# An Examination of Nature-based Solutions for Coastal Adaptation in Southern Sweden

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Abstract

While grey infrastructure, such as sea walls, have been the traditional method of mitigating coastal hazards there has been an increasing interest in adapting using natural processes, known as Nature-based Solutions (NbS). As with most places in the world, southern Sweden is facing an increase in coastal hazards due to climate change related sea level rise. There is a need to understand the utility of NbS for coastal adaptation in areas such as southern Sweden. To this end, an adapted systematic review of relevant academic literature was conducted along with interviews with key stakeholders for the southern Swedish town of Halmstad. A variety of themes about NbS emerged from the literature. This included: capacity for risk reduction, time and space scale considerations, flexibility provided by self-adapting and self-repairing capacities, common regulating, cultural, and provisioning ecosystem services, public perceptions, connection to equity, direct and indirect costs, design consideration, and the most common challenges NbS face. Similarly, themes emerged from the interviews about the Swedish context. These included: ecosystem services applicable to Halmstad, Swedish perspectives of NbS, costs, data gap challenges, and the Swedish regulatory framework for coastal adaptation. Within these topics, ran the theme that all these characteristics have context specific qualities. There are many challenges in the implementation of NbS. Significantly, they are best implemented using a holistic approach, which is difficult to achieve. Overall, NbS are well worth pursuing, as they offer multiple benefits and flexibility as adaptation measures.

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## Summary

By the end of the century, coastal flooding is projected to cost €210 billion and affect 1.6-3.9 million EU citizens annually if no adaptation measures are taken (Vousdoukas et al., 2020). In Sweden, eight percent of residences are within three kilometers of the coast and five meters of current mean sea level (Riksbanken, 2020). Sweden's coastline is highly important for economic purposes and leisure activities. However, in the northern portion of the country, land uplift from glacial rebound offsets climate change-related sea level rise. The southern portion of the country is experiencing sea level rise, which is leading to an increase in coastal hazards, such as flooding and erosion, making coastal adaptation a necessity. Halmstad is one such town experiencing an increase in exposure to hazards. While throughout the world adaptation has traditionally been done by hardening the coastline with grey infrastructure measures, like sea walls, there is growing interest in using natural processes for adaptation. This type of measure is widely referred to as Nature-based Solutions (NbS).

NbS is an umbrella concept referring to using natural phenomena to solve societal challenges. These can be used for a myriad of objectives, provided through ecosystem services including disaster risk reduction. This thesis explores the holistic utility of NbS for adapting to and mitigating coastal hazards in southern Sweden. To achieve this, the study used a mixed-methods approach consisting of a review of relevant academic literature along with interviews with key stakeholders. The contents of the literature and interviews were coded into themes and then synthesized to address the research purpose.

The main themes that emerged about NbS from these methods were: capacity for hazard risk reduction, the time and space scale considerations, their flexibility, common regulating ecosystem services, common cultural ecosystem services, common provisioning ecosystem services, public perceptions, how NbS is tied to social equity, direct and indirect costs, design considerations, the Swedish regulatory framework for coastal adaptation and the most common challenges NbS face.

Coastal NbS can reduce risk related to flooding and erosion. While uncertainty remains related to the amount of hazard reduction each type of NbS can provide, studies indicate that NbS can provide as much, and sometimes even more, protection than grey infrastructure. However, it takes years or even decades for NbS to establish enough to reach their full protection potential. Another scale consideration is that NbS take significant space to implement, which can be challenging in dense areas. Additionally, the protection benefits are experienced by the region, not just the community impacted by the land allocation and use decisions for the NbS.

One of the biggest benefits of NbS compared to grey infrastructure is their increased flexibility, which is particularly useful when designing adaptation measures under the current uncertainty related to degree of impacts under climate change. NbS can self-adapt to changing conditions, meaning they can provide more protection as sea levels increase. Additionally, NbS have some capacity for self-repair. While useful, this can take significant time, meaning supplemental repair may still be desirable.

Another highly desirable characteristic of NbS is that they are not single purpose, but instead provide multiple benefits through their ecosystem services. The ecosystem services most often described in the literature, other than risk reduction, were carbon mitigation (regulating

service), recreation and tourism (cultural service), and support wildlife/biodiversity (provisioning service).

Stakeholder engagement is beneficial to the success of NbS projects, as is the public's acceptance. There is a positive correlation between an individual's risk perception and the probability of an adaptive measure being implemented. Once an adaptation measure is implemented, it gives a sense of increased security. This sense of security can stimulate additional development in high-risk areas, thus overall increasing the vulnerability of the community instead of decreasing the community's risk.

NbS, and the way benefits are distributed, is tied to equity in a community. Benefits may not be equitably distributed, and the adaptation measure may not be overall positive for everyone. Equity is currently only considered at a surface level by many Swedish agencies. There are various frameworks that these agencies can use to better include social justice concerns in their projects, which include suggestions such as broadening participation and focusing on areas with low institutional capacity. The current separatory approach and lack of data can be addressed through additional agency collaboration and knowledge sharing programs.

Cost is another consideration for agencies deciding on adaptation measures. NbS are generally financially cheaper than grey infrastructure. Additionally, they avoid many of the indirect costs of grey infrastructure, such as erosion and aesthetics. The costs of NbS are highly dependent on context specific factors, such as the initial state of the ecosystem and local labor costs.

In designing NbS, considering the local context is necessary. Part of this is considering what benefits are the most important to the local community. While multiple benefits are attainable from a single project, there are tradeoffs between benefits. Thus, it is important to ensure you are optimizing the benefits most important to the specific community. These multiple benefits, and the complexity of the intersection of ecology and risk means NbS is best implemented using a transdisciplinary approach. Despite this, most studies are focused on a single discipline.

Additionally, the separation between government agencies and research departments makes using a transdisciplinary approach difficult. The Swedish coastal regulatory framework is highly flexible, but lacks an incentive structure and is time consuming. Additionally, there is a mismatch between the law, which puts adaptation responsibility onto the homeowners, and inhabitants who expect the municipality to be responsible.

There are additional challenges that are true in Sweden and the larger context. One of the most common challenges was a lack of data, due to the field being new. Additionally, climate change itself poses a data challenge for NbS. There remains uncertainty about how ecosystems will respond to climate change. For example, drought and high temperatures can lead to dune vegetation dying, which will reduce their effectiveness for risk reduction.

# List of Abbreviations

| | |
|---|---|
| CBA | Cost Benefit Analysis |
| CPI | Consumer Price Index |
| DOI | Digital Object Identifiers |
| EU | European Union |
| IUCN | International Union for Conservation of Nature |
| O&M | Operation and Maintenance |
| NbS | Nature-based Solutions |
| SEPA | Swedish Environmental Protection Agency (Naturvårdsverket) |
| SGI | Swedish Geotechnical Institute (Statens Geotenkniska Institut) |
| US | United States |

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# 1. Introduction

Coastal areas are important. In the European Union (EU), the coasts contain a higher proportion of the population (21%) than correlates to the proportion of land area (15%) (Jarratt & Davies, 2020). As a result, there is a high density of infrastructure in coastal areas. Consequently, “[t]he economic value of coastal areas within 500 meters from the European seas totals between €500-1 000 billion” (European Commission, n.d.). Much of this infrastructure is related to the tourist sector (Jarratt & Davies, 2020). Coastal areas host over 50% of total EU hotel bed capacity, making tourism the biggest employer in coastal areas (Jarratt & Davies, 2020).

At the same time, climate change poses a significant risk for coastal areas (Galgoczi, 2017). Europe is facing as much as a meter or more of extreme sea level rise by the end of the century (Vousdoukas et al., 2020). Coastal flooding currently costs €1.4 billion per year (2015 values) and affects an average of 100 000 EU citizens annually (Vousdoukas et al., 2020). Without adaptation, those costs are projected to grow to €210 billion by the end of the century and affect 1.6-3.9 million EU citizens annually (Vousdoukas et al., 2020).

All EU countries with a coastline are projected to experience an increase in coastal flood risk (Vousdoukas et al., 2020). Both the high importance of coastal areas and their increasing risk to sea level rise hold true in Sweden; 8% of homes are within 3 kilometers of the coast within 5 meters of current mean sea level (Riksbanken, 2020). However, postglacial rebound means that land rise in the central and northern portions of the country compensates for some of the sea level rise, thus dampening the effects (SEPA, 2017). However, land rise in the south is very small and thus the shoreline will still experience global sea level rise effects, Figure 1 (SEPA, 2017). Due to sea level rise, southern Sweden is facing substantial increases in erosion and flooding (SEPA, 2017).

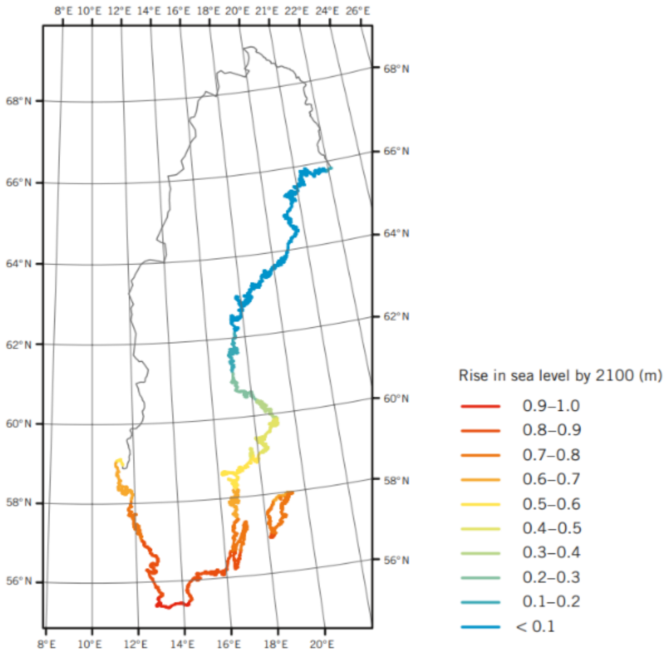


*Figure 1: Net uplift minus sea level rise under a 1 meter rise in sea level (SEPA, 2014, p. 17)*

While coastal challenges are relatively minor in Sweden, they are still important for safeguarding the 82% of the population and their infrastructure who live in coastal regions (RISC-KIT, 2017). This thesis looks closer at the city of Halmstad, which at the time this thesis was written, was in the process of planning for new adaptation measures in its coastal zone.

Traditionally, grey infrastructure, such as sea walls, have been the main means for dealing with coastal floods. However, there is growing recognition that natural systems can be adapted to provide coastal protection, along with other co-benefits (European Environment Agency, 2021). This type of nature-inspired measure is generally referred to as Nature-based Solutions (NbS). In the past five years, there has been a significant increase in the literature about NbS and is projected to continue to grow (Li et al., 2021). In Sweden, there is growing interest in NbS, as shown by the creation of the Swedish Geologic Institute (SGI) catalog of NbS (SGI, 2021), and the 2021 publication by the Swedish Environment Protection Agency (SEPA) of a Nature-based Solutions Report (SEPA, 2021). Despite this, there remain many research gaps about NbS (Barquet et al., 2021).

## *1.1. Research Purpose*

The aim of this thesis is to holistically explore the utility of Nature-based Solutions (NbS) for coastal hazard mitigation in southern Sweden and similar contexts. Since NbS are highly context dependent, this study is based on contexts relevant to southern Sweden, but many of the results are relevant in wider contexts.

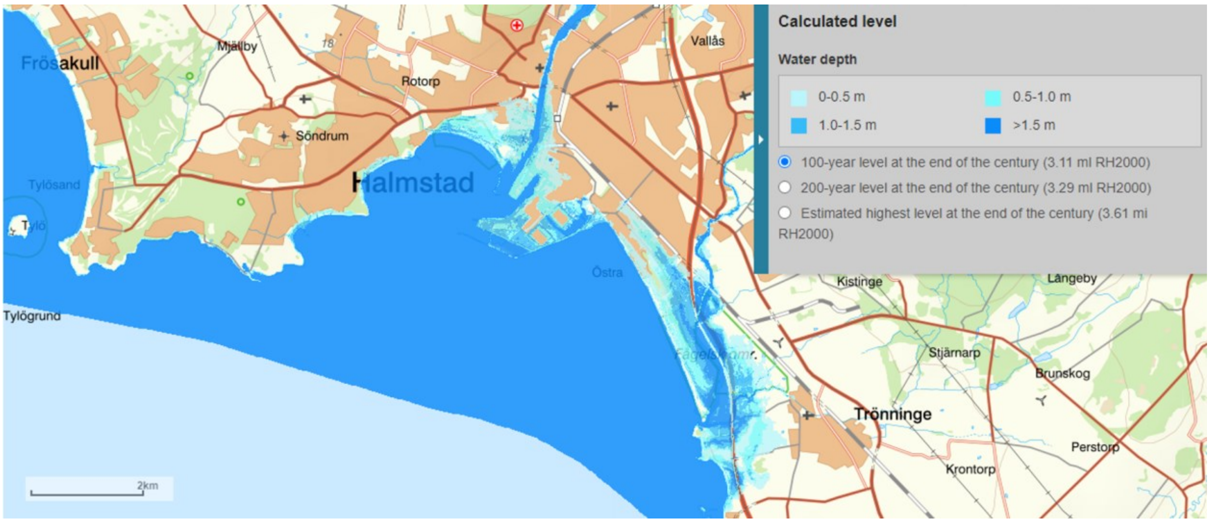
## *1.2. Halmstad Context*

*Figure 2: Context Map for Halmstad Adapted from Lantmäteriet (2020)*

The municipality of Halmstad is in Halland County in southwestern Sweden, as shown on Figure 2. The city of Halmstad's population has just over 70 000 residents (Statistikmyndigheten SCB, 2019). The beach town is "widely known as one of Sweden's biggest tourist destinations" and thousands of tourists visit it every summer (Halmstad, 2019). The tourist industry is so important to Halmstad that the Environmental Code has a provision about the necessity of giving tourism and outdoor life special consideration along all of Halland's coast (Halmstad, 2018).

Halmstad is one of the biggest timber export ports in the country and has a university with 11 500 students, which are also important components of the economy (Halmstad, 2019). The largest employers are the municipality and the county (Halmstad, 2019). Halland has the highest rate of employment in Sweden (Halland, 2020). Since 1970, its population has grown at twice the average rate for Sweden. In 2019, it had the third largest population increase in the county (Halland, 2020).

Due to climate change and rising sea levels, Halmstad is expected to face increased risk of floods, erosion, and heat waves (Halmstad, 2018). Halmstad has a local effect that causes sharply raised local water levels, making water levels 50-100 centimeters higher in Halmstad compared to nearby west coast towns (SMHI, 2018). This makes Halmstad particularly exposed to high water levels during extreme weather and wind (Halmstad, 2018). Figure 3 shows flood depths during a 100-year event under future climate projections. Water levels in Halmstad are predicted to be 3.11 meters higher than the reference height from the year 2000 during such an event (MSB, 2018).



● 100-year level at the end of the century (3.11 ml RH2000)
○ 200-year level at the end of the century (3.29 ml RH2000)
○ Estimated highest level at the end of the century (3.61 ml RH2000)

*Figure 3: Predicted coastal flooding in Halmstad (MSB, 2018)*

## 2. Conceptual Background: Overview of NbS

NbS is an umbrella term for many different types of projects, of which disaster risk reduction is simply one type (European Environment Agency, 2021). Figure 4 shows the different purposes NbS can be harnessed for. In 2008, the World Bank first mentioned the term NbS (Barquet et al., 2021). The International Union for Conservation of Nature (IUCN) started promoting the concept the following year (Cohen-Shacham et al., 2016). Their definition has been widely adopted and is as follows: "[a]ctions to protect, sustainably manage and restore natural or modified ecosystems that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits" (Cohen-Shacham et al., 2016, p. 2). Since then, the concept of NbS has been widely adopted in research (Li et al., 2021) and policy (PEDRR & FEBA, 2020).

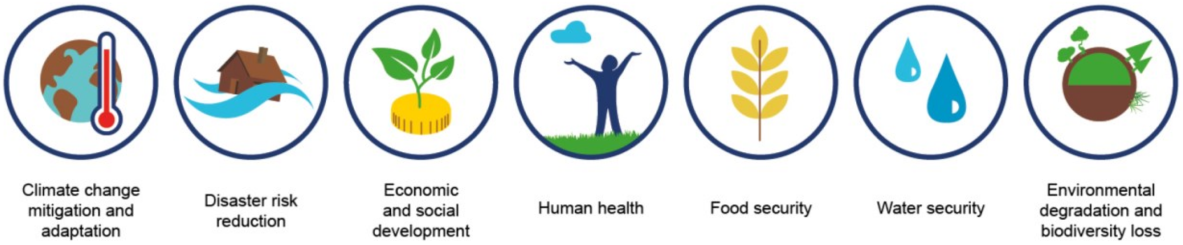


*Figure 4: Overview of the uses of NbS (IUCN, 2020)*

Another important actor behind the mainstreaming of the concept is the EU, which defines NbS as: "solutions to societal challenges that are inspired and supported by nature, which are cost-effective, simultaneously provide environmental, social and economic benefits and help build resilience" (European Environment Agency, 2021, p. 17). While both the IUCN and EU highlight the importance of NbS for addressing environmental and societal challenges, the EU's definition has a stronger emphasis on the economic co-benefits from NbS.

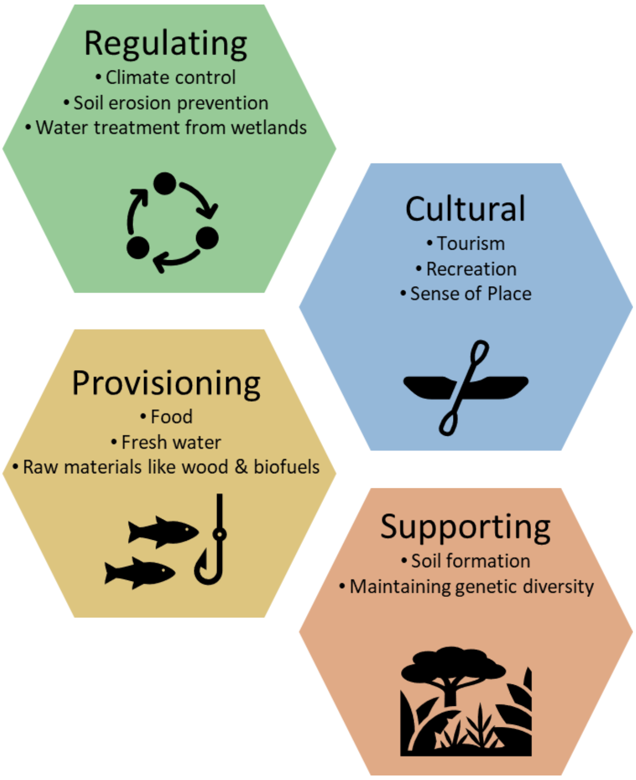


*Figure 5: Ecosystem Services Examples Adapted from AECOM, n.d.*

A common trait across the different conceptualizations of NbS is their importance for the provision of ecosystem services, which are "the benefits people derive from ecosystems" (Millennium Ecosystem Assessment, 2005). There are four categories of these services, as presented in Figure 5: regulating, cultural, provisioning, and supporting (Millennium Ecosystem Assessment, 2005). As defined by FAO (n.d.): regulating services are benefits that provide moderation, such as air quality improvement and flood reduction; cultural services are benefits that are non-material, such as aesthetics, education, and cultural identity; provisioning services are benefits that are material, such as food, wood and water; and supporting services are the services that are necessary to support the other types of services, such as maintaining genetic diversity. Because of their indirect impact on human systems, supporting services are rarely emphasized in designing of NbS. Thus, for the purposes of designed NbS, the focus is on regulating, cultural, and provisioning ecosystem services.

The focus of this study is NbS for disaster risk reduction, climate change adaptation. Climate change adaptation is “the process of adjustment to actual or expected climate and its effects, in order to moderate harm or exploit beneficial opportunities” (IPCC et al., 2018, p. 542) and disaster risk reduction is “[t]he concept and practice of reducing disaster risks through systematic efforts to analyse and manage the causal factors of disasters, including through reducing exposure to hazards, lessening vulnerability of people and property, wise management of land and the environment, and improving preparedness for adverse events” (Alcayna, 2020, p. 6). Before the term NbS became mainstream, there were other terms used to refer to the use of natural systems to provide these services. For coastal disaster mitigation, these terms include green infrastructure, blue infrastructure, blue-green infrastructure, ecosystem-based adaptation, and ecosystem-based disaster risk reduction. There are a variety of different measures used to coastal adaptation for disaster risk reduction. Traditional engineered measures, or grey infrastructure, include dikes, seawalls, waterproofing homes, and raising infrastructure. NbS measures include wetlands, shellfish reefs, seagrass, and sand dunes.

# 3. Methodology

## *3.1. Literature Review*

The methodology used was an adapted version of a systematic review. Systematic reviews serve to reduce bias, limit subjectivity, and increase transparency (Haddaway et al., 2015). They have their roots in medical science, where they became popular in the 1990s (Dawkins et al., 2019); the approach started being adapted into the Conservation field in 2006 (Haddaway et al., 2015). Berrang-Ford et al. (2015) has called for systematic reviews to be used more widely in evaluating adaptation measures:

> the adaptation literature is arguably in greater need of systematic synthesis of existing knowledge if we are to document if adaptation is taking place and respond to areas of highest impact and/or vulnerability, evaluate whether adaptation support is translating into actions, facilitate comparison of adaptations across regions and sectors, ensure resources are being appropriately invested, and inform governance systems on the current status and gaps in adaptation action. (p. 756)

The methodology in this literature review was adapted to fit the scope and time delimitations. The methodological approach consisted of the following steps, adapted from Berrang-Ford et al. (2015), Dawkins et al. (2019), and (Aall et al., 2020) which are described in more detail below:

1. Establish research purpose and method plan
2. Search strategy
3. Evaluate relevance against established criteria
4. Code selected documents

First, search terms were developed with the aim of addressing the research purpose described in the Research Purpose section. Key concepts were identified as being a necessary part of the search string to limit the results while capturing papers that were relevant to the study. The five parts of the search term include 1) location (e.g. coastline); 2) type (e.g. nature-based); 3) adaptation; 4) costs and benefits; and 5) the hazard being solved (e.g. flood). These terms and their synonyms were then combined to create a search string. Before being finalized, the search string was tested in Web of Science database. This test compared several search strings with slight differences to ensure that the papers being returned were relevant and comprehensive. For example, (Coast* OR Shoreline) AND (Nature Based OR Natur* OR Green) AND (Adaptation* OR Measure* OR Solution* OR Engineering OR Protection OR infrastructure) AND (Cost OR Benefit OR Economic OR Effectiv*) AND (Hazard OR Flood OR Erosion OR Risk) returned 754 results. Changes between this search string and the final search string reduced this to 155 results. From a scan of the articles, these extra results were not relevant compared to the final search term. The final search string is:

*Search string:* (Nature Based OR Nature-Based OR Green OR Blue OR hybrid) AND (Adaptation* OR Measure* OR Solution* OR Engineering OR Protection OR Mitigation) AND (Cost OR Benefit OR Economic) AND (Coast* OR Shoreline) AND (Flood OR Erosion OR Sea Level Rise)

Once the search string was determined, it was used in two databases: Scopus and Web of Science. The purpose of using two databases was to reduce bias that may occur within an individual database (Haddaway et al., 2015). While traditionally robust systematic review use five to ten academic databases, research has shown that using more than two to three may have little additional benefit (Haddaway et al., 2015).

The search was limited to documents in English published within the last five years (2017-2021).

The Web of Science database had 155 results and Scopus had 53 results. The two sets of results were compared using original code in Excel's visual basic applications (VBA) to compare article digital object identifiers (DOIs) to remove duplicates. Articles that did not provide DOIs were compared manually to remove duplicates.

Once duplicates were removed, the titles and abstracts of articles were screened to ensure they meet the following eligibility criteria. Due to limited literature that is Sweden specific, the literature review is applicable to not only Sweden, but also a broader context. However, given that context is a significant part of how a society experiences the benefits and tradeoffs of NbS, papers had to be set in a context that was applicable to Sweden. Similarly, the measure had to be one with some potential to be used in Sweden. A wide range of solutions were included under this criterion, however some measures were excluded, such as mangroves which cannot grow in Sweden. Following the scope of the project, the focus was on coastal protection; therefore papers that focused on protection from other hazards, such as stormwater management were removed. Likewise, the focus was on a physical measure, not policy or a framework. Additionally, the focus of the measure(s) was climate adaptation, not mitigation. A schematic view of the documents at each stage of the process is presented below in Figure 6. The documents selected for analysis are presented in Appendix A.

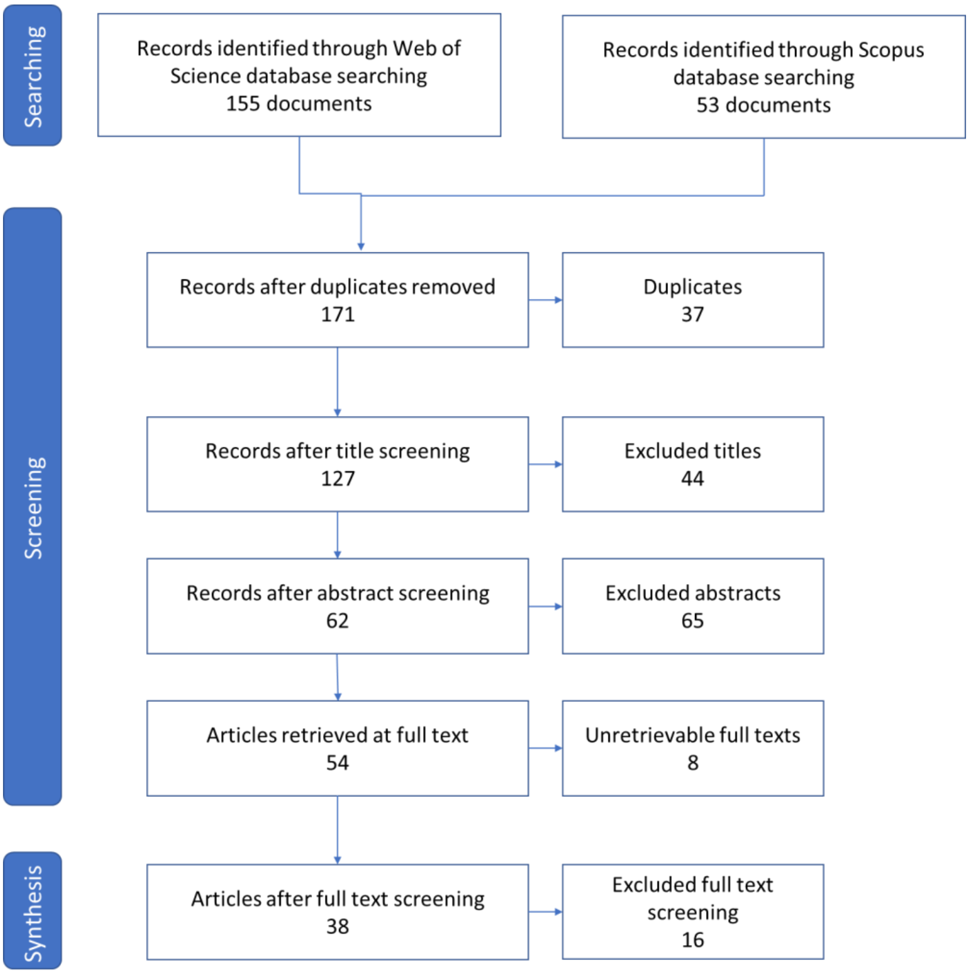


*Figure 6: Results of the document selection process. Adapted from Haddaway et al. (2018)*

After the documents were selected for analysis, their contents were coded into themes that were deduced from the literature. The results of the coding were then synthesized to address the research purpose.

### *3.2. Interviews*

In addition to the literature review, interviews were conducted with a variety of key stakeholders for Halmstad. Interviews were used in addition to the literature review because interviews are useful for filling knowledge gaps, particularly gaps that include complex behaviors (Young et al., 2018). Since there is very little peer review literature about NbS in Sweden, interviews were used to fill this knowledge gap. The interviews served to supplement the literature review by contextualizing coastal adaptation strategies into the local context as well as to provide expert insight.

A semi-structured approach was used with pre-generated interview guides. Questions were based on the major themes that emerged from the literature. They were developed after the literature was coded, but before it was fully analyzed. Questions were also tailored to each interviewee, to capture their perspective on the various costs, benefits, and challenges facing Sweden, with a focus on the project's case study – Halmstad. These interview guides can be found in Appendix B. The semi-structured style increases the ability of the interviewees to shape the discussion, thus reducing the influence of pre-conceived biases of the interviewer compared to a fully structured interview (Young et al., 2018).

Interviews were conducted with a variety of key stakeholders who were selected to provide viewpoints from a broad range of experiences and, based on one of the sampling techniques by Young et al. (2018), for being knowledgeable. An initial stakeholder mapping was carried out based on two tracks: the first track followed the list of stakeholders previously mapped in the project associated with the thesis – HydroHazards. The second track was through the network of experts associated with the faculty. In both tracks, an iterative approach was applied whereby one expert recommended a new informant. The list of informants was discussed with staff from the project to ensure accuracy and objectivity. The stakeholders interviewed included three local researchers, two engineering consultants, two municipal employees, and three national government employees.

Due to the prevailing situation at the time with the Covid-19 pandemic, interviews were conducted over video conferences, using either Zoom or Microsoft Teams. These interviews were recorded and transcribed using Otter software. After transcription, the interviews were coded into the themes using Nvivo software. The coding themes emerged from the questions asked and the information the interviewees shared. The results of the coding were then synthesized.

# 4. Results

## 4.1. Overview of the Literature

The literature included in the review was coded into thematic areas. The articles that refer to each thematic area are presented in Table 1, on page 11.

### *4.1.1. Description of Selected Documents*

The 38 documents reviewed are a mixture of real-world analysis, including case studies, and simulations/modeling. As shown on Figure 7, the papers covered a variety of different adaptation measures, including wetlands/marshes, dunes/beach nourishment, shellfish and coral reefs, and kelp/aquaculture. Fourteen of the articles covered multiple measures. Five articles did not address any particular measure, instead referring to coastal adaptation and NbS in more general terms.

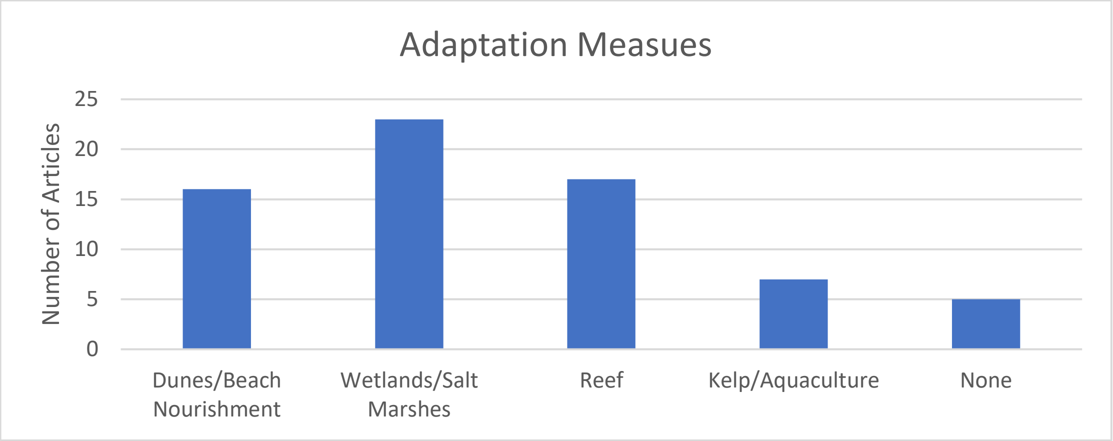


*Figure 7: Adaptation Measures Represented in Articles*

The reviewed articles were associated with 59 different locations (many articles had multiple locations). Article locations were defined by the authors and downloaded from their respective databases. Due to the scope of the project, most of the articles were associated with western countries. Twenty-six of these were associated with North America and twenty-five with Europe, as shown on Figure 8.

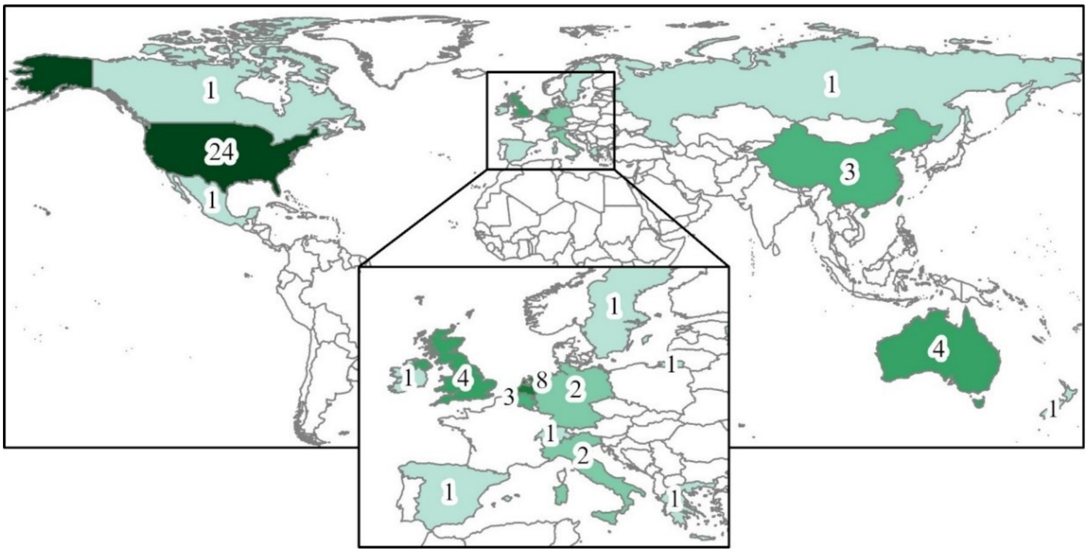


*Figure 8: Map of Article Locations (Esri, 2019)*

*Table 1: Literature by Thematic Area*

| ***Theme*** | ***Num.*** | ***Relevant Literature*** |
|---|---|---|
| Hazard Reduction | 30 | Almarshed et al., 2020; Arkema et al., 2017; Davlasheridze et al., 2019; Du et al., 2020; Fernández-Montblanc et al., 2020; Ghiasian et al., 2021; Griggs & Patsch, 2019; Harris & Ellis, 2020; Hobbie & Grimm, 2020; Lawrence et al., 2019; Moosavi, 2017b; Morris et al., 2018, 2019, 2019, 2020; Narayan et al., 2017; Nelson et al., 2020; Nordstrom, 2019; Odériz et al., 2020, 2020; Powell et al., 2019; Reguero et al., 2018; Ruckelshaus et al., 2020; Smith, 2017; Sutton-Grier et al., 2018; Sutton-Grier & Sandifer, 2019; Thorslund et al., 2017, 2017; Van Coppenolle & Temmerman, 2020; van Wesenbeeck et al., 2017; Vuik et al., 2019; Whelchel et al., 2018; L. Zhu et al., 2020; Z. Zhu et al., 2020 |
| Scale Considerations | 9 | Davlasheridze et al., 2019; Hobbie & Grimm, 2020; Moosavi, 2017b; Morris et al., 2018; Narayan et al., 2017; Nelson et al., 2020; Powell et al., 2019; Sutton-Grier et al., 2018; van Wesenbeeck et al., 2017 |
| Flexibility | 12 | Almarshed et al., 2020; Hobbie & Grimm, 2020; Morris et al., 2018, 2019, 2020; Nelson et al., 2020; Powell et al., 2019; Reguero et al., 2018; Van Coppenolle & Temmerman, 2020; van Wesenbeeck et al., 2017; Vuik et al., 2019; Whelchel et al., 2018 |
| Regulating | 18 | Arkema et al., 2017; Hobbie & Grimm, 2020; Jarratt & Davies, 2020; Kassakian et al., 2017; Kok et al., 2021; Morris et al., 2018; Narayan et al., 2017; Powell et al., 2019; Ruckelshaus et al., 2020; Sutton-Grier et al., 2018; Sutton-Grier & Sandifer, 2019; Thorslund et al., 2017; Van Coppenolle & Temmerman, 2020; Van der Biest et al., 2017; van Wesenbeeck et al., 2017; Vuik et al., 2019; Whelchel et al., 2018; L. Zhu et al., 2020 |
| Cultural | 15 | Almarshed et al., 2020; Arkema et al., 2017; Ghiasian et al., 2021; Hobbie & Grimm, 2020; Jarratt & Davies, 2020; Kok et al., 2021; Morris et al., 2018, 2020; Powell et al., 2019; Reguero et al., 2018; Ruckelshaus et al., 2020; Sutton-Grier et al., 2018; Sutton-Grier & Sandifer, 2019; Van der Biest et al., 2017; Vuik et al., 2019 |
| Provisioning | 18 | Almarshed et al., 2020; Arkema et al., 2017; Foti et al., 2020; Ghiasian et al., 2021; Kok et al., 2021; Moosavi, 2017b; Morris et al., 2018, 2020; Narayan et al., 2017; Powell et al., 2019; Reguero et al., 2018; Sutton-Grier et al., 2018; Sutton-Grier & Sandifer, 2019; Thorslund et al., 2017; Van Coppenolle & Temmerman, 2020; Van der Biest et al., 2017; Vuik et al., 2019; L. Zhu et al., 2020 |
| Perception | 5 | Han et al., 2020; Hobbie & Grimm, 2020; Nelson et al., 2020; Smith, 2017; Whelchel et al., 2018 |
| Equity | 3 | Arkema et al., 2017; Hobbie & Grimm, 2020; Nelson et al., 2020 |
| Costs | 24 | Aerts, 2018; Almarshed et al., 2020; Du et al., 2020; Fernández-Montblanc et al., 2020; Ghiasian et al., 2021; Griggs & Patsch, 2019; Harris & Ellis, 2020; Hobbie & Grimm, 2020; Kassakian et al., 2017; Kok et al., 2021; Lawrence et al., 2019; Moosavi, 2017b; Morris et al., 2018, 2019, 2020; Narayan et al., 2017; Powell et al., 2019; Reguero et al., 2018; Ruckelshaus et al., 2020; Smith, 2017; Sutton-Grier et al., 2018; Van Coppenolle & Temmerman, 2020; Van der Biest et al., 2017; Vuik et al., 2019; Whelchel et al., 2018; L. Zhu et al., 2020 |
| Design | 10 | Almarshed et al., 2020; Foti et al., 2020; Hobbie & Grimm, 2020; Jarratt & Davies, 2020; Kok et al., 2021; Morris et al., 2019; Narayan et al., 2017; Powell et al., 2019; Thorslund et al., 2017; Whelchel et al., 2018 |
| Challenges | 36 | Aerts, 2018; Almarshed et al., 2020; Arkema et al., 2017; Davlasheridze et al., 2019; Fernández-Montblanc et al., 2020; Ghiasian et al., 2021; Griggs & Patsch, 2019; Han et al., 2020; Harris & Ellis, 2020; Hobbie & Grimm, 2020; Jarratt & Davies, 2020; Kassakian et al., 2017; Kok et al., 2021; Lawrence et al., 2019; Moosavi, 2017b; Morris et al., 2018, 2019, 2019, 2020; Narayan et al., 2017; Nelson et al., 2020; Nordstrom, 2019; Odériz et al., 2020; Powell et al., 2019; Reguero et al., 2018; Ruckelshaus et al., 2020; Smith, 2017; Sutton-Grier et al., 2018; Sutton-Grier & Sandifer, 2019; Thorslund et al., 2017; Van Coppenolle & Temmerman, 2020; Van der Biest et al., 2017; van Wesenbeeck et al., 2017; Vuik et al., 2019; Whelchel et al., 2018; L. Zhu et al., 2020; Z. Zhu et al., 2020 |

These articles came from a variety of research areas, which reflects the cross-discipline nature of NbS. As with locations, many articles had multiple associated disciplines. Figure 9 shows the research areas with more than one paper included in the review. These research areas cut across a variety of scientific disciplines. The seven categories that only had a single paper included the more social fields of study of international relations, construction building technology, business economics, and social sciences other topics.

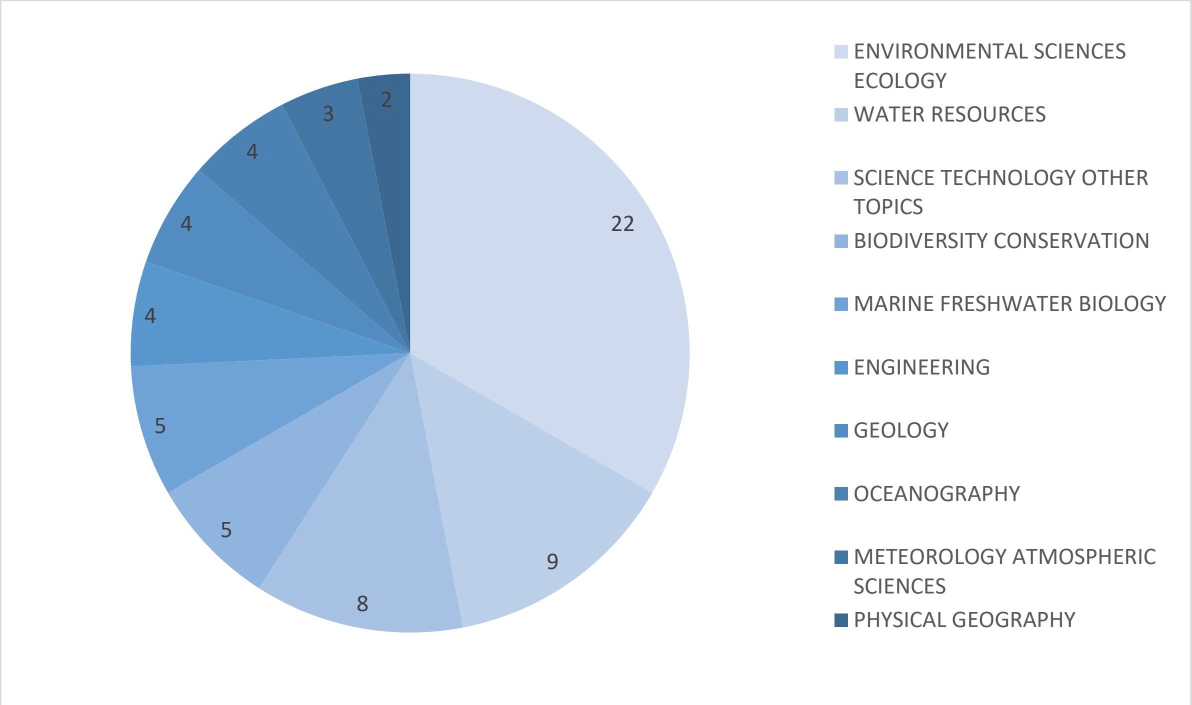


*Figure 9: Research Areas of Represented in Articles*

### *4.1.2. Hazard Reduction*

Natural infrastructure can be effective at mitigating coastal risks, to the same, or sometimes even greater extent as grey infrastructure (Powell et al., 2019). However, there is more uncertainty about the hazard risk reduction benefits of NbS compared to grey infrastructure (Morris et al., 2019; Powell et al., 2019), 30 out of the 38 document reviewed described the risk reduction potential. There were several thematic areas within the theme of risk reduction that were described in much of the literature reviewed, as presented in Table 2.

*Table 2: Hazard Risk Reduction Literature*

| ***Theme*** | ***Num.*** | ***Relevant Literature*** |
|---|---|---|
| Wave Reduction | 17 | Arkema et al., 2017; Fernández-Montblanc et al., 2020; Ghiasian et al., 2021; Griggs & Patsch, 2019; Hobbie & Grimm, 2020; Moosavi, 2017; Morris et al., 2018; Narayan et al., 2017; Powell et al., 2019; Reguero et al., 2018; Ruckelshaus et al., 2020; Sutton-Grier et al., 2018; Van Coppenolle & Temmerman, 2020; van Wesenbeeck et al., 2017; Vuik et al., 2019; Whelchel et al., 2018; L. Zhu et al., 2020 |
| Erosion Reduction | 5 | Harris & Ellis, 2020; Moosavi, 2017; Morris et al., 2018, 2019; Sutton-Grier et al., 2018 |
| Sedimentation | 3 | Hobbie & Grimm, 2020; Moosavi, 2017; Morris et al., 2018 |
| Bed friction | 5 | Fernández-Montblanc et al., 2020; Ghiasian et al., 2021; Morris et al., 2018; Odériz et al., 2020; Vuik et al., 2019 |

Wave reduction was the most prominent coastal risk reduction mechanism described in the literature. The main ways wave reduction were addressed was either through percentage of wave height reduction, absolute wave height reduction, and percentage of wave energy reduction. These are all useful measures, though it is difficult to convert between them. Additionally, the effectiveness of wave reduction is dependent on a variety of factors, including the type of NbS (Whelchel et al., 2018), the location (whether it is a high or low energy coastline) (Whelchel et al., 2018), the wave height to water depth (Ghiasian et al., 2021), the purpose of restoring the ecosystem (i.e. conservation or risk reduction) (Hobbie & Grimm, 2020), and localized practices (Powell et al., 2019). For example, oyster reefs may not be effective at wave height reduction in areas with destructive oyster harvesting practices (Powell et al., 2019).

Average wave height reduction percentages ranged from 31% to 72% (Morris et al., 2018; Reguero et al., 2018; Whelchel et al., 2018). For coral reefs, average wave height reduction is 70%, for saltmarshes is 72%, for mangroves is 31%, for seagrass/kelp beds is 36% (Morris et al., 2018; Whelchel et al., 2018), 60% for wetlands, 60% for barrier islands, and 60% for oyster reef (Reguero et al., 2018). This is comparable to low-crested detached breakwaters which range from 30-70% (Morris et al., 2018). It is notable that these are averages and there can be significant differences within NbS types for wave reduction. For example, the effectiveness of salt marshes varies by width (Z. Zhu et al., 2020). Kelp is a prime example of variation within a type of NbS. A synthesis of case studies found an average of 36% wave height reduction for kelp (Morris et al., 2018; Whelchel et al., 2018). However, on the low end, one case study found no evidence of shoreline protection (Morris et al., 2020) and on the high end of the spectrum for the wave energy measure, a 1996 case study measured 70% to 85% wave energy reduction (L. Zhu et al., 2020). The difference in results can be largely explained by the diversity of kelp species and morphologies (Morris et al., 2020). Arkema et al. (2017) found that wave height attenuation for kelp varies from about 60% for thick-stemmed kelp to none for giant kelp. Giant kelp is very flexible and adapted to movement with the large swells common to Southern California, while the thick-stemmed kelp on the Norwegian coast was short (<3 m) and thick-stemmed (Arkema et al., 2017). This highlights how different species can make significant differences in the risk reduction properties of NbS and the importance of site-specific simulations.

The mechanisms that reduce wave height and energy vary greatly depending on the type of NbS. The basic mechanism is that submerged objects create drag and turbulence, which reduces the energy in the water, as shown on Figure 10 (Arkema et al., 2017). This applies to whether the measures are permanently submerged, such as oyster reefs, or temporarily inundated, such as sand dunes. The same basic dampening mechanism can also be created by canopies, such as kelp or mussel aquaculture fields (Arkema et al., 2017; L. Zhu et al., 2020). These mechanisms make

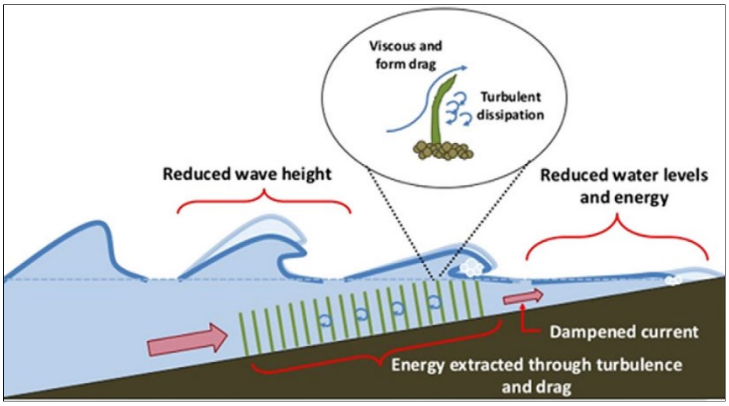


*Figure 10: Coastal Wave Reduction Mechanism (Arkema et al., 2017)*

NbS generally more effective in shallow water (Vuik et al., 2019). Energy is also reduced through wave breaking and bottom friction (Vuik et al., 2019). This can occur through subtidal NbSs causing localized water shallowing, which promotes wave breaking (Morris et al., 2018).

The more friction that can be created, the more effective the NbS tends to be. This was described in literature for coral reefs (Ghiasian et al., 2021), salt marshes (Vuik et al., 2019), and dunes (Fernández-Montblanc et al., 2020; Odériz et al., 2020). In artificial reefs, adding dense coral aggregations was found to mitigate an additional 10% of wave height and 14% of wave energy (Ghiasian et al., 2021). Perhaps this is the reason that Morris et al. (2018) found that restored reefs only dissipated 61% of the same wave energy that natural reefs dissipated. In dunes, submerged vegetation was found to increase friction, which caused a reduction in wave energy, which in turn reduced flow velocity, the area of wave action and erosion (Fernández-Montblanc et al., 2020).

The wave height reduction to NbS size is a non-linear relationship (Narayan et al., 2017). During Hurricanes Katrina and Wilma, the majority of the storm surge reduction was most effective in the first few hundred meters of wetland with any additional reduction exponentially lower (Narayan et al., 2017). Another study demonstrated that estimating these impacts based on the results of a single NbS may be inaccurate. Thus, Thorslund et al., (2017) argue that "although knowledge in many cases is still limited, evidence suggests that the aggregated effects of multiple wetlands in the landscape can differ considerably from the functions observed at individual wetland scales" (p. 1). Benefits occur from the interactions of wetlands with their surrounding landscape, and thus to evaluate benefits, one must look at the wetlandscape as a whole (Thorslund et al., 2017)

Energy attenuation reduces erosion, leading to shoreline stabilization (Moosavi, 2017). Natural habitats can also take it a step further and cause sediment deposition and vertical biomass buildup, which can eventually result in beach building (Moosavi, 2017). It also diminishes storm surges, which reduces flooding damages (Hobbie & Grimm, 2020; Reguero et al., 2018; Van Coppenolle & Temmerman, 2020). Determining the amount of flood damage reduction is difficult because flood depth-damage curves are dependent on a range of factors, including local building codes and structure design, which makes them geographically specific (Arkema et al., 2017). At present, such curves have generally only been created where data and modeling expertise are common, such as the United States, Australia, Germany, the Netherlands, and the United Kingdom (Arkema et al., 2017). An additional limitation is that damage models generally do not include assessments of damage to industry (Davlasheridze et al., 2019).

### *4.1.3. Scale Considerations*

There are two main components to scale: time and space. Of the nine papers that discussed some version of scale, one talked about both types, four papers discussed time, and four papers discussed space, as presented in Table 3.

*Table 3: Scale Considerations Literature*

| ***Theme*** | ***Num.*** | ***Relevant Literature*** |
|---|---|---|
| Time | 5 | Moosavi, 2017; Morris et al., 2018; Nelson et al., 2020; Powell et al., 2019; Sutton-Grier et al., 2018 |
| Space | 5 | Davlasheridze et al., 2019; Hobbie & Grimm, 2020; Narayan et al., 2017; Nelson et al., 2020; van Wesenbeeck et al., 2017 |

An important consideration is that it takes years, or even decades, for NbS to reach their full protection potential, while grey infrastructure reaches it immediately (Nelson et al., 2020; Powell et al., 2019). For example, oyster reefs provided 18.7% wave energy reduction immediately after deployment, compared to 44.7% a year later (Morris et al., 2018). Similarly, a salt marsh was found to provide 6.9% wave energy reduction immediately after deployment and 31.4% a year later (Morris et al., 2018). However, this also means that NbS effectiveness can strengthen with time, while grey infrastructure generally degrades and requires more maintenance as it ages (Sutton-Grier et al., 2018). While strengthened effectiveness over time is a benefit, the longer timeframe before getting full benefits can create a challenging mismatch between the short term and the long term perspectives (Nelson et al., 2020), particularly for decision-makers who very often work with shorter timeframes. Also, it should be noted, that this long time horizon is somewhat countered by grey infrastructure having a limited lifespan while NbS have longer lifespans (Moosavi, 2017). For example, in one breakwater project, it was recognized that encouraging oysters using EConcrete oyster disk units increased the lifespan of the project because oysters naturally build calcium carbonate deposits that can provide repairs (Moosavi, 2017).

To provide meaningful protection, NbS generally require a fairly large amount of space (Hobbie & Grimm, 2020). However, measures for coastal protection provide regional benefits, not just local ones (Davlasheridze et al., 2019). For example, after Hurricane Sandy many of the areas located upstream of wetlands still had significant flooding reduction effects due to the wetlands (Narayan et al., 2017). This is challenging because those who receive the upstream benefits are often in different communities than the ones impacted by the land allocation and use decisions for the NbS, which means the benefits and the costs of establishing NbS might not be equitable. Thus, there is a need to work across ecological and political boundaries (Nelson et al., 2020). The space requirement can also be difficult to meet in urban areas (van Wesenbeeck et al., 2017)

### *4.1.4. Flexibility*

One of the benefits that NbS tend to have over grey infrastructure is flexibility. Twelve of the papers touched on the concept of flexibility in various ways, as presented in Table 4.

*Table 4: Flexibility Literature*

| ***Theme*** | ***Num.*** | ***Relevant Literature*** |
|---|---|---|
| Adaptive capacity | 9 | Hobbie & Grimm, 2020; Morris et al., 2018, 2019, 2020; Powell et al., 2019; Reguero et al., 2018; Van Coppenolle & Temmerman, 2020; Vuik et al., 2019; Whelchel et al., 2018 |
| Self-repairing capacity | 7 | Almarshed et al., 2020; Hobbie & Grimm, 2020; Morris et al., 2018, 2020; Nelson et al., 2020; Powell et al., 2019; van Wesenbeeck et al., 2017 |

Coastal ecosystems are dynamic systems, which gives them some adaptive capacity in response to climate change (Morris et al., 2018). For example, sub-surface root growth expansion and sedimentation in wetlands and salt marshes can help build land and keep up with sea level rise (Hobbie & Grimm, 2020; Reguero et al., 2018; Van Coppenolle & Temmerman, 2020; Vuik et al., 2019). There is also evidence suggesting that healthy oyster reefs will adapt to keep up with sea level rise (Reguero et al., 2018). This is in contrast to grey infrastructure, which would need expensive retrofits in order to adapt to additional risk (Du et al., 2020; van Wesenbeeck et al., 2017; L. Zhu et al., 2020). Thus, the ability to adapt to climate adds to the cost effectiveness of NbS (Reguero et al., 2018).

It is important to note that this adaptation has limits. It requires adequate space for expansion between the coastline and area of development (Hobbie & Grimm, 2020). Additionally, despite NbS's potential to adapt to capacity, empirical studies show that in many cases the measures are not adapting fast enough to keep pace with sea level rise (Powell et al., 2019). Ultimately, the ability of NbS to adapt can be useful in that expensive upgrades will not be necessary. However, it will not prevent the gradual inland shifting of the coastline under climate change (Hobbie & Grimm, 2020). Still, there are numerous examples of the importance of easily being able to adapt coastline measures to future increases in risk (Du et al., 2020)

The same dynamic ability that allows ecosystems to adapt also gives them the ability to self-repair after storm events with minimal outside inputs. However, recovery can take a significant amount of time, sometimes even decades (Almarshed et al., 2020). Thus, while NbS have the capacity to self-repair, active repair may still be desirable (Almarshed et al., 2020). The downside of the dynamic nature of ecosystems is that natural variation creates uncertainty in the amount of protection NbS can provide (Morris et al., 2018). For example, aboveground biomass varies seasonally, which will impact wave attenuation (Morris et al., 2018). This variation and uncertainty can be a barrier in widely implementing NbS as part of coastal defense building. While it is difficult to design NbS to a particular standard, they do not experience catastrophic failure if the measure is exposed to an extreme storm event that is beyond its design standards (Nelson et al., 2020).

### *4.1.5. Regulating Ecosystem Services*

While the literature generally did not divide ecosystem services into different categories, papers describe the three main types of ecosystem services: regulating, cultural, and provisioning. Since the focus of this study was on NbS for coastal hazard risk reduction, the risk reduction aspect of regulating ecosystem services was presented separately above. Excluding risk reduction, there were five types of regulating ecosystem services described in the literature, as shown in Table 5.

*Table 5: Regulating Services Literature*

| ***Theme*** | ***Num.*** | ***Relevant Literature*** |
|---|---|---|
| Carbon Mitigation: Sequestration and Storage | 12 | Arkema et al., 2017; Kassakian et al., 2017; Kok et al., 2021; Morris et al., 2018; Narayan et al., 2017; Powell et al., 2019; Ruckelshaus et al., 2020; Thorslund et al., 2017; Van Coppenolle & Temmerman, 2020; van Wesenbeeck et al., 2017; Whelchel et al., 2018; L. Zhu et al., 2020 |
| Pollution Reduction | 3 | Thorslund et al., 2017; Van der Biest et al., 2017; Vuik et al., 2019 |
| Nutrient Cycling | 7 | Morris et al., 2018; Powell et al., 2019; Sutton-Grier et al., 2018; Thorslund et al., 2017; Van Coppenolle & Temmerman, 2020; Van der Biest et al., 2017; L. Zhu et al., 2020 |
| Water Provisioning and Quality | 7 | Kok et al., 2021; Powell et al., 2019; Sutton-Grier et al., 2018; Thorslund et al., 2017; Van Coppenolle & Temmerman, 2020; Van der Biest et al., 2017; L. Zhu et al., 2020 |
| Public Health | 5 | Hobbie & Grimm, 2020; Jarratt & Davies, 2020; Powell et al., 2019; Sutton-Grier & Sandifer, 2019; Van der Biest et al., 2017 |

Of the regulating services mentioned in the literature, carbon mitigation was the most common. There are two ways of mitigating carbon: carbon sequestration, which is the process of capturing carbon, and carbon storage, which is the storing of the carbon. Sometimes carbon sequestration refers to both the process of capturing and storing carbon. Out of the twelve papers that mentioned carbon mitigation, eleven described carbon sequestration and four described carbon storage, showing that the focus was clearly on carbon sequestration. While most NbS have the capacity to do some amount of carbon mitigation, there is some disagreement in the literature about some of the measures. One review article found no evidence that coral reefs, kelp, or shellfish reef provided carbon mitigation (Morris et al., 2018), while one review paper found evidence that coral reefs provide carbon mitigation while still supporting the idea that oyster reefs did not (Powell et al., 2019), and a third study looking at aquaculture farms found that kelp can provide carbon mitigation (L. Zhu et al., 2020). This variation in findings is likely due to a variety of factors. The rates of carbon sequestration and storage vary not only depending on the type of NbS, but also the health of the ecosystem, the soil retention capacity, the location, vegetation density, and age of the measure (Ruckelshaus et al., 2020). There is some evidence that coastal ecosystems may be better than terrestrial forests at storing carbon as there are higher rates of organic carbon in the coastal sediments (Powell et al., 2019). However, as coastal habitats degrade or are destroyed, they will release the carbon stored (Ruckelshaus et al., 2020), harming climate mitigation efforts.

Ecosystems have the ability to retain other pollutants as well. For example, air pollution can be reduced through vegetation capture (Van der Biest et al., 2017). One way ecosystems demonstrate this is by helping nutrient cycling. Every type of NbS reviewed increased nutrient cycling, including dunes, reefs, kelp, salt marsh/wetlands, and seagrass (Morris et al., 2018; Powell et al., 2019). Reducing nutrient load reduces risk of algal blooms and hypoxia (Powell et al., 2019). A case study in the river delta near the Aral Sea found that nutrient loads downstream decreased after circular flow in a wetlandscape, despite upstream nutrient load increases (Thorslund et al., 2017). Research at two coastal wetlands in Sweden both showed evidence of nutrient retention capacity (Thorslund et al., 2017).

Pollution retention and nutrient cycling are some of the ways in which ecosystems provide water filtration (Powell et al., 2019), which was described as an ecosystem service in seven papers. Just as with nutrient cycling, every type of NbS reviewed helped increase water quality including dunes, reefs, kelp, salt marsh/wetlands, and seagrass (Morris et al., 2018; Powell et al., 2019). In addition to water purification, one study on dunes (Van der Biest et al., 2017) and another on wetlands (Thorslund et al., 2017) also described the ability of NbS to regulate water provisioning, which includes soil moisture regulation and groundwater level replenishment. However, in the study on coastal dunes in Belgium, the value of water quality and water provision services was relatively small compared to the risk reduction and recreation services (Van der Biest et al., 2017). The low value of water related services is due to contextual factors, such as the low market price of water (Van der Biest et al., 2017).

Providing clean drinking water and reducing air pollutant loads reduces the risk for diseases such as cancer (Van der Biest et al., 2017). There are also indicators that ecosystem losses may be increasing the prevalence of inflammatory-based diseases (e.g. allergies, asthma, type 2 diabetes) due to lower exposure during childhood to diverse microbiota (Sutton-Grier & Sandifer, 2019). Additionally, there is some evidence that biodiversity may reduce transmission of infectious diseases; for example neighborhoods with wetlands have lower dengue rates, even after controlling for socio-economic factors, such as population density (Sutton-Grier & Sandifer, 2019). In addition to physical health, there is strong evidence that NbS also improves mental health, through services such as providing a sense of place (Sutton-Grier & Sandifer, 2019), cultural heritage (Powell et al., 2019; Reguero et al., 2018; Sutton-Grier & Sandifer, 2019), aesthetic values (Sutton-Grier & Sandifer, 2019), and reducing mental fatigue (Jarratt & Davies, 2020). One study postulated that these mental health effects may help with disaster recovery by reducing post disaster health problems such as stress (Sutton-Grier & Sandifer, 2019).

#### *4.1.6. Cultural Ecosystem Services*

There were three types of cultural ecosystem services described in the literature, as outlined in Table 6. Public Health is both a regulating and a cultural service; it was described above under regulating services.

*Table 6: Cultural Services Literature*

| ***Theme*** | ***Num.*** | ***Relevant Literature*** |
|---|---|---|
| Public Health | 5 | Hobbie & Grimm, 2020; Jarratt & Davies, 2020; Powell et al., 2019; Sutton-Grier & Sandifer, 2019; Van der Biest et al., 2017 |
| Recreation and Tourism | 14 | Almarshed et al., 2020; Arkema et al., 2017; Ghiasian et al., 2021; Jarratt & Davies, 2020; Kok et al., 2021; Morris et al., 2018, 2020; Powell et al., 2019; Reguero et al., 2018; Ruckelshaus et al., 2020; Sutton-Grier et al., 2018; Sutton-Grier & Sandifer, 2019; Van der Biest et al., 2017; Vuik et al., 2019 |
| Education | 4 | Jarratt & Davies, 2020; Morris et al., 2018; Sutton-Grier & Sandifer, 2019; Van der Biest et al., 2017 |

Public health is particularly connected to cultural services for mental health. One of the ways that NbS improve mental health is by providing recreation spaces. This was a major focus of the literature, with 14 papers mentioning recreation and/or tourism in some form. Recreation and tourism are so tightly linked to NbS that 9 of the 14 papers discuss both recreation and tourism. Recreation takes many forms including fishing, hunting (Powell et al., 2019; Reguero et al., 2018), running, and walking (Sutton-Grier & Sandifer, 2019). Having these recreation spaces attracts tourists. One study suggested that the tourism potential of a place is a function of the environmental features, such as beaches and reefs, and coastal infrastructure that tourists use, such as roads and hotels (Ruckelshaus et al., 2020). Since NbS naturally provide some of these environmental features, implementing them has the potential to increase tourism in the area. Since tourism is a major employer in many coastal areas it is generally important to coastal economies (Ruckelshaus et al., 2020). NbS can also help to increase eco-tourism (Powell et al., 2019).

Eco-tourism can be one of the ways that NbS serve as valuable research and education resources (Jarratt & Davies, 2020). Education was mentioned as another value added by four papers. However, how NbS added this value was further elaborated on.

#### *4.1.7. Provisioning Ecosystem Services*

There were three main types of provisioning services described in the literature, which can be found in Table 7.

*Table 7: Provisioning Services Literature*

| ***Theme*** | ***Num.*** | ***Relevant Literature*** |
|---|---|---|
| Support Wildlife/ Biodiversity | 13 | Almarshed et al., 2020; Arkema et al., 2017; Foti et al., 2020; Ghiasian et al., 2021; Kok et al., 2021; Morris et al., 2018, 2020; Powell et al., 2019; Sutton-Grier et al., 2018; Thorslund et al., 2017; Van der Biest et al., 2017; Vuik et al., 2019; L. Zhu et al., 2020 |
| Fisheries | 11 | Arkema et al., 2017; Kok et al., 2021; Moosavi, 2017; Morris et al., 2018, 2020; Narayan et al., 2017; Powell et al., 2019; Reguero et al., 2018; Sutton-Grier et al., 2018; Van Coppenolle & Temmerman, 2020; L. Zhu et al., 2020 |
| Provision food and raw materials | 8 | Arkema et al., 2017; Kok et al., 2021; Morris et al., 2018; Powell et al., 2019; Sutton-Grier & Sandifer, 2019; Van Coppenolle & Temmerman, 2020; Van der Biest et al., 2017; L. Zhu et al., 2020 |

Half of the papers on provisioning ecosystem services described various forms of wildlife support in relation to ecosystem services. Every type of NbS in the literature was found to support wildlife in at least one way, including coral reef, kelp, salt marsh, wetlands, dunes, and shellfish reefs (Morris et al., 2018). This support comes in the form of habitat creation (Arkema et al., 2017, 2017; Kok et al., 2021), providing food/foraging grounds (Powell et al., 2019), and spawning, nesting and nursery grounds (Powell et al., 2019; Vuik et al., 2019). All of this contributes to many NbS supporting a high amount of biodiversity, sometimes including threatened and endangered species (Almarshed et al., 2020; Morris et al., 2020). As mentioned above, the amount of support varies, not only between types of NbS, but also within a particular type. For example, research on ecosystem services of dunes found that dunes in the early stages of succession supported more biodiversity than dunes in later stages (Van der Biest et al., 2017).

The papers highlighted the NbS habitats as being particularly helpful for birds, invertebrates, shellfish (Powell et al., 2019), and fish. Providing support for fish and fisheries was the second most mentioned ecosystem service when considered separately from general wildlife support. The ways in which fish are supported are the same as other wildlife: through habitat (Sutton-Grier et al., 2018), food, and nurseries (Kok, 2021; Powell, n.d.); thus its prominence in the literature is likely related to the importance of productive fisheries as a food source. Terrestrial NbS, such as dunes, do not support fisheries, but every type of natural aquatic NbS reviewed did support fisheries (Morris et al., 2018). Part of implementing NbS can also include planting native plant species (Powell et al., 2019), in which case NbS also helps with plant species preservation. The evidence for restored habitats is less robust (Morris et al., 2018), but it is likely that this is largely due to a research gap.

The ability to support productive fisheries is just one of the ways in which NbS can supply raw materials, such as food. NbS being able to support raw materials was mentioned in seven of the articles, with a particular focus on the ability of NbS to supply wood (Van Coppenolle & Temmerman, 2020; Van der Biest et al., 2017). The provisioning of raw materials is supported by dunes, kelp, mangroves, saltmarsh, seagrass and shellfish reefs (Morris et al., 2018).

#### *4.1.8. Perceptions*

Public perception is an important consideration for any adaptation measure. Several studies either touched upon the importance of perception or upon what public perception of NbS currently looks like, as presented in Table 8.

*Table 8: Perception Literature*

| ***Theme*** | ***Num.*** | ***Relevant Literature*** |
|---|---|---|
| Importance of perception | 3 | Han et al., 2020; Hobbie & Grimm, 2020; Nelson et al., 2020 |
| Perception of Measures | 4 | Han et al., 2020; Hobbie & Grimm, 2020; Smith, 2017; Whelchel et al., 2018 |

The importance of people's risk perception to the success of NbS measures was highlighted in the literature. Han et al. (2020) found a positive correlation between individual's risk perception and the probability of an adaptive measure being implemented. Another study found that public acceptance is an important factor in the success of NbS (Hobbie & Grimm, 2020), while Nelson et al. (2020) found that stakeholder engagement provides substantial benefits for the effectiveness of NbS.

One of the more consistent findings of the literature was that adaptation measures give the perception of increased security and safety (Han et al., 2020; Hobbie & Grimm, 2020; Whelchel et al., 2018). The literature particularly highlighted this perception of safety when implementing grey infrastructure. This sense of security can stimulate the building of more infrastructure in areas with high risk, thus overall increasing the vulnerability of the community instead of decreasing the community's risk (Han et al., 2020). This is sometimes referred to as the safe development paradox (Han et al., 2020).

Another part of public perception entails considering what the public values most when it comes to adaptation measures. A survey study in North Carolina in the United States (US) amongst property owners found that when asked for the top three criteria they considered most important in an adaptation measures effectiveness was ranked highest, followed by cost, durability, and finally ecological impact whereas other criteria, such as aesthetics, permitting, and water access, were rarely prioritized (Smith, 2017). Additionally, property owners ranked "sills and plantings higher than sills alone for effectiveness and durability, which indicates an understanding of the wave amelioration properties of natural vegetation" (Smith, 2017, p. 357). However, when asked which shoreline type was the most effective "32% of property owners selected bulkheads [grey infrastructure], followed by riprap (20%) and planting alone (21%)" (Smith, 2017, p. 353). A previous study in Alabama also found that homeowners were receptive to the use of NbS (Smith, 2017).

### *4.1.9. Equity*

Doing financial calculations alone, such as cost benefit analysis (CBA), to evaluate adaptation measures does not capture the full picture. It misses other considerations, such as how the adaptation measure fits into the picture of societal equity. Three articles described this, as shown in Table 9.

*Table 9: Equity Literature*

| ***Theme*** | ***Num.*** | ***Relevant Literature*** |
|---|---|---|
| Equity | 3 | Arkema et al., 2017; Hobbie & Grimm, 2020; Nelson et al., 2020 |

Financial analysis does not capture who pays the costs and who receives the benefits. Even when benefits are higher than the costs, the benefits may not be equitably distributed and the adaptation measure may not be overall positive for everyone (Nelson et al., 2020). This is exacerbated by the fact that quantifying risk reduction benefits are generally based partially on housing prices (Arkema et al., 2017), which means financial benefits appear higher in areas where housing values are higher, even when fewer people are receiving these benefits.

There is a recognition that risk reduction measures are frequently implemented in a way that is unequal, raising social justice concerns. As one study put it "[t]hose who are most likely to experience climate change impacts within and across cities may also be those with the least access to nature-based relief from those impacts" (Hobbie & Grimm, 2020, p. 10). This is largely because poorer communities are frequently located in areas with higher exposure and also may not have resources for recovery or adaptation measures (Arkema et al., 2017; Hobbie & Grimm, 2020), while most urban green spaces are generally in wealthier areas (Hobbie & Grimm, 2020). This is exacerbated by green gentrification (Hobbie & Grimm, 2020), which happens when NbS create or exacerbate processes of gentrification due to the added value from implementing NbS which translates into increased property and rental prices.

In addition, when adaptation measures are in the planning and decision making stages, vulnerable people are rarely consulted, and sometimes even deliberately excluded (Hobbie & Grimm, 2020). This lack of representation can lead to the rise of new inequalities (Hobbie & Grimm, 2020). In order for NbS to be equitable and effective it is crucial that all stakeholders are consulted and included (Hobbie & Grimm, 2020; Nelson et al., 2020).

### *4.1.10. Costs*

Just as there are numerous types of adaptation measure benefits, there are also various types of costs. There are installation costs, operation and maintenance costs, land costs, aesthetic costs, and ecosystem costs. These types of costs can be divided into direct costs and indirect costs, the literature that contained relevant information is presented in Table 10 and described in more detail below.

*Table 10: Cost Literature*

| ***Theme*** | ***Num.*** | ***Relevant Literature*** |
|---|---|---|
| Direct costs | 19 | Aerts, 2018; Almarshed et al., 2020; Du et al., 2020; Fernández-Montblanc et al., 2020; Ghiasian et al., 2021; Griggs & Patsch, 2019; Harris & Ellis, 2020; Hobbie & Grimm, 2020; Kassakian et al., 2017; Kok et al., 2021; Moosavi, 2017a; Morris et al., 2018; Powell et al., 2019; Reguero et al., 2018; Smith, 2017; Sutton-Grier et al., 2018; Van Coppenolle & Temmerman, 2020; Vuik et al., 2019; L. Zhu et al., 2020 |
| Indirect costs | 16 | Almarshed et al., 2020; Griggs & Patsch, 2019; Harris & Ellis, 2020; Kok et al., 2021; Lawrence et al., 2019; Moosavi, 2017a; Morris et al., 2018, 2019, 2020; Narayan et al., 2017; Odériz et al., 2020; Powell et al., 2019; Ruckelshaus et al., 2020; Thorslund et al., 2017; Van der Biest et al., 2017; Whelchel et al., 2018 |

The direct costs of grey infrastructure are generally better understood than the costs associated with NbS due to their long-term use and vetted design specifications (Powell et al., 2019). At the same time, due to grey infrastructure's degradation, there can be unpredicted hidden costs in traditional hard structures (Powell et al., 2019). The costs of NbS vary based on multiple factors (Aerts, 2018; Fernández-Montblanc et al., 2020; Powell et al., 2019; Reguero et al., 2018), including the type of NbS/habitat (Aerts, 2018; Powell et al., 2019), the location (Aerts, 2018; Powell et al., 2019; Reguero et al., 2018), local labor costs, the economy, whether the work is creation or restoration, restoration technique (Aerts, 2018), and the initial health of the ecosystem (Kassakian et al., 2017). All these factors lead to significant variations in costs. For example, one review article found wetland restoration costs in the United States ranging from less than $85 000 to over $230 000 per hectare, in 2016 consumer price index (CPI) adjusted dollars (Aerts, 2018).

While the costs vary, studies comparing the cost, CBA, or cost effectiveness of grey infrastructure to NbS, show grey infrastructure was more expensive or had a lower cost benefit/cost effective ratio (Almarshed et al., 2020; Du et al., 2020; Hobbie & Grimm, 2020; Powell et al., 2019; Smith, 2017; Van Coppenolle & Temmerman, 2020). For example, a cost effectiveness study of the gulf coast found an average benefit to cost ratio for NbS above 3.5 (Reguero et al., 2018). One of the reasons NbS are cheaper is that they generally require less maintenance compared to grey infrastructure (Moosavi, 2017; Smith, 2017; Van Coppenolle & Temmerman, 2020). This is not only supported by academic literature, but also by homeowner surveys that found that homeowners with natural shorelines reported lower yearly shoreline maintenance, and lower post-hurricane repair costs, compared to those with bulkheads (Smith, 2017). While low maintenance costs are widely supported in the literature, specific operation and maintenance (O&M) costs are generally not widely available (Aerts, 2018). In case studies, O&M costs are frequently aggregated with installation costs (Aerts, 2018). Additionally, cost information is more often in non-peer-reviewed reports, making collecting and assessing its quality difficult (Aerts, 2018). Another consideration is NbS frequently requires ongoing monitoring, which is not as necessary for grey infrastructure (Moosavi, 2017)

Ecosystem costs are a large component of the indirect costs and are frequently not included in project economic analysis. The ecosystem cost described most frequently for grey infrastructure was erosion (Almarshed et al., 2020; Griggs & Patsch, 2019; Harris & Ellis, 2020; Whelchel et al., 2018). Grey coastal near-shore infrastructure works by creating a hard barrier that alters sedimentation patterns (Almarshed et al., 2020; Griggs & Patsch, 2019). This affects dune & beach development (Whelchel et al., 2018). The steep slopes created by the barrier reflects the wave energy, creating scour in front of the infrastructure (Ruckelshaus et al., 2020). This not only diminishes the beach in front (Morris et al., 2020), but can even create such additional bottom shear stress that it leads to the collapse of sea walls (Ruckelshaus et al., 2020).

Erosion as well as grey infrastructure measures, can reduce beach access (Griggs & Patsch, 2019; Morris et al., 2020) and aesthetics (Griggs & Patsch, 2019; Morris et al., 2020; Whelchel et al., 2018). This in turn can decrease the number of tourists (Whelchel et al., 2018). Grey infrastructure can also degrade ecosystems and a number of other ecosystem services (Morris et al., 2019; Odériz et al., 2020; Ruckelshaus et al., 2020; Thorslund et al., 2017). As described in the Costs section, this can include a decrease in water quality (Ruckelshaus et al., 2020) and habitat and species loss (Whelchel et al., 2018).

There were also ecosystem costs associated with artificial NbS. The ecosystems supported by artificial structures are generally less diverse than natural habitats (Lawrence et al., 2019; Morris et al., 2018) and are made up of more non-native species (Morris et al., 2018). While this effect on ecosystem services is understudied, it is likely to impact their ability to provide ecosystem services (Lawrence et al., 2019).

### *4.1.11. Design*

While the different potential benefits of NbS have been described above, which co-benefits exist for a particular project depends largely on the design objective(s). The main themes relating to design are presented in Table 11.

*Table 11: Design Literature*

| ***Theme*** | ***Num.*** | ***Relevant Literature*** |
|---|---|---|
| Design Purpose | 5 | Almarshed et al., 2020; Foti et al., 2020; Hobbie & Grimm, 2020; Kok et al., 2021; Whelchel et al., 2018 |
| Complexity | 6 | Foti et al., 2020; Jarratt & Davies, 2020; Morris et al., 2019; Narayan et al., 2017; Powell et al., 2019; Thorslund et al., 2017 |

Common objectives include: increasing biodiversity, supporting conservation, tourism, recreation, risk reduction, and climate mitigation (Whelchel et al., 2018). While NbS can achieve multiple objectives (Whelchel et al., 2018), it is difficult to maximize all benefits. For example, NbS that focus on risk reduction do not automatically enhance biodiversity (Hobbie & Grimm, 2020). The different objectives can even have conflicting needs, such as green spaces requiring mowing to maintain recreation areas, which can harm biodiversity (Hobbie & Grimm, 2020). Thus, to create the project that best needs the community's needs, it is important to clarify the project objectives (Whelchel et al., 2018). What benefits best meet local needs is dependent on the setting and questions such as: what is the local demand for each benefit? (Almarshed et al., 2020; Kok et al., 2021). These objectives will shape which adaptation strategy is selected as well as how the selected adaptation strategy is designed. The multiple objectives approach evaluates the project in relation to multiple benefits, while grey infrastructure evaluation is generally evaluated solely in relation to risk reduction (Whelchel et al., 2018).

When designing NbS it also important to consider site dynamics. Fully evaluating NbS can be difficult because looking at projects in isolation can miss critical linkages with surrounding ecosystems (Thorslund et al., 2017). It is also necessary to consider other linkages, such as the dynamics between soil and water for the site (Jarratt & Davies, 2020). Systems thinking is the best approach for successfully implementing NbS (Jarratt & Davies, 2020), which increases the complexity of project evaluation. This complexity is heighted by the fact that the nature of NbS requires combining knowledge from multiple disciplines, particularly engineering and ecology (Foti et al., 2020; Morris et al., 2019). Despite this, studies are generally focused on a single discipline (Morris et al., 2019; Narayan et al., 2017). Even in economic evaluations of ecosystems, there is rarely collaboration between the ecological modeling and risk modeling communities (Narayan et al., 2017). Increased collaboration between disciplines could greatly increase design effectiveness.

### *4.1.12. Challenges*

As is typical in research, most articles described challenges and additional research questions associated with NbS. Not all the challenges could be included here, and some of them, such as challenges associated with societal equity and complexity, are described in more detail above. The most common challenges are presented in Table 12.

*Table 12: Challenges Literature*

| ***Theme*** | ***Num.*** | ***Relevant Literature*** |
|---|---|---|
| Impact of climate change on NbS | 10 | Aerts, 2018; Kassakian et al., 2017; Morris et al., 2018, 2020; Narayan et al., 2017; Nordstrom, 2019; Odériz et al., 2020; Powell et al., 2019; Sutton-Grier & Sandifer, 2019; Whelchel et al., 2018 |
| Limited Data | 11 | Aerts, 2018; Almarshed et al., 2020; Ghiasian et al., 2021; Morris et al., 2018, 2019; Nelson et al., 2020; Reguero et al., 2018; Ruckelshaus et al., 2020; Sutton-Grier & Sandifer, 2019; Whelchel et al., 2018; L. Zhu et al., 2020 |
| Variation with Context | 8 | Aerts, 2018; Arkema et al., 2017; Kok et al., 2021; Morris et al., 2019; Powell et al., 2019; Sutton-Grier & Sandifer, 2019; Van der Biest et al., 2017; Whelchel et al., 2018 |

One of the most common challenges is also the one NbS is being used to address: climate change. While NbS can be leveraged to adapt to and mitigate climate change, there is also concern about the impact climate change may have upon NbS (Aerts, 2018; Kassakian et al., 2017; Narayan et al., 2017; Odériz et al., 2020; Powell et al., 2019; Sutton-Grier & Sandifer, 2019; Whelchel et al., 2018). For example, dune vegetation can die off during droughts and high temperatures, which would reduce the effectiveness of the dunes as a risk reduction measure (Nordstrom, 2019). While the literature discussed the potential ability of ecosystems to adapt (see Flexibility), uncertainty remains about how ecosystems will adapt to climate change and other anthropogenic disturbances (Powell et al., 2019; Whelchel et al., 2018), and how ecosystem services will be impacted (Whelchel et al., 2018). Additionally, existing ecosystem services are already being degraded by other human impacts, such as overfishing and coastal development (Aerts, 2018). Many types of ecosystems, including salt marshes/wetlands (Whelchel et al., 2018) and kelp (Morris et al., 2020) are being displaced either due to early impacts of climate change or other human impacts. More NbS are needed simply to maintain the existing level of ecosystem services (Kassakian et al., 2017). In Delaware Bay, 45 000-109 000 acres require restoration at approximately $230 000/acre to retain the existing level of ecological services (the range is dependent upon whether the projects are preventative or restoration after loss) (Kassakian et al., 2017). Generally, this destruction is most prominent in areas with the highest population, which is particularly unfortunate since this is where their services are most needed (Morris et al., 2018). This paradox is further compounded by the historical prioritization of conservation projects in areas with lower population densities and development (Reguero et al., 2018).

NbS are highly location specific. This is partly because of climatic settings (Kok et al., 2021), but also physical site considerations, such as slope (Whelchel et al., 2018), the existing natural system (Kok et al., 2021), and even the salinity of a subtidal zone play a role (Powell et al., 2019). Van der Biest et al. (2017) urged hesitation in applying the results of their case study to other sites without further investigation. The complexity caused by being location specific is compounded by NbS still being in the early stages of research (Ghiasian et al., 2021; Nelson et al., 2020; Sutton-Grier & Sandifer, 2019; L. Zhu et al., 2020). Additionally, there are a limited number of projects and tools to draw information from (Almarshed et al., 2020; Morris et al., 2019; Nelson et al., 2020; Reguero et al., 2018; Ruckelshaus et al., 2020; Whelchel et al., 2018), especially for effectiveness and cost quantification information (Reguero et al., 2018). This limits the ability to compare grey and green infrastructure (Aerts, 2018). Comparisons are also imperfect unless tested in the same environmental conditions, which is rare (Morris et al., 2018). Additionally, much of the research focuses on natural ecosystems; there is less evidence to indicate if artificial or restored ecosystems provide the same level of services as their natural counterparts (Morris et al., 2018).

The type and extent of ecosystem services varies significantly among projects, even within the same type of measure. These context variations stem from a mixture of socio-economic factors, including management strategies, and environmental factors, including the geomorphic and habitat characteristics (Arkema et al., 2017, p. 7). They also vary depending on the state of the ecosystem; degraded ecosystems provide less services than their healthy counterparts (Sutton-Grier & Sandifer, 2019).

The implementation of NbS also faces regulatory barriers (Powell et al., 2019; Whelchel et al., 2018). Though these exact barriers differ by location, regulations are generally designed for more traditional grey infrastructure. Additionally, funding more frequently goes to traditional infrastructure project than NbS (Whelchel et al., 2018).

### *4.2. Interviews on the Swedish Context*

The interviewees, their roles, and their organization are presented in Table 13. The number assigned to the interviewee in the table is used to reference data from that interviewee in the sections below. The two SEPA employees were interviewed together, and thus their responses are sometimes attributed to both people, by a number 7, and when appropriate were sometimes attributed to one, by a 7A or 7B.

*Table 13: Interviewees and their Roles*

| Reference Number | Name | Job Title | Organizational Type | Organization |
|---|---|---|---|---|
| 1 | Björn Almström | PhD candidate researching NbS | University | Lund University |
| 2 | Caroline Hallin | Associate senior lecturer | University | Lund University |
| 3 | Charlotta Lövstedt | Senior consultant | Engineering consultancy firm | DHI Sverige AB |
| 4 | Emanuel Schmidt | Coastal engineer | Engineering consultancy firm | SWECO Sverige AB |
| 5 | Hanna Billmayer | Climate adaptation strategist | Municipal | Halmstad |
| 6 | Magnus Larsson | Professor | University | Lund University |
| 7/7A | Anki Weibull | Coordinator nature-based solutions | National | SEPA |
| 7/7B | Timo Persson | Climate adaptation coordinator | National | SEPA |
| 8 | Jessica Gunnarsson | Planner for threatened species | Municipal | Lansstyelsen |
| 9 | Anette Björlin | Strategist climate change adaptation | National | SGI |

The major themes that arose in the interviews were related to the interviewees views on ecosystem services, perceptions towards NbS, costs, data challenges, and regulatory framework. These themes are presented below in this order, which corresponds to the order similar themes from the literature were presented above.

Adaptation is a fairly new topic at the national level (7). For a long time, the focus of agencies like Swedish EPA was on climate change mitigation (7). Though in more recent years, agencies have expanded their role to include adaptation as it became clear climate change was unavoidable (7). Coastal adaptation in Sweden is focused on the southern part of the country, where the population density is higher and sea level rise is more significant (7,9). Halmstad is already experiencing regular flooding, which can cause significant economic damage (5). For example, the port, which serves as a transit port for cars, had just received a new shipment in 2015 when it was flooded, ruining all the cars (5).

### *4.2.1. Ecosystem Services*

One of the topics covered was the various co-benefits from NbS that could be applicable to Halmstad and which of these, beyond risk reduction, were perceived as being the most beneficial. The benefits described most often included their ability to create recreation spaces (1,2,4) and increase biodiversity (1,3,7A,8,9). While biodiversity is highly valued, when looking at the political landscape, people are generally human centered, which means that NbS are likely more attractive for coastal adaptation purposes than biodiversity purposes (7). Concurrent with recreation spaces are increased overall aesthetics (1) and tourism (2). In addition to attracting tourists, green spaces help people living in the area by contributing to physical and mental health, particularly for "people with the lower income that don't have the ability to go away on holiday, it's so important that they also get green areas close vicinity from where they live" (7A). Amongst other health improvements, green spaces can provide noise reduction and air quality improvements (7A). One researcher also highlighted that NbS are easily adaptable under changing conditions (1). Given the high uncertainty of what will happen under climate change, the adaptability factor is useful: "if the sea level rises with 3 mm per year, it's quite easy to every 10 years put on 3 mm of sediment on your salt marsh, and then it will cope with sea level rise" (1).

### *4.2.2. Perceptions towards NbS*

Multiple interviewees discussed how much people in Sweden value green spaces. When SGI conducted a survey about what people in Southern Sweden consider most important to protect, many said nature and recreation spaces were the most valuable things to save (9). There seems to be an understanding that "you can always move a road, but you can never get the value back if it's a cultural object or [natural area]" (9). People particularly value having recreation spaces along the coast (4). When asked what criteria the public is likely to find most important, interviewees ranked cost (4,6,7), aesthetics (4), risk reduction (7,9), and biodiversity (4,8) highest.

Though national employees viewed risk reduction as one of the most important criteria to the public (7,9), one of the engineering consultants (who works closely with municipalities) disagreed; in their experience, risk perception in Sweden is very low, making the risk reduction potential of a measure less important to the public (4). SGI's study similarly suggested that people moving into new areas by the coast were generally not concerned about sea level rise (9). Thus, marginal increases in risk reduction from adaptation measures are frequently undervalued (4). Additionally, implementing any adaptation measure can also be challenging because some areas face political opposition to addressing climate change, meaning that they view reducing risk related to climate change as unnecessary (4,9).

Due to this still being early stages for using NbS, the interviewees cautioned that their answers on the public's perception was not based on a wealth of experience. While the public is excited about using NbS for adaptation, the people who are most exposed to coastal hazards seem less excited (6). People generally tend to feel they have a higher degree of protection with grey infrastructure (3,6). However, people do not always understand that measures, such as beach nourishment, is there to protect them (3,7A). This matches the other consultant's experience, that people do not generally know what their options are (4). Thus, it is important to build public acceptance and understanding (7B). Due to the high value placed on natural spaces, it seems likely that residents of Halmstad could value NbS over grey infrastructure (8).

#### *4.2.3. Costs*

As discussed above, costs are perceived as one of the most important considerations for adaptation measures. While a lack of project cost data within Sweden makes estimating costs difficult (1), NbS costs are estimated to be much higher in Sweden compared to many western countries (2). One researcher estimated that a beach nourishment project would cost approximately twice the amount in Sweden compared to the Netherlands, excluding the permitting cost, just due to the cost of extracting sand (2). Additionally, there are a lot of uncertainties related to cost and it is highly site specific (1). For example, the cost of soil will vary significantly depending on whether it can be sourced locally or imported from a distance (1). Furthermore, small-scale projects cost more per area than larger scale projects because certain costs do not scale directly, such as the costs to mobilize a construction crew and permitting costs (1). This is true for both grey infrastructure and NbS (1). Many costs, such as transporting sand scale down to cost less per unit on big projects; big projects also have more buffer when something goes wrong (1). One of the researchers also pointed out the indirect costs of grey infrastructure including "recreation, aesthetics, leeside erosion, and increased waves, due to erosion in front of like a revetment" (1). However, due to the limited examples of NbS in Sweden, the full extent of impacts, whether benefits or costs, is not known (4). Many of the interviewees talked about maintenance. Due to their dynamic nature, maintaining NbS effectiveness can be quite maintenance intensive (1,6). In many places, much of this maintenance is done by volunteers. As there is not a strong volunteer culture when it comes to disaster management in Sweden, it is likely that maintenance costs would be higher in Sweden (1).

Land is another significant cost for NbS, which makes it a challenge. Urban densification was a strong norm in Sweden (7B). While this practice has many advantages, such as climate mitigation since it allows for efficient public transportation, it does mean that land values are high, which makes it difficult to find space available for NbS (7B). This holds true for Halmstad, which has largely considered grey solutions for coastal flooding due to a lack of coastal space to build NbS (5). While Sweden does not have much unoccupied land near populated areas, the country in general does have a relatively high amount of sparsely populated land (2). This space could be an opportunity to implement NbS, particularly for research purposes (3).

#### *4.2.4. Data Challenges*

Besides maintenance of NbS, key informants highlighted that lack of data was another major challenge for implementing NbS (3,4,6,7), including lack of knowledge regarding NbS' effectiveness (7b), a lack of Swedish examples (3), lack of monitoring projects for learning (6), and a lack of people with the experience in fields like physical processes that are important for implementing adaptation projects (6). The lack of data regarding effectiveness is particularly pronounced in Sweden because most of the modeling data is for sandy beaches (6). While Sweden does have sandy beaches, most beaches consist of mixed material moraine beaches that resulted from the glaciation process (6). Another example of lack of data, is the lack of knowledge about physical processes. Sweden only had two tide gauges, one on the east coast and one on the west coast (6), and very few wave gauges (9). Local conditions vary significantly, making this limited data a difficult problem when designing NbS (9).

Some of these challenges are starting to be addressed. For example, SGI has created a database of NbS projects in Sweden (7,9), which currently contains around twenty to twenty-five projects (9). The focus of the SGI, as a geologic institute, is erosion and stability projects (9). SGI is also working to create country-specific building design guidance (9). The field of coastal professionals is rapidly growing, as is reflected in the number of conference attendees (4). According to one of the engineering consultants, this has increased from 20 to 30 attendees five years ago to around 200 today (4).

Other data related challenges include the potential for unintended consequences (4). For example, efforts to increase native biota generally include the removal of invasive species (6,8). As a result of their removal, dunes lack stabilizing vegetation, which leads to erosion and inland migration (6,8). While this consequence is often considered acceptable by the various involved stakeholders (8), it is still important to consider such unintended consequences (6). It is also important to consider the time scale of these consequences. As native species establish over time, not only will erosion decrease, but sediment accumulation begins (8).

As with any adaptation measure, the data challenges are exacerbated by uncertainty due to climate change (5). The uncertainty makes it harder to determine the tradeoffs a municipality should prioritize (5). For example, if building a sea wall, a higher wall provides protection for a more extreme sea level rise scenario (5). However, the higher the wall the more it blocks the view of the ocean, which dramatically reduces aesthetics, while a shorter wall could be incorporated into the design of the city to provide services like seating (5).

### *4.2.5. Regulatory Framework*

Another challenge interviewees are concerned about is the regulatory framework. In practice, Sweden does not have clear responsibility allocations for who is responsible for coastal adaptation. There is no authority for coastal flooding at either the national or municipal levels (2). While landowners are legally responsible for managing their coastal hazards through actions such as ensuring their properties are built safely, municipalities often play an informative role and sometimes even take on responsibility of projects (2). Sweden also does not have any standards for coastal protection (2,7A). Instead of creating a project to preset design standards each coastal project goes through a permitting process (2). In terms of the global community, this is a unique way to approach these projects (2). It serves as both an opportunity and a challenge. NbS can be difficult to design to grey infrastructure standards, due to factors such as its context specific nature. Thus, the additional flexibility provided by the permitting process makes the approval process proceed more smoothly (2). Authorities generally have a positive attitude about NbS, which combined with the flexibility in the permitting process, means it may be easier to implement NbS in Sweden compared to many other places in the world.

While this process provides flexibility, it is also very time consuming (2, 4). For example, a beach nourishment project can take five to ten years to process a permit (4). Not only are the permits time consuming, but the process also varies, which makes designing to it difficult, thus increasing the time even more. This is largely because the requirements for the NbS is up to each municipality. Requirements considered include: the socioeconomic benefit, economic perspective, societal perspective, and minimizing damage to the environment (2).

In addition to having varying requirements, the knowledge of the people evaluating the permits varies. Due to coastal adaptation being a relatively small part of the duties of a municipality, the municipality often lacks expertise in this area (2). This can lead to the projects being approved without full evaluation by experts (2). The knowledge gap is exacerbated by people often working in silos (7B,9). Municipalities tend to organize their work according to departments, such as traffic or water, without communicating with other departments (7B). People generally have their expertise, such as engineer or education, without much crossover (7B). This is the opposite of what is needed to implement NbS, which are complex ecological systems that require transdisciplinary knowledge (7B).

The municipalities also have the challenge of balancing equality, as required by the law, with the municipalities need for income to provide services (5). In order to provide public services, municipalities require tax income, which is higher from wealthier areas (5). Also, the people living directly on the coast are generally wealthier (5). This makes ensuring equality in project implementation difficult (5). It is also made difficult due to a mismatch between the law and people’s expectations. While the law states that property owners are responsible for coastal protection, inhabitants are often under the impression the municipality will undertake the protection projects (5). In addition, tourist towns must balance protecting tourist beaches versus beaches favored by families (5). Municipalities have a responsibility to their residents, who use local family beaches (5). However, some towns, such as Halmstad, depend on tourism (5). Thus, for the economy, it is also necessary to protect the tourist beaches. This makes prioritizing protection difficult (5).

# 5. Discussion

This section relates the literature and interview results to each other and the research aim: to explore the utility of NbS for adapting and mitigating risk to coastal hazards in southern Sweden. To put the results into context, additional research was consulted.

## *5.1. Implementation Barriers*

Part of considering the utility of NbS for coastal adaptation in Sweden is considering not only the potential of NbS, but also the current state of NbS. The most common topic raised in the literature, and a common topic in the interviews, was the various implementation challenges facing NbS. These challenges include knowledge gaps, data gaps, space requirements, uncertainty related to the extent of hazard increase under climate change, and regulatory barriers. These barriers are why municipalities are not considering NbS when evaluating coastal adaptation options. For example, Halmstad did not include NbS as a coastal option in their recent flood protection assessment report, instead choosing to focus on a grey infrastructure barrier, such as is shown on Figure 11 (Sweco, 2020). While grey infrastructure may indeed be the best choice, not including NbS in the evaluation could mean the municipality is not optimizing their coastal defense. According to the interviews, this lack of inclusion was largely due to space concerns along the coast. The municipality was not aware of NbS options, such as oyster reefs, that can be utilized offshore similarly to the barriers being considered. This reinforces the interview finding that knowledge sharing and data gaps are a large barrier facing the implementation of NbS.

*Figure 11: A rendering of one of the storm surge barriers being considered by Halmstad (Sweco, 2020)*

One of the difficulties with knowledge and data gaps is that addressing this challenge takes time, to collect data. Taking time to reduce these gaps would mean delaying implementation of NbS projects. It could even result in delaying disaster risk reduction measures more generally since the additional data could help decision makers better compare different options. This could lead to damages if a hazard occurs during the postponement. Additionally, delaying implementation can lead to the project itself costing more. For example, Kassakian et al., (2017) highlight how delaying restoration action in the Delaware Bay could lead to doubling the amount of wetland requiring restoration simply to provide ecosystem services at their current level. Thus, while gathering data is important, it is also critical to make sure addressing this challenge does not lead to postponing implementation.

## *5.2. NbS Works Best Under a Holistic Approach*

From the literature on Design, it is clear that NbS in a wide range of contexts are highly complex systems that require a transdisciplinary approach. Part of the complexity is that NbS provide multiple ecosystem services in the form of regulating services, cultural services, and provisioning services. The three described most often described in the literature, other than risk reduction were carbon sequestration and storage (regulating service), recreation and tourism (cultural service), and support wildlife/biodiversity (provisioning service).

The complexity and multiple benefits of NbS can make assessing and designing projects difficult. Interviews revealed how measures are often implemented in silos due to the separation between government agencies, as presented in the Regulatory Framework section. Agencies work on different policy objectives and time scales, even when there is mission overlap (Froy, 2010), like climate adaptation (Singleton et al., 2021). This leads to each department creating its own infrastructure solution without consideration of other potential parallel efforts, which means the solution will only solve the problem they have been tasked with. For example, SGI's efforts on coastal projects focus on coastal erosion. As a result, if they were to assess a project, they may only account for the erosion protection benefit, rather than assessing other ecosystem services. While this may lead to the best project for mitigating erosion, it could also be a missed opportunity to create a multi-benefit project that also provides other services such as flood protection, biodiversity, and spaces for recreation.

Instead, a joint approach can be used to address the goals of multiple agencies with a single project. As shown on Figure 12, this type of approach could be financially more effective than a traditional one due to both fewer projects being needed to meet the same goals and because NbS can be cheaper than grey infrastructures (Beyer & Anderson, 2020). While this level of collaboration is difficult and rare, there is evidence in the literature that it is possible (Beyer & Anderson, 2020). It can be facilitated through knowledge-sharing programs, which can be achieved through activities like creating a city-wide knowledge platform (Kabisch et al., 2016). Collaboration can also be facilitated through partnerships, not only between government agencies but also with citizens, NGOs, businesses, and any other potential stakeholders (Kabisch et al., 2016).

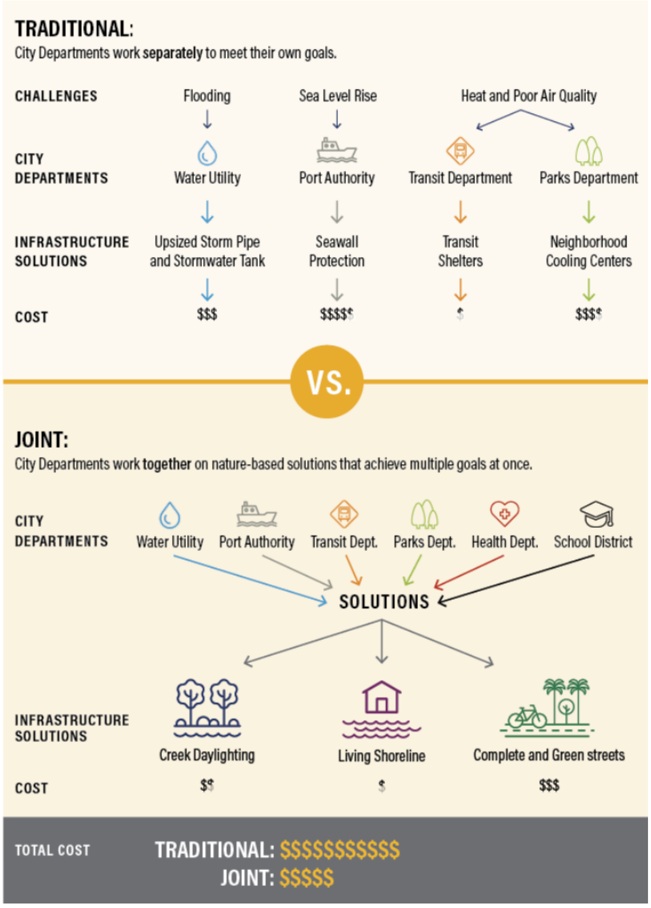


*Figure 12: NbS joint infrastructure Approach compared to traditional approaches (Beyer & Anderson, 2020)*

Incorporating the multiple benefits of NbS during the project assessment is also difficult when using assessment strategies designed for grey infrastructure, where the cost assessments compare the one benefit of risk reduction to costs. For instance, The Europe 2020 strategy explicitly required CBA for major projects (European Commission, 2014). However, this approach can lead to less than optimal outcomes such as prioritizing the protection of areas with higher economic value, which could deepen social inequalities. This cost analysis assessment approach frequently simply compares the economic benefits of risk reduction to the direct costs of the project. This works well for grey infrastructure, which generally has one main benefit (risk reduction), but a large advantage of NbS is the multiple benefits (Whelchel et al., 2018). However, including the additional benefits and the indirect costs is not always simple. While some benefits and costs are easy to quantify, others are more subjective and have no benchmarks, such as the value of cultural goods or recreation (UNFCC, 2011). Perhaps this has been part of the reason that in Sweden "thus far the tendency has been to prioritize economic actors at the expense of others, resulting in insufficient and unequal climate outcomes" (Singleton et al., 2021, p. 2). One way to address these problems is to use a more holistic approach in project assessment. One option is using a multi-criteria analysis to consider adaptation against multiple criteria (e.g. cost, risk reduction, public perception, recreation, and wildlife support) is an option increasingly used in the literature, as it allows a range of stakeholders to assign a weight to each criterion making the approach more participatory and flexible to community's needs (UNFCC, 2011). While multi-criteria analysis are not always participatory, they, along with many other project assessment tools, can be utilized in a participatory manner.

### *5.3. Local Project Assessment and Design*

A common thread through all the themes present in the literature is the amount the specific context impacts every attribute of NbS; such as the topography impacting the scale, both in terms of space and time, necessary for NbS to reach its protection potential. Additionally, the state of the landscape before the implementation of NbS influences whether simple or full installation is needed. Other types of ecosystem services also vary. For instance, the ability of NbS to sequester and store carbon, a regulating service, depends on soil retention capacity and vegetation density. A measure's capacity and the mechanisms by which it supports wildlife and enhances biodiversity, an important provisioning service, is affected by climate and the measure's location compared to migration patterns. The type of recreation enjoyed by the public, a valuable cultural service, depends on local regulations and preferences for recreation.

The location-specific nature of NbS also affects its cost, as is generally true for any type of adaptation measure. Both direct financial costs and indirect costs vary based on contextual factors. Direct costs are affected by cost of building materials, local labor costs and the initial health of the ecosystem at the time of implementation. Indirect costs of grey infrastructure, such as erosion and changes in aesthetics, are dependent on local characteristics such as topography.

This highly location-specific nature means that accurate project assessment should be conducted using context-specific data. An initial step in the planning and design of NbS is deciding what objectives are most important for the project to fulfill. There are frequently trade-offs with trying to optimize ecosystem services. For example, the solution that provides the most risk reduction may not provide as many other co-benefits, thus different objectives must be prioritized to accurately assess whether the NbS will meet the community's needs.

Even the societal challenges that adaptation measures face are context-specific. As highlighted in the interviews, in Sweden, limited coastal data coupled with the regulatory framework hinder the incorporation of NbS into the planning process. The lack of coastal data in Sweden makes it difficult to use context-specific data for coastal NbS. Sweden's coastal regulatory framework is more flexible than most places, which is a significant advantage for implementing NbS. However, it is also highly time-intensive, lacks an incentive structure, and results in projects being evaluated by municipalities that lack the expertise to do a proper evaluation. Low awareness of NbS also impacts public perceptions and openness towards their use for coastal mitigation and adaptation.

### *5.4. NbS Potential to Deepen Inequalities*

The literature in the Equity section found that disaster risk reduction measures are often implemented in a way that deepens inequalities. Benefits are frequently distributed inequitably and who bears the costs is often not the same as who receives the benefits. For example, the literature in Scale Considerations found that upstream residents frequently are benefited, though they do not pay for the downstream land use decisions. Where the space comes from is one of the larger equity concerns for NbS since they are generally space intensive. Despite there being several ways NbS could deepen inequalities, making it an important consideration for Halmstad or any other place implementing NbS, only four of the thirty-eight papers reviewed included equity in their assessments. A recent review by Cousins (2021) confirms the issues of equity is lacking in NbS studies.

This gap is also present in the current Swedish approach to NbS. When gentrification was raised in the interviews, interviewees seemed uncertain whether green gentrification was an issue of concern in Sweden or how they would start to address it. Social justice concerns were also identified as a gap by a intersectionality study conducted by Singleton et al. (2021). They found that in Sweden to date, "climate policy-making has largely focused on technological innovations and economic incentives, with inattention to social dimensions" (Singleton et al., 2021, p. 2). Though key Swedish government agencies mention justice, equity, and equality in their policy documents, this inclusion is currently "rather superficial and unsystematically addressed" (Singleton et al., 2021, p. 16).

Altogether, social justice is something that needs to be considered when implementing adaptation projects to avoid creating and deepening inequalities. While climate justice is not yet fully integrated into Swedish adaptation efforts, there is opportunity to do so. There are a number of frameworks and theories that can help inform about how to implement NbS with consideration to social components and reducing vulnerabilities (Cousins, 2021). These include suggestions such as increasing and broadening participation, and focusing on areas with low financial or institutional capacity (Cousins, 2021).

Part of broadening participation is considering the public's perception of adaptation measures. Similarly to equity, public perception was a theme that emerged from the literature. However, none of the papers had a sole focus on the issue. Findings from the interviews carried out as part of this thesis flagged the deep appreciation for nature, biodiversity, and recreation spaces. The interviewees' experiences also found that with engagement and education, people can become more accepting of NbS as a form of risk mitigation. Combined, this suggests there might be cultural pre-conditions that increase the chances that Swedes accept NbS for coastal adaptation, though previous studies have found the public has had a general preference for grey infrastructure in Sweden (Barquet et al., 2018) and elsewhere (Fernandes & Guiomar, 2018).

### *5.5. NbS as a No-Regret Solution*

Some areas in Sweden face the additional challenge of political opposition to addressing climate change, as described in the Perceptions towards NbS section. This opposition means it may be politically easier to implement adaptation measures that are beneficial regardless of the future impact of climate change. Thus, a no-regret solution may be desirable. A no-regret solution is a measure that is beneficial regardless of whether climate change is more severe than predicted, less severe, or is fully mitigated (ACT, 2013; Baills et al., 2020). The review found that NbS are highly flexible both due to their capacity for self-adaptation and self-repair. This allows risk reduction to be achieved over a larger range of variables. The benefits do not have to only be risk reduction benefits either. They can be tangible, like wildlife services, or intangible benefits, such as education about flooding (Baills et al., 2020). Regardless of climate change, NbS can provide services such as protection against urban heat island effect (Naumann et al., 2014), recreation services, biodiversity, and water protection. This, combined with flexibility, makes NbS generally considered to be no regret (Naumann et al., 2014).

As presented in the Costs section, NbS generally have a higher benefit to cost ratio/cost efficiency than grey infrastructure. However, since NbS require significant space, which can be a challenge in cities, NbS alone may not be enough to fully reduce the risk. Thus, creating a hybrid approach that uses both NbS and grey infrastructure, can be superior than either option on their own. This was supported by Du et al. (2020) who found hybrid approaches overall outperformed either type of adaptation measure. Thus, a hybrid solution may be considered the best no-regret solution.

### *5.6. Limitations of Adaptation*

Adaptation, whether grey, NbS or hybrid, can only go so far in reducing hazard risk. There is no NbS that will reduce wave energy by 100%. One of the challenges brought up in the review and in the interviews was the difficulty of designing a system when the extent of future risk is uncertain. The risk will vary significantly depending on the amount of climate mitigation conducted. Regardless of the amount of adaptation conducted, mitigation is required to reduce risk. Coastal adaptation should not be considered a replacement for climate mitigation.

Even with climate mitigation, it would be prohibitively expensive and simply unaffordable to protect all communities at risk, as research has shown for coastal cities in the US (LeRoy & Wiles, 2019). In these cases, managed retreat, which is "the purposeful movement of people and infrastructure out of" areas vulnerable to hazards (Siders, 2019, p. 239), will need to be at least as part of the solution in some places. Despite this, it was not raised in the literature or in the interviews. However, it is one of the potential responses to increasing coastal hazards. The three options are: (1) Do Nothing; (2) Adapt/Protect; (3) Retreat. Do nothing is generally included in adaptation evaluations as the base case that the adaptation measure is compared against, but retreat is frequently not included at all. While retreat is unpopular and has its own set of concerns it should still be included in these evaluations so that all potential options are considered. The way the literature and adaptation approaches are currently framed makes Do Nothing appear to be the only option when adaptation is infeasible.

# 6. Conclusion

As interest and research in NbS have grown, there is a need to increase understanding of the utility of NbS. As NbS are highly context specific, such utility will be based on the context in which it is being implemented. This thesis sought to increase understanding of the utility of NbS for coastal adaptation in southern Sweden. Understanding the utility includes understanding the main advantages of NbS, challenges they face, and ways in which this field can be improved.

One of the biggest advantages of NbS is that they are not singular in purpose. Instead, each project provides a variety of ecosystem services. While which ecosystem services are provided will depend on the type of NbS and the context in which it is implemented, the ones described most frequently in the literature were carbon sequestration and storage (regulating service), recreation and tourism (cultural service), and support wildlife/biodiversity (provisioning service). However, there can be trade-offs for providing the services. Achieving everything within a single project is infeasible. This makes choosing the design purpose and prioritizing the benefits important.

Another highly valued characteristic of NbS is their increased flexibility, compared to grey infrastructure. Given the uncertainty of the impact of climate change, this additional flexibility is highly beneficial. NbS provide this flexibility through their capacities for self-adaptation and self-repair. Additionally, when NbS do require adaptation it is easier than adapting grey infrastructure. Adding additional soil height to wetlands is easier than adding height to a sea wall.

Not only do NbS have co-benefits and more flexibility than grey infrastructure, but they are also frequently cheaper. While costs are largely context-based, the literature highlighted that NbS are generally more cost effective and have a higher benefit to cost ratio than grey infrastructure. However, costs are likely to be higher in Sweden compared to many developed contexts, partly due to higher expected maintenance costs and partly due to costs associated with the permitting process.

While there are many benefits to NbS, there are also many challenges that they face. Space is one such challenge. Generally, NbS are more space intensive than grey infrastructure. However, coastal NbS can be in the water offshore, making the space requirements easier to meet. Space constraints in urbanized coasts calls for more hybrid approaches that combine grey, green and blue infrastructures.

Implementation of NbS can be hindered by the regulatory framework, which is highly context specific. In Sweden, this process is both an advantage, due to its flexibility, and a disadvantage, due to the permitting process time intensive nature and lack of an incentive structure.

Another challenge hindering coastal NbS in Sweden is the lack of coastal data. Lack of data makes project assessment and decision making more difficult. Collecting more data takes time, but delaying implementation to remedy the lack of data could lead to higher implementation costs and could lead to more damages if a hazard occurs during postponement.

Another common challenge is approaching NbS in a silo. NbS are inherently interdisciplinary, so studying them in the traditional single disciplinary approach can miss critical linkages.

Similarly, assessing these projects in a silo can reduce the benefits considered in project evaluation. Silo organizational structures in municipalities and other government structures are one of the main challenges for implementation, in contrast to grey infrastructure, where the allocation of responsibilities and budget lines are clearer. This can be addressed through collaboration and knowledge sharing programs.

Another way the field of NbS can be improved is in the project assessment stage. Traditional methods of assessing adaptation measures, such as CBA, are generally insufficient for NbS, due to factors such as their multiple benefits. Multicriteria analysis can provide an improved alternative for evaluating NbS projects. One of the benefits of multicriteria analysis is the way different criteria are weighted can be determined by the various stakeholders. Since research shows perception plays a significant role in the success of a project, being able to include the public's perception in decision making is important. In Sweden, the public seem most interested in risk reduction, cost, biodiversity, and recreation.

Another way this field can improve is more consideration of social justice. There are concerns about NbS deepening inequalities, such as the unequal distribution of benefits and costs and NbS leading to green gentrification. Despite these concerns, equity is an understudied and under considered aspect of NbS, both in Sweden and in the literature at large.

NbS offer many benefits for coastal defense. While there are challenges which can and should be addressed through further research and modifying planning processes, this can be done while simultaneously implementing NbS projects.

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# Appendices

## *Appendix A – Literature included in the Review*

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## *Appendix B – Interview Guides*

### Interview Guide for Björn Almström (1)

1. What coastal NbS measures do you think would work in Sweden (particularly Halmstad/the west coast)? Both from an ecosystem appropriateness and from a land availability
    - Wetlands, oyster reef, seagrass, dunes, coral reefs….
2. What grey and NbS measures are pretty comparable for costs and benefits?
3. What NbS could work?
    - Halmstad right now is considering using a storm surge barrier to protect against coastal inundation. I think they are concerned about keeping access to the port, any ideas for what could work?
4. Do you know of any coastal NbS or Ecosystem Based Adaptation Projects in Sweden (West Coast) such as beach nourishment
    - What challenges did they face?
    - Do you know what costs they project had (both monetary and other)
    - Unexpected impacts
    - What benefits did they projects have?
    - Were they successful?
    - Is there anyone you can think of that might be good to talk to about these projects?
5. How do you think the general public perceive NbS in Sweden? How do they view them compared to grey infrastructure?
    - Would people accept them as a coastal protection?
6. What challenges do NbS face in Sweden?
    - Regulatory? (the literature mentions that engineering standards aren't designed with NbS type projects in mind)
    - Push/pull EU and Sweden are simultaneously incentivizing and regulating.
    - Public acceptance?
    - Modeling?
    - Governance structure?
7. What do you think the non-risk reduction benefits of coastal NbS in Sweden are (give examples?)
    - Can these be achieved in Halmstad/west coast?
8. What non-risk reduction benefits and costs are tend are of concern in coastal grey infrastructure in western Sweden?
9. What do you think Halmstad could do besides raise the port?
10. Do you think Sweden has any unique challenges when it comes to adapting to climate change?
11. Are the costs of NbS in Sweden comparable to other locations in the western world (Europe, US, Australia, New Zealand, Canada)?
12. What criteria is most important to you when considering adaptation measures?
    - Total Cost
    - Cost Effectiveness
    - Tourism, recreation, and Cultural heritage
    - Risk reduction
    - Flexibility
    - Social justice
    - Any others
13. Challenges related to cost estimation of NbS in Sweden?
14. Is flooding or erosion generally the bigger concern in Western Sweden?
15. What NbS work well in Sweden?

**Interview Guide for Caroline Hallin (2)**

1. What Coastal NbS measures do you think would work in Sweden (particularly Halmstad/the west coast)? Both from an ecosystem appropriateness and from a land availability
    - Wetlands, oyster reef, seagrass, dunes, coral reefs….
2. What grey and NbS measures are pretty comparable for costs and benefits?
3. What NbS could work?
    - Halmstad right now is considering using a storm surge barrier to protect against coastal inundation. I think they are concerned about keeping access to the port, any ideas for what could work?
4. Do you know of any Coastal NbS or Ecosystem Based Adaptation Projects in Sweden (West Coast) such as beach nourishment?
    - What challenges did they face?
    - Do you know what costs they project had (both monetary and other)
    - Unexpected impacts
    - What benefits did they projects have?
    - Were they successful?
    - Is there anyone you can think of that might be good to talk to about these projects?
5. How do you think the general public perceive NbS in Sweden? How do they view them compared to grey infrastructure?
    - Would people accept them as a coastal protection?
6. What challenges do NbS face in Sweden?
    - Regulatory? (the literature mentions that engineering standards aren't designed with NbS type projects in mind)
    - Push/pull EU and Sweden are simultaneously incentivizing and regulating.
    - Public acceptance?
    - Modeling?
    - Governance structure?
7. What do you think the non-risk reduction benefits of coastal NbS in Sweden are (give examples?)
    - Can these be achieved in Halmstad/west coast?
8. What non-risk reduction benefits and costs are tend are of concern in coastal grey infrastructure in western Sweden?
9. What do you think Halmstad could do besides raise the port?
10. Do you think Sweden has any unique challenges when it comes to adapting to climate change?
11. Are the costs of NbS in Sweden comparable to other locations in the western world (Europe, US, Australia, New Zealand, Canada)?
    - Who can I talk to on this?
12. What criteria is most important to you when considering adaptation measures?
    - Total Cost
    - Cost Effectiveness
    - Tourism, recreation, and Cultural heritage
    - Risk reduction
    - Flexibility
    - Social justice
    - Any others

**Interview Guide for Charlotta Lövstedt (3)**

1. What Coastal NbS measures do you think would work in Sweden (particularly Halmstad/the west coast)? Both from an ecosystem appropriateness and from a land availability
    - Wetlands, oyster reef, seagrass, dunes, coral reefs….
2. How do you think the general public perceive NbS in Sweden? How do they view them compared to grey infrastructure?
    - Would people accept them as a coastal protection?
3. What challenges do NbS face in Sweden?
    - Regulatory? (the literature mentions that engineering standards aren't designed with NbS type projects in mind)
    - Push/pull EU and Sweden are simultaneously incentivizing and regulating.
    - Public acceptance?
    - Modeling?
    - Governance structure?
4. What do you think the non-risk reduction benefits of coastal NbS in Sweden are (give examples?)
    - Can these be achieved in Halmstad/west coast?
5. Do you think Sweden has any unique challenges when it comes to adapting to climate change?
6. Are the costs of NbS in Sweden comparable to other locations in the western world (Europe, US, Australia, New Zealand, Canada)?
7. What criteria is most important to you when considering adaptation measures?
    - Total Cost
    - Cost Effectiveness
    - Tourism, recreation, and Cultural heritage
    - Risk reduction
    - Flexibility
    - Social justice
    - Any others
8. Is erosion or flooding a bigger coastal concern in Halmstad?
9. What do you think Halmstad could do to adapt to Coastal Flooding?
10. Why do you think Halmstad isn't considering NbS for Coastal solutions?
11. Are there any other benefits of coastal adaptation (grey or NbS) that we haven't talked about yet that you can think of?
12. Are there any other costs of coastal adaptation (grey or NbS)?

**Interview Guide for Emanuel Schmidt (4)**

1. What Coastal NbS measures do you think would work in Sweden (particularly Halmstad/the west coast)? Both from an ecosystem appropriateness and from a land availability
    - Wetlands, oyster reef, seagrass, dunes, coral reefs….
2. How do you think the general public perceive NbS in Sweden? How do they view them compared to grey infrastructure?
    - Would people accept them as a coastal protection?
3. What challenges do NbS face in Sweden?
    - Regulatory? (the literature mentions that engineering standards aren't designed with NbS type projects in mind)
    - Push/pull EU and Sweden are simultaneously incentivizing and regulating.
    - Public acceptance?
    - Modeling?
    - Governance structure?
4. What do you think the non-risk reduction benefits of coastal NbS in Sweden are (give examples?)
    - Can these be achieved in Halmstad/west coast?
5. Do you think Sweden has any unique challenges when it comes to adapting to climate change?
6. Are the costs of NbS in Sweden comparable to other locations in the western world (Europe, US, Australia, New Zealand, Canada)?
7. What criteria is most important to you when considering adaptation measures?
    - Total Cost
    - Cost Effectiveness
    - Tourism, recreation, and Cultural heritage
    - Risk reduction
    - Flexibility
    - Social justice
    - Any others
8. Is erosion or flooding a bigger coastal concern in Halmstad?
9. What do you think Halmstad could do to adapt to Coastal Flooding?
10. Why do you think Halmstad isn't considering NbS for Coastal solutions?
11. Are there any other benefits of coastal adaptation (grey or NbS) that we haven't talked about yet that you can think of?
12. Are there any other costs of coastal adaptation (grey or NbS)?

**Interview Guide for Hanna Billmayer (5)**

1. Is Halmstad worried about beach erosion or flooding?
    - Do you add sand to the beach?
2. Does Halmstad dredge the harbor?
3. Do the beaches have dunes?
4. Why weren't coastal NbS considered in the recent Halmstad Flood Protection report?
    - It looks like only a storm surge barrier was considered
5. What Coastal NbS measures do you think would work in Halmstad Both from an ecosystem appropriateness and from a land availability
    - Wetlands, oyster reef, seagrass, dunes, coral reefs….
6. How do you think the general public perceive NbS in Halmstad? How do they view them compared to grey infrastructure?
    - Would people accept them as a coastal protection?
7. What do you think the challenges of NbS are in Halmstad?
8. What do you think the non-risk reduction benefits of coastal NbS in Halmstad are (give examples?)
9. What non-risk related costs or benefits are you concerned about for grey infrastructure in Halmstad?
10. What challenges do NbS face in Halmstad?
    - Regulatory? (the literature mentions that engineering standards aren't designed with NbS type projects in mind)
    - Push/pull EU and Sweden are simultaneously incentivizing and regulating.
    - Public acceptance?
    - Modeling?
    - Governance structure?
11. What criteria is most important to you when considering adaptation measures?
    - Total Cost
    - Cost Effectiveness
    - Tourism, recreation, and Cultural heritage
    - Risk reduction
    - Flexibility
    - Social justice
    - Any others
12. Do you think Halmstad or Sweden have any unique challenges when it comes to adapting to climate change?
13. What beaches are most important to keep for tourism in Halmstad?
14. Are the costs of NbS in Sweden comparable to other locations in the western world (Europe, US, Australia, New Zealand, Canada)?
    - Who can I talk to on this?

**Interview Guide for Magnus Larsson (6)**

1. What challenges do NbS face in Sweden?
    - Regulatory? (the literature mentions that engineering standards aren't designed with NbS type projects in mind)
    - Push/pull EU and Sweden are simultaneously incentivizing and regulating.
    - Public acceptance?
    - Modeling?
    - Governance structure?
2. Do you know of any Coastal Nature Based Solutions or Ecosystem Based Adaptation Projects in Sweden (West Coast) such as Falsterbo (beach nourishment) & Ystad (beach nourishment)
    - What challenges did they face?
    - Do you know what costs they project had (both monetary and other)
    - Unexpected impacts
    - What benefits did they projects have?
    - Were they successful?
    - Is there anyone you can think of that might be good to talk to about these projects?
3. How do you think the general public perceive NbS in Sweden? How do they view them compared to grey infrastructure?
    - Would people accept them as a coastal protection?
4. What NbS could work?
    - Halmstad right now is considering using a storm surge barrier to protect against coastal inundation. I think they are concerned about keeping access to the port, any ideas for what could work?
5. What criteria is most important to you when considering adaptation measures?
    - Total Cost
    - Cost Effectiveness
    - Tourism, recreation, and Cultural heritage
    - Risk reduction
    - Flexibility
    - Social justice
    - Any others
6. What do you think the non-risk reduction benefits of coastal NbS in Sweden are (give examples?)
    - Can these be achieved in Halmstad/west coast?
7. What non-risk reduction benefits and costs are tend to be of concern in coastal grey infrastructure in western Sweden?
8. Are the costs of NbS in Sweden comparable to other locations in the western world (Europe, US, Australia, New Zealand, Canada)?
9. Challenges related to cost estimation of NbS in Sweden?
10. Is flooding or erosion generally the bigger concern in Western Sweden?
11. What NbS work well in Sweden
12. Do you think Sweden has any unique challenges when it comes to adapting to climate change?

**Interview Guide for Swedish Environmental Protection Agency (7) with Anki Weibull (7A) and Timo Persson (7B)**

1. What do you see as the NbS with the potential to work as Coastal Adaptation in Sweden?
    - Wetlands, oyster reef, seagrass, dunes, coral reefs….
2. What are the biggest challenges in implementing coastal NbS?
3. Ex: regulatory, governance structure, public acceptance, modeling/data
4. Do you think Halmstad or Sweden have any unique challenges when it comes to adapting to climate change?
5. What are the biggest NbS co-benefits that you think Sweden is interested in?
6. How do you think the general public perceives NbS as a risk reduction measure?
7. Are the costs of NbS in Sweden comparable to other locations in the western world (Europe, US, Australia, New Zealand, Canada)?
8. Do you think municipalities are widely looking at NbS solutions for coastal adaptation?
    - Why do you think they aren't being considered more widely?
    - What barriers do you think need to be overcome?
9. Are there other costs of coastal adaptation, other than the direct financial cost?
10. What criteria do you think is most important when considering adaptation measures?
    - Total Cost
    - Cost Effectiveness
    - Tourism, recreation, and Cultural heritage
    - Risk reduction
    - Flexibility
    - Social justice
    - Any others
11. Should Sweden (especially the Halmstad area) be most concerned with erosion or flooding?
12. Which problem do NbS have the most potential to help address

**Interview Guide for Jessica Gunnarsson (8)**

1. What have been the big challenges with implementing the sand field?
2. What are the costs associated with the project?
3. What level of risk reduction and other benefits are you expecting with the project?
4. How do you think the general public perceive NbS in Halmstad? How do they view them compared to grey infrastructure?
    a. Would people accept them as a coastal protection?
5. What do you think the challenges of NbS are in Halmstad?
6. What criteria is most important to you when considering adaptation measures?
    a. Total Cost
    b. Cost Effectiveness
    c. Tourism, recreation, and Cultural heritage
    d. Risk reduction
    e. Flexibility
    f. Social justice
    g. Any others
7. What Coastal NbS measures do you think would work in Halmstad Both from an ecosystem appropriateness and from a land availability
    a. Wetlands, oyster reef, seagrass, dunes, coral reefs….
8. What beaches are most important to keep for tourism in the Halmstad area?
9. Do you think Halmstad or Sweden have any unique challenges when it comes to adapting to climate change?

**Interview Guide for Anette Björlin (9)**

13. Should Sweden (especially the Halmstad area) be most concerned with erosion or flooding?
    - It looks like the catalog is focused on erosion, is that because it is SGI's mandate area or because it is viewed as a larger issue in Sweden?
    - What problem do you think NbS have the biggest potential to address in Sweden?
14. What do you see as the coastal NbS with the most potential in in Sweden?
    - Wetlands, oyster reef, seagrass, dunes, coral reefs….
15. What are the biggest challenges in implementing coastal NbS?
    - Ex: regulatory, governance structure, public acceptance, modeling/data
    - Do you think Sweden has any unique challenges when it comes to adapting to climate change?
16. Do you think municipalities are widely looking at NbS solutions for coastal adaptation?
    - Why do you think they aren't being considered more widely?
    - What barriers do you think need to be overcome?
17. What do you see as SGI's role in NbS? (e.g. knowledge source)
    - How you disseminate the catalog?
    - How do you find projects to include in the catalog?
18. What criteria do you think is most important when considering adaptation measures?
    - Total Cost
    - Cost Effectiveness
    - Tourism, recreation, and Cultural heritage
    - Risk reduction
    - Flexibility
    - Social justice
    - Any others
19. What are the biggest NbS co-benefits that you think Sweden is interested in?
20. Are the costs of NbS in Sweden comparable to other locations in the western world (Europe, US, Australia, New Zealand, Canada)?
21. Are there other costs of coastal adaptation, other than the direct financial cost?
22. How do you think the general public perceives NbS as a risk reduction measure?
23. Any other things you've learned in the process of creating the catalog?