informs people about their functions and aesthetics, attracting tourists and benefiting local businesses, communities, and the local economy. Additionally, this promotion can inspire people to engage with nature, encouraging both locals and foreigners to participate in conservation, preservation, and restoration projects, thus supporting nature-based solutions.

Mangroves, in particular, offer cultural advantages. In nations like Malaysia and Tanzania, families engage in mangrove foraging as a cherished tradition, fostering bonding experiences. Traditional wisdom concerning the significance and reverence for mangroves is passed down from generation to generation, such as the understanding not to capture juvenile fish. For many coastal inhabitants who have resided in these areas for generations, mangroves are a customary feature, instilling a sense of belonging and ancestral ties. These services are direct, non-use values that can not be monetised but hold significant importance for the people living within or around mangroves for generations.

Furthermore, ecosystems like mangroves and coral reefs provide invaluable services for scientific research, offering insights into ecosystem functions and benefits, and furthering the study of their socio-economic values. These ecosystems also serve educational purposes through books and direct engagement, such as field trips, allowing people to learn about and observe these natural environments firsthand.

5.2 Ecosystem Benefits of Coral Reefs

5.2.1 [C.R1] Wave attenuation

Coral reefs can attenuate waves through the dissipation of energy in waves by disrupting the motion of water particles in a wave through friction. This is due to the intricate shapes and sizes of corals that form a 'barrier' along the coast.

Quantification and Valuation:

Depending on the location, land use, and cover, the value of coastal floods amounts to US $36 billion in avoided damages to build capital for flood events of 1/25 year occurrences over 8700 km^2 of land. The values differ per country; a study on the global flood protection by coral reefs provides an overview (Figure 5.3) of not only the avoided damages to built capital (in USD) but also relative to the national economy and population (GDP - Gross Domestic Product), highlighting the importance of coral reefs to smaller island nations as well (Beck et al., 2018).

Annual averted damages ($ millions)			Annual averted damages/GDP	
1	Indonesia	639	Cayman Islands	0.98
2	Philippines	590	Belize	0.37
3	Malaysia	452	Grenada	0.30
4	Mexico	452	Cuba	0.25
5	Cuba	401	Bahamas	0.16
6	Saudi Arabia	138	Jamaica	0.14
7	Dom. Republic	96	Philippines	0.13
8	United States	94	Antigua & Barbuda	0.13
9	Taiwan	61	Dom. Republic	0.11
10	Jamaica	46	Malaysia	0.09
11	Vietnam	42	Seychelles	0.06
12	Myanmar	33	Turks & Caicos	0.06
13	Thailand	32	Guadeloupe	0.05
14	Bahamas	14	Indonesia	0.04
15	Belize	9	Solomon Islands	0.04

Annual expected benefit of reefs for flood protection in terms of annual averted damages to built capital ($ millions per year) and relative to Gross Domestic Product (GDP). The values are the difference in expected damages to built capital with and without reefs

Figure 5.3: Countries that receive the most flood protection benefits from coral reefs. Retrieved and adapted from (Beck et al., 2018)

5.2.2 [C.R2] Erosion control

By the attenuation of waves, coral reefs help reduce the strength of waves and subsequently reduce erosion of the coastline. On most coasts, there are already grey structures in place, which are subject to erosion. A case study done in Sri Lanka in 2006, concluded that damage or loss of reefs led to an estimated erosion of 40 cm per year on the south and west coasts (Wittmer & Gundimeda, 2010). Coral reefs also create tranquil water conditions that enhance sediment deposition in areas that need it, such as developing mangrove forests (Akram et al., 2023).

Quantification and Valuation:

Similarly to mangroves, the valuation of erosion control by coral reefs can be assessed through avoided costs related to the reduced need for coastal nourishment and the maintenance or construction of hard structures. This valuation involves calculating the cost of replacing coral reefs with artificial hard structures for coastal protection, expressed in USD per kilometre of coral reef. This approach underscores the economic value of coral reefs in mitigating coastal erosion and their critical role in coastal protection (Wittmer & Gundimeda, 2010).

5.2.3 [C.R3] Carbon sequestration

Corals sequester carbon through the formation of calcium carbonate ($CaCO_3$) to build their skeleton. Although, authors Allemand et al., 2010 argue that corals are only a minor source of carbon sequestration and do not act as a carbon sink, they still have a crucial role in sequestering with rates of 70 to 90 million tons of carbon per year.

Quantification and Valuation:

Similarly to mangroves, the monetisation of carbon sequestration by coral reefs is done through the avoided social costs of carbon (SCC), and the values obtained in section 5.1.4 can be applied here to estimate the economic benefits of carbon sequestration by coral reefs.

5.2.4 [C.P1] Provides nutrition

In Southeast Asia, coral reef fisheries are estimated to bring a total value of **US $2.4 billion per year.** More specifically, the coral reefs found in Indonesia and the Philippines amount to an estimated annual economic benefit of **US $1.6 billion** and **US $1.1 billion per year,** respectively (Orozco et al., 2021).

According to the IUCN, the islands of the Indian Ocean off the coast of Africa are a diversity hotspot for coral fisheries. There are octopuses, lobsters, and sea cucumbers found in the corals of Comoros. All of which can be captured for consumption and selling at market prices. However, due to overexploitation, climate change, and ocean pollution among others, coral reefs are under great threat and must be restored, conserved, and preserved sustainably to continue providing services that benefit humans long term (Vieille et al., 2022).

5.2.5 [C.P2] Materials & [C.P3] Ornamental resources

- **Sand Particles:**

Coral can be crushed into fine particles and mixed with other soil components for construction purposes. This use leverages the structural properties of coral to enhance building materials.

- **Jewellery:**

Coral is often used in the manufacturing of jewellery, typically on a local scale. These pieces can range from simple adornments to intricate designs, showcasing the natural beauty of coral.

These are two examples of the raw materials that coral reefs can provide. However, harvesting corals for these purposes can be highly detrimental to their health and the overall ecosystem. The extraction process can damage coral structures, disrupt marine habitats, and hinder the numerous ecological services that healthy coral reefs offer, such as coastal protection, biodiversity support, and tourism.

Therefore, it is strongly discouraged to practise these forms of coral reef exploitation. Sustainable alternatives and practices should be promoted to ensure the preservation and health of coral reefs, safeguarding their ecological and economic benefits for future generations.

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6. Discussion

The use of the elaborated methodology of a SCBA can integrate both qualitative and quantitative evaluations of the two coastal ecosystems: mangroves and coral reefs. Although some ecosystem services may lack direct monetary value, the results of this research provide methods to quantify and monetise these services for analysing NbS projects. It also explains why certain services can not or have not yet been quantified and monetised.

For many countries in Eastern Africa and Southeast Asia researched in this study, mangroves and coral reefs are already present. By examining all external conditions of the area of interest, decision-makers can identify and prioritise areas for potential preservation and/or restoration of these ecosystems. This approach ensures that relevant ecosystem services are identified, quantified, and incorporated into decision-making processes, enhancing the effectiveness and sustainability of NbS initiatives.

Decision-makers may question the time component of using NbS for coastal protection, as it takes years to grow a full mangrove forest or reef barrier. However, there are immediate benefits, such as provisioning services, that are generated within months. Additionally, the cumulative revenue from these benefits increases significantly over time, provided that the ecosystems are maintained sustainably.

Mangroves and coral reefs have a synergistic relationship that maintains coastal environment stability (Carlson et al., 2021; Kathiresan & Alikunhi, 2011). The presence of coral reefs helps shape the coastline and protect mangroves and other CE including seagrass meadows further upshore. Mangroves, as plant-based marine habitats, host diverse species and provide nurseries for juvenile and adult organisms, acting as "mobile links" between mangroves and coral reefs while maintaining water quality through natural processes. In return, coral reefs shield mangroves from continuous wave action (Moberg & Folke, 1999). Simultaneously, mangroves protect reefs by trapping sediment discharge from terrestrial water bodies (Connolly & Lee, 2007). This mutual exchange of services complicates effective quantification and monetisation. Therefore, in this study, only the production services from mangroves and coral reefs, such as fish catch, are valued to simplify the process and avoid double counting, which can be seen through the simplified interactions of the ecosystem, translated into a systems diagram.

Moreover, the systems diagram effectively illustrates the connections between regulatory, production, and cultural services. Due to the complexity of the system, many of these services are prone to being double counted. Additionally, the use of certain services can impede the performance of others. For example, harvesting mangroves for wood reduces their population and impairs their ability to provide regulatory services such as wave attenuation and waste assimilation. This is crucial to consider when assessing the different benefits, especially over time, because not all services can be beneficial simultaneously.

Determining beneficiaries for each benefit varies significantly depending on the location. In smaller island nations, businesses such as resorts and restaurants are often locally owned, directly benefiting the local population. In contrast, in developing countries where many amenities and businesses are owned by large chain companies or foreign entities, there can be dissatisfaction regarding the equitable distribution of benefits among local communities. Encouraging fair agreements between foreign owners and locals could ensure that benefits are shared more equitably within these communities.

Additionally, this study showed that quantifying many cultural services remains complex. While methods like contingent valuation or the WTP approach can effectively assign values, they often introduce significant uncertainties because stated preferences may not align with actual behaviour. In contrast, services such as paid recreation and amenities like hotels can be more accurately quantified using revealed data, market prices, and travel costs.

The challenge of accurately valuing these services can lead to resistance from investors considering alternatives that include NbS. Nonetheless, the conservation of ecosystems and hence biodiversity plays a crucial role in human well-being. Despite there not being precise monetary values to certain services, the awareness that NbS promote happiness, health, tranquillity, mindfulness, thrill, a sense of belonging and more among people, should suffice to consider NbS as an alternative with manifold benefits.

7. Conclusion

The inventory of ecosystem services provided by mangroves and coral reefs, as presented in this research, offers a valuable synthesis of their socio-economic benefits as NbS for coastal protection and provisioning for coastal populations. This conclusion encapsulates the primary findings of the study by addressing key research questions.

The first main question explored was "What are the ecosystem services of mangroves and coral reefs?" This investigation categorised regulatory, provisioning, and cultural services according to the CICES, the MEA, and the TEEB. The identification process traced these services from ecosystem functions, ecosystem services and to the final welfare impacts on humans. This systematic review highlighted the overlaps and links in services that lead to one another and prevent double counting.

The second main question formulated was "What are the socio-economic benefits, in monetary value where possible, of mangrove and coral reef ecosystems?". This question focused on Eastern Africa and Southeast Asia, utilising specific case studies and regional research to quantify and value these services through various valuation methods. The research revealed several gaps in quantification and valuation, highlighting areas needing further studies and investigation.

The third question, "Who are the beneficiaries (stakeholders)?", went hand in hand with the second question. Through literature reviews and case studies, the study identified beneficiaries of these services and linked them to their respective end benefits.

The fourth and final research question formulated, "How can the monetised socio-economic benefits of mangrove and coral reef ecosystems be integrated into a SCBA?". Recommendations elaborated on how these results can be applied in future projects considering NbS for coastal protection, emphasising their multifaceted benefits that traditional engineered solutions can not replicate.

Overall, this research provides a comprehensive understanding of the ecosystem services and socio-economic benefits of mangroves and coral reefs, offering insights crucial for informed decision-making and sustainable coastal management.

8. Recommendations

To apply the results of this study in future projects for different regions and countries, the first step involves identifying similar ecosystems within those areas. Secondly, a contextual analysis should then be conducted to understand the local environment. Additionally, adjusting for present-day values involves considering factors such as price indices, inflation rates, and currency exchange rates.

While this overview highlights many common services provided by mangroves and coral reefs, it is important to recognise that each region may have unreported benefits that require identification, assessment, and quantification. This underscores the need for stakeholder involvement in future projects. Local inhabitants possess invaluable knowledge about the functions and services of coastal ecosystems and are best positioned to contribute to their conservation, preservation, and restoration efforts. Their insights can inform decision-makers, designers, and project engineers regarding their preferences, concerns, and perspectives.

Once all ecosystem services are identified, analysts can employ benefit transfer methods using literature and research findings from studies on similar ecosystems to determine economic values. It is crucial to align these values and quantifications with local policies and management frameworks to ensure relevance and legitimacy. Emphasising sustainable management of these ecosystems is vital for the success of NbS projects. Finally, documenting and reporting these processes and keeping stakeholders informed throughout are essential steps. Local stakeholders often play a key role in maintaining ecosystems effectively.

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10. Appendices

Appendix A: Damage functions per land use/damage class for Africa and Asia

(Huizinga et al., 2017)

Residential & content

Africa

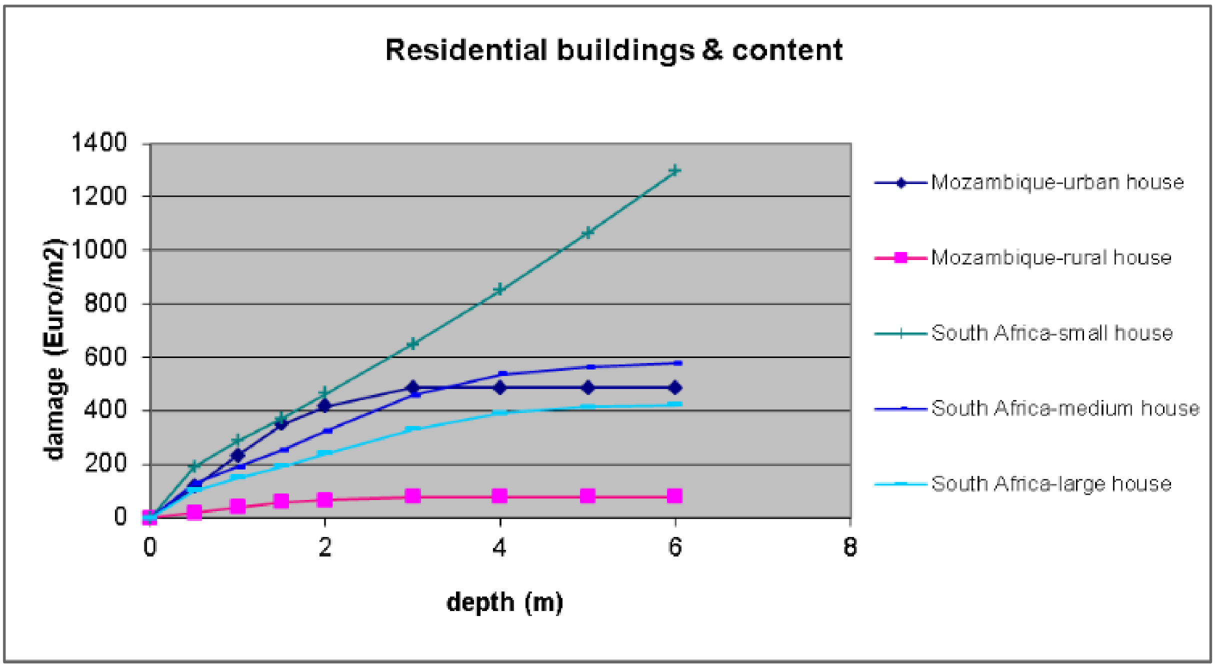

Figure 10.1: Residential buildings and content damage per square meter in Africa

Asia

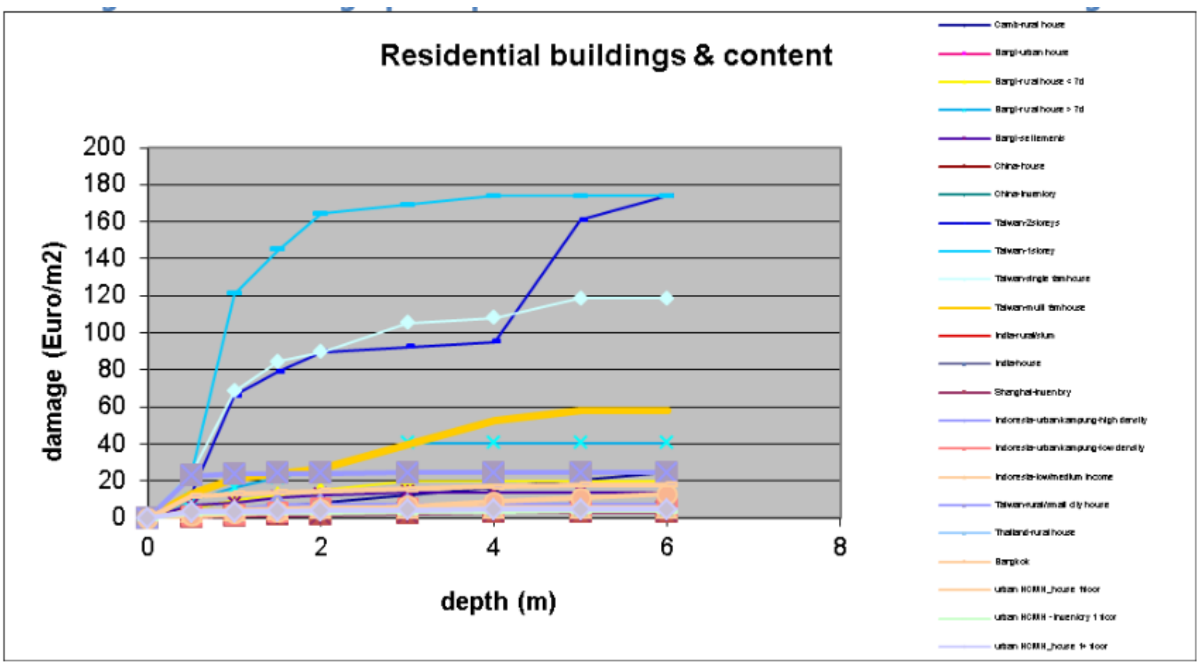

Figure 10.2: Residential buildings and content damage per square meter in Asia.

Commerce

Africa: There is no data available to produce a commerce damage function for Africa (Huizinga et al., 2017).

Asia

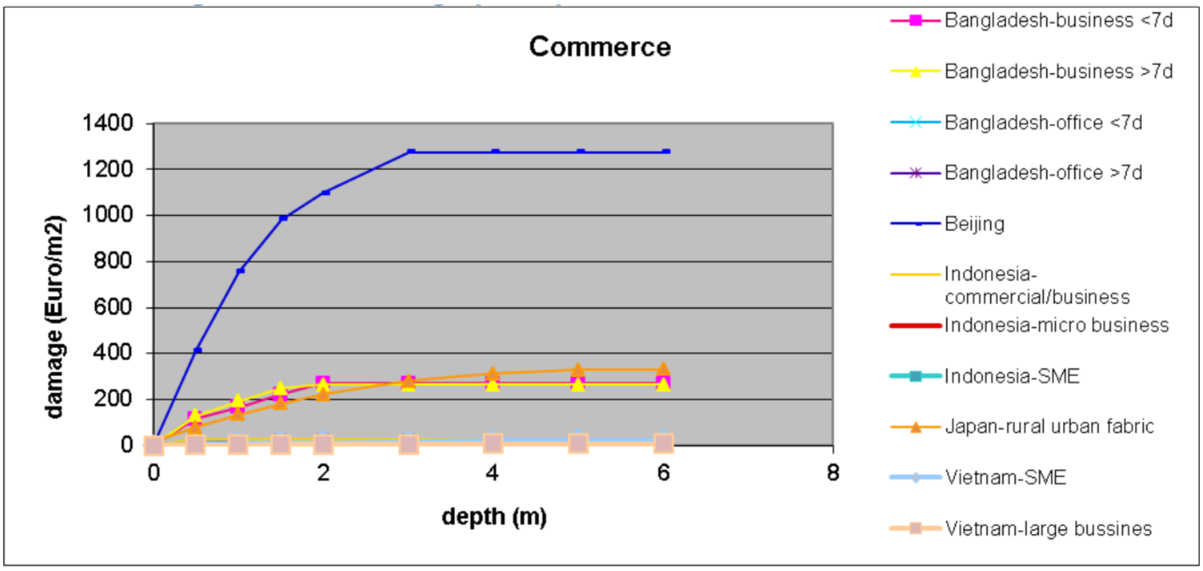

Figure 10.3: Commerce damage per square meter in Asia.

Industry

Africa

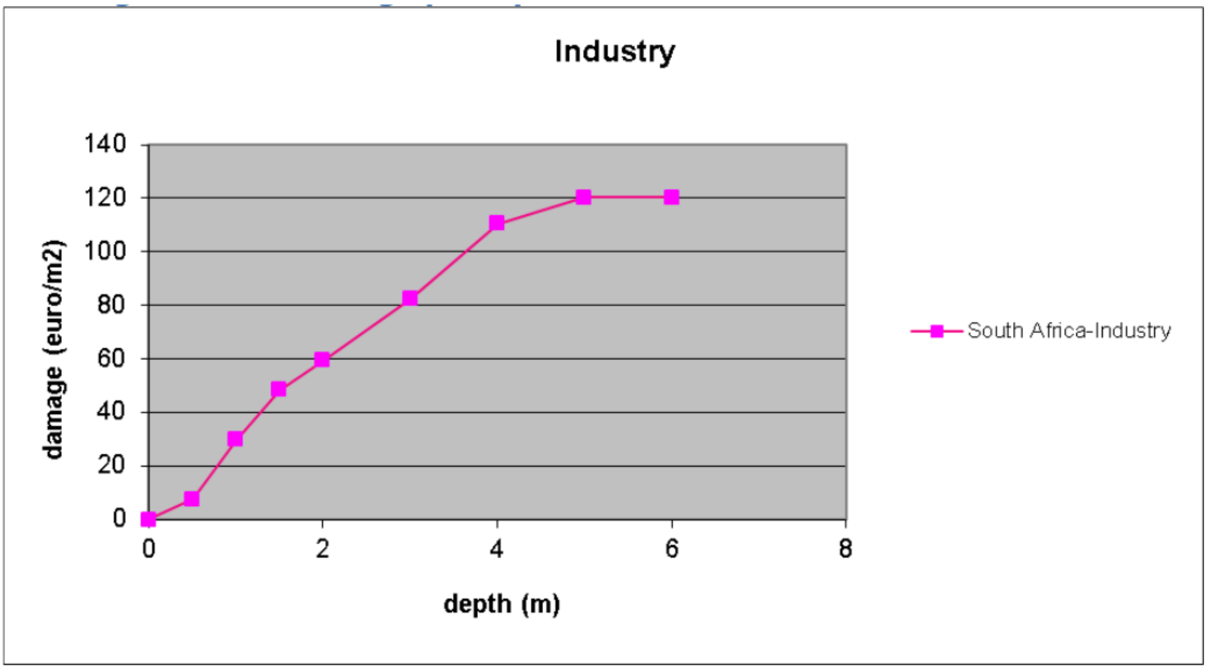

Figure 10.4: Industry damage per square meter in Africa

Asia

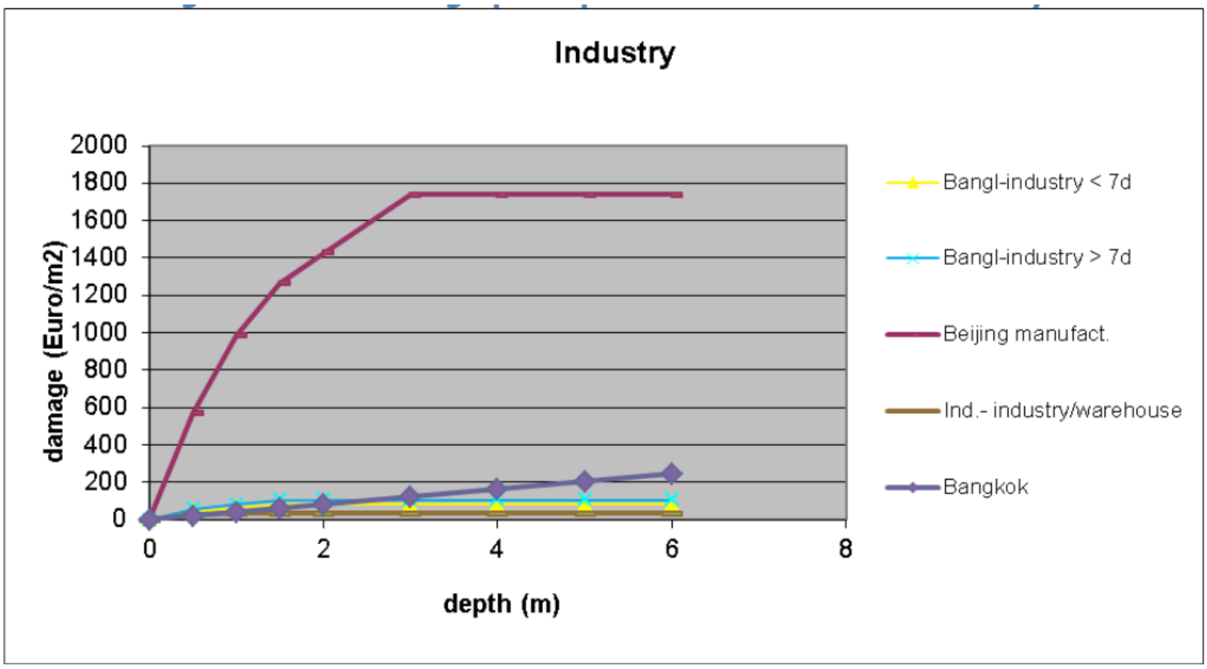

Figure 10.5: Industry damage per square meter in Asia.

<u>Transport</u>

Africa: There is no data available to produce a transport damage function for Africa (Huizinga et al., 2017).

Asia

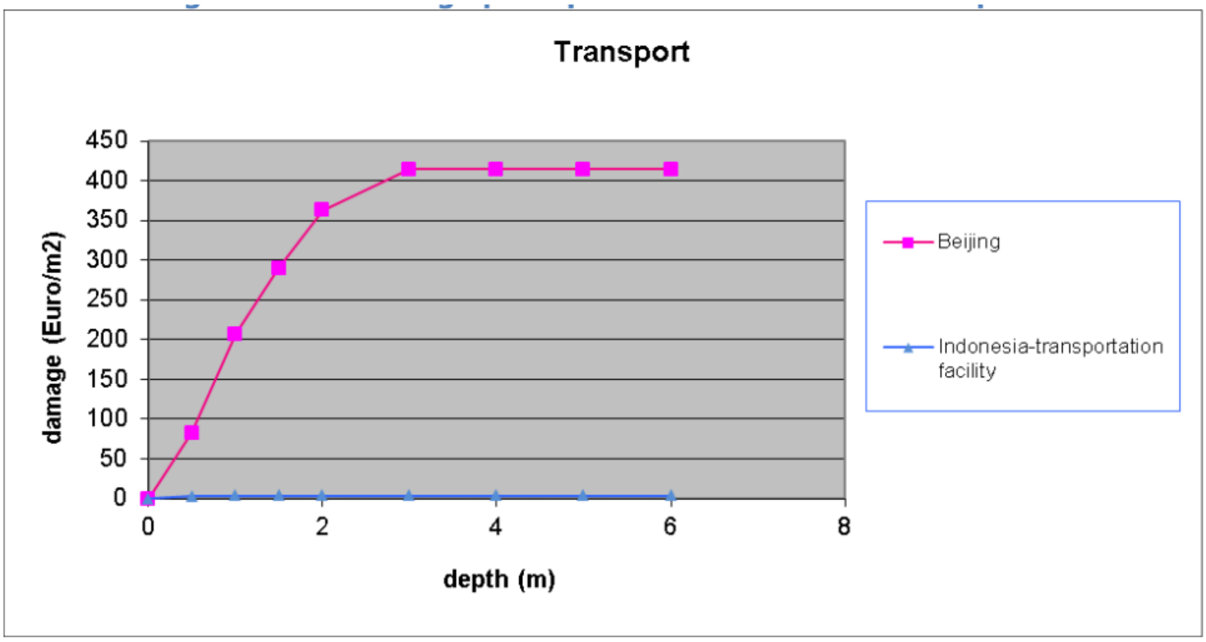

Figure 10.6: Transport damage per square meter in Asia.

Agriculture

Africa: There is no data available to produce an infrastructure damage function for Africa. Reported maximum damages for Mozambique were repair costs for national roads 1069 €/m (price year 2010) and repair costs for national railways 203 €/m (price year 2010) (Huizinga et al., 2017).

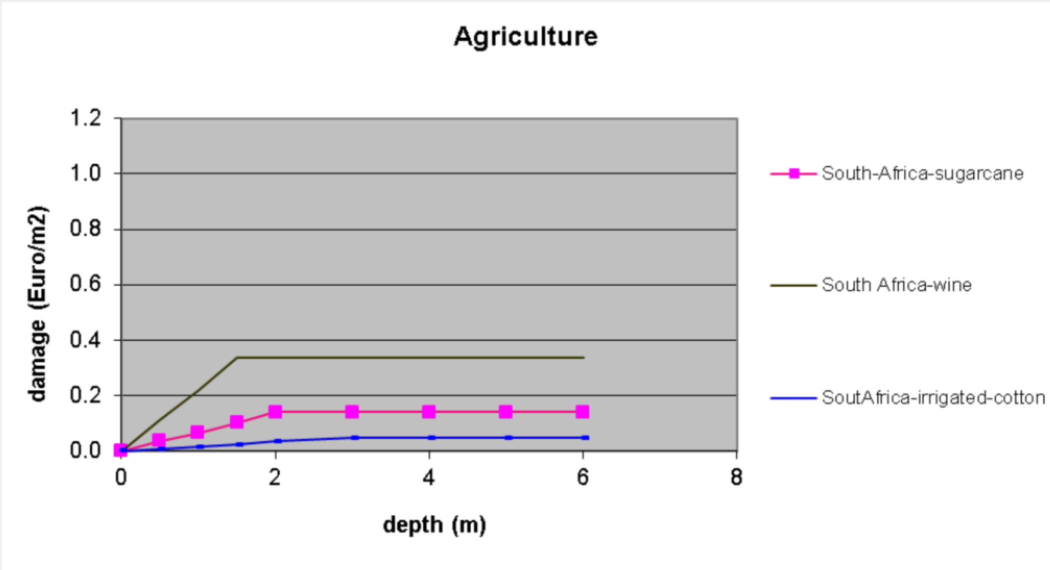

Figure 10.7: Agriculture damage per square meter in Africa.

Asia: Data only found for Vietnam and Bangladesh, where the cost per meter road is reported to be 1€/m and repair costs per meter of road in Bangladesh are about 10€/m, respectively. The calculated average value for Asia was 17€/m (Huizinga et al., 2017).

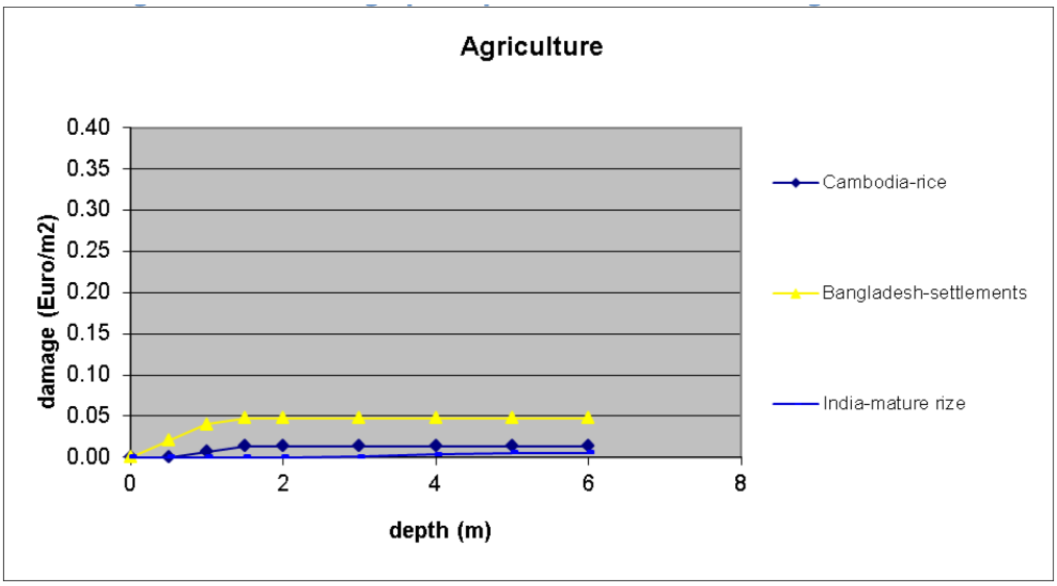

Figure 10.9: Agriculture damage per square meter in Asia.

Appendix B: Study on wind-attenuation capacities of mangroves

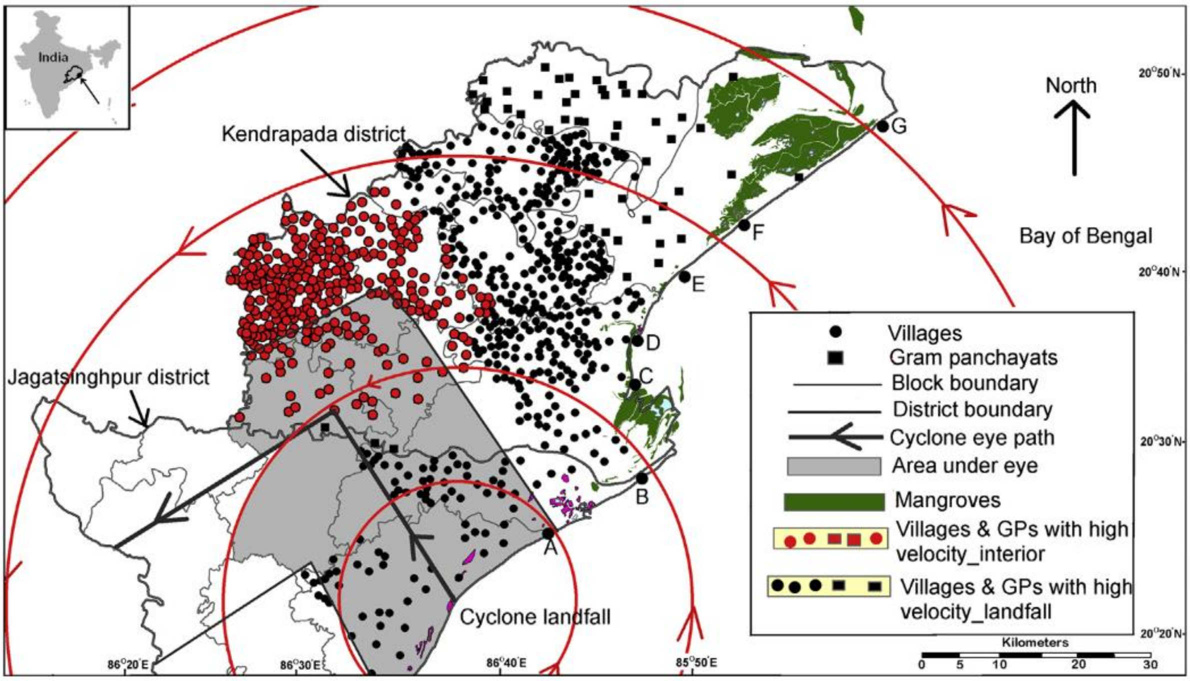

Figure 10.10: Villages and areas under cyclone eye and presence of mangroves studied in Odisha, India. Retrieved from *(Das & Crépin, 2013)*

Radial distance from the landfall (km)	Expected house damage (%)		Average mangrove width (km)	Actual average house damage per village (FC/Adult males) (%)			
	$\rho = 1.5$	$\rho = 2$		Villages within 10 km from coast	Villages within 10–20 km from coast	Villages within 20–30 km from coast	Villages within 30–40 km from coast
15.1–25.5	>65	>56.4	0	110[a]	95.5	81	No village
25.5–28	59.9–65	50.5–56.3	0	65	51.5	No village	No village
28–34.5	49.5–59.8	39.1–50.4	0	88.1	41.6	55.6	No village
			1.36	71	46.8	37.7	31
34.5–41	42.5–49.4	32–39	0	No village	No village	No village	No village
			2.61	48.7	43.2	39	No village
41–50	35.5–42.4	25.1–31.9	0	33.9	21	16.8	No village
			0.48	37.5	30	21	No village
50–59	30.4–35.4	20.5–25	0	17.9	13	9	13
			0.44	7.3	7.4	12.7	15.3
59–82	23.1–30.3	14.1–20.4	0	18.6	No village	No village	No village
			1.86	8.7	7.1	5.6	7.7

Figure 10.11: House damage in villages of storm eye wall area lying within different bandwidths from landfall point of cyclone to coastline. Retrieved from (Das & Crépin, 2013)