Quantifying the Climate Mitigation benefits of Nature-based “Green” Flood Control Infrastructure

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Disclaimer

This report was produced as part of the UBC Sustainability Scholars Program, a partnership between the University of British Columbia and various local governments and organisations in support of providing graduate students with opportunities to do applied research on projects that advance sustainability across the region.

This project was conducted under the mentorship of Watershed Watch Salmon Society staff. The opinions and recommendations in this report and any errors are those of the author and do not necessarily reflect the views of Watershed Watch Salmon Society or the University of British Columbia.

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Executive Summary

In coastal areas, the development of flood control defenses is essential to protect human communities and their livelihoods. Over the past century, "grey" flood control infrastructure (such as floodgates, dams, and seawalls) has become ubiquitous in coastal areas. The proliferation of this infrastructure is associated with unwanted ecological and environmental side effects as well as ever-rising construction and maintenance costs. In contrast, "green" flood control infrastructure (such as mangrove forests, marshes, and seagrasses) offers nature-based solutions for flood control that also improve fish assemblage, aquatic biodiversity, and flood resiliency at a lower cost. There is a paradigm shift underway from traditional flood control infrastructure to green alternatives, including nature-based solutions and hybrid green-grey flood control infrastructure (such as natural shoreline armouring, set-back dikes and fish-friendly flood gates and pumps). While green flood control infrastructure can provide many benefits compared to grey flood control infrastructure, these benefits are not well quantified. One benefit that is very poorly documented is the climate mitigation potential of green/nature-based flood control solutions, i.e., their sequestration of greenhouse gases as compared to grey infrastructure. There is a need to evaluate how green infrastructure can help to support climate mitigation goals. This project aims to quantify and compare the climate mitigation benefits of nature-based "green" flood control infrastructure and traditional "grey" constructions. The key objectives of the project were to:

1. conduct a literature review and collect information on grey and green flood control infrastructure used in river floodplains, including marshes, and tidal channels;
2. quantify and compare the ecological benefits and the lifetime greenhouse gas emissions/sequestration uses of grey and green infrastructures;

3. conduct a comparative assessment of the economic costs of grey and green infrastructure; and,
4. identify gaps in the current information and provide recommendations for future research.

Based on this work, it was found that replacing grey infrastructure with green, or choosing to install green infrastructure instead of grey could offer improvements in habitat quality, fish migration, and aquatic biodiversity. Incorporating nature-based green FCI offers protection from floods and sustains or restores habitat and aquatic biodiversity. However, there is a dearth of comparable data on GHG emissions and carbon sequestration for green and grey infrastructure. For the studies that do exist, there are a wide range of units of measurement and a lack of data standardization that would be needed to allow the different types of infrastructure to be compared.

From an economic point of view the implementation of green infrastructures offers cost-effective alternatives for flood protection while enhancing opportunities of economic importance not provided by traditional coastal defenses.

Based on an analysis of literature and data on GHG emissions, this report identifies information gaps and offer a set of recommendations to be considered for future work, to better understand the climate mitigation benefits of green flood control infrastructure. It was found that very little information is available to understand and compare the climate mitigation properties of the different types of green FCI and how they compare to grey FCO.

The key recommendations is that life cycle assessments and cost analyses should be performed to understand the climate mitigation properties of the different types of green FCI and how they compare to grey FCI.

Introduction

In estuaries and coastal floodplains, the development of flood control infrastructure (FCI) is a common practice to diminish or prevent the detrimental effects of floodwater on communities, infrastructure, and farms. Some of the most common methods used for flood control include the construction of levees, dikes, dams, which are commonly referred to as ‘grey FCI’. It is well established that grey FCI affects aquatic connectivity and ecosystems. For example, in North America, Europe and Northern Asia, 71% of large river systems are controlled by dams or the water flow is modified with dikes and levees that often dampen flow regimes and reduce river floodplain connectivity (Dynesius and Nilsson 1994; Arthington et al. 2010). In addition, grey FCI can affect shoreline biodiversity, biogeochemical cycling, and fish production. In many instances, existing grey infrastructure is inadequate to address increased flood risk due to climate change, and it requires costly maintenance.

To overcome these challenges, there is growing interest in the development of nature-based alternatives, which are also called “green” FCI. Green FCI is ecosystem-based flood defenses that are more sustainable and cost-effective than grey FCI, while controlling flooding (Morris et al., 2018). Green FCI can stabilize shorelines in a more natural manner thus providing several added benefits such as improving water quality, fisheries production, marine biota, and the ecological and recreation value of the coast. From an environmental perspective, the construction and development of green FCI is associated with less GHG emissions and environmental impacts (Heery et al., 2020). The systematic evaluation of these impacts via a Life Cycle Assessment (LCA) would provide an opportunity to assess the biological and environmental consequences of grey and green infrastructure types. This information would help to support climate change mitigation and sustainability goals.

Green FCI tends to consume more space than grey infrastructure in highly urbanized coastal cities where space is a limited resource. Under such circumstances, the development of green FCI can be replaced with intermediate alternatives between grey and green i.e., hybrid or grey-green infrastructure. Hybrid infrastructure is a combination of nature-based and built structures e.g., a shellfish reef placed in front of a seawall can form the first line of defense against storm surges, as well as offering other services such as water filtration and biodiversity enhancement.

This project aimed to quantify and compare the climate mitigation benefits of nature-based "green" flood control infrastructure and traditional "grey" constructions. Based on an analysis of literature and data on GHG emissions, this report identifies the significant information gaps in the literature, and offers a set of recommendations to be considered for future work.

Methodology of Literature Review

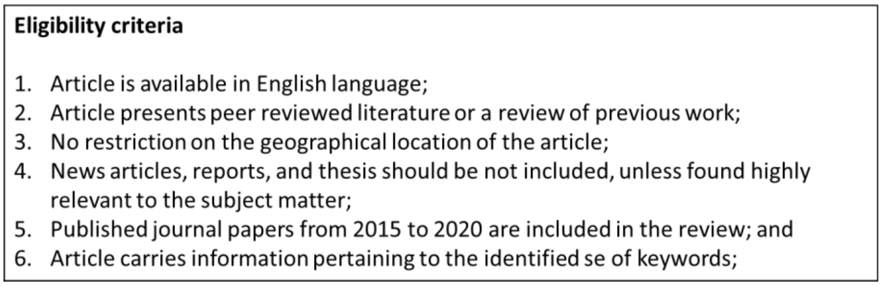
To achieve the objective of the project, the methodology of systematic literature review was followed to identify, collect, and evaluate the relevant literature on flood control infrastructure and its impacts. Systematic literature review refers to a "practice of collecting all empirical evidence that match the pre-specified eligibility criteria and helps to answer a research question in organized fashion". In general, this task starts by defining the research question, identifying keywords, establishing inclusion and exclusion criteria, searching literature within scientific databases, record keeping of articles, and their evaluation as per the question. To avoid researchers' bias, this process follows an iterative investigation rather than linear or sequential methods. As a result, the final output provides a comprehensive summary of the existing knowledge on the given subject while maintaining a certain level of precision and accuracy.

Following this methodology, this literature review started with the identification of electronic databases and keywords to be used to search literature. For preliminary assessment, the literature was searched within Google Scholar, followed by final assessment within Science Direct and Engineering Village. A record of keywords was maintained and updated to obtain more refined results (Table 1). Then, the reviewer established an inclusion and exclusion criteria to complete sorting and screening of the articles (Table 2). For initial screening, the reviewer considered the title, summary or abstract of the articles. As a result, duplicate records were removed, and a selection of the most relevant articles were obtained for detailed analysis. The full-text PDF for each of the articles in final selection was obtained, formatted with Adobe Acrobat X Pro^{R} for text recognition, and imported into Mendeley library to proceed further with the extraction of information and analysis. The schematics of the systematic literature review as followed in this research are provided in Figure 1.

Table 1. List of keywords used in the search of literature.

1st priority keywords	**2nd priority keywords**
Tide gates, Dikes, Impoundment, Dam, Flood mitigation, Flood control, Salmon, Fish behaviour Habitat availability, Migratory delay, Salt marsh, Living shorelines	Coastal resilience, Coastal flooding, Flood risk control, Fish diversity, Nature-based infrastructure, Soft engineering, Life-cycle costs, Carbon sequestration, Methane emissions

Table 2 List of criteria for selection of literature.



Eligibility criteria

1. Article is available in English language;
2. Article presents peer reviewed literature or a review of previous work;
3. No restriction on the geographical location of the article;
4. News articles, reports, and thesis should be not included, unless found highly relevant to the subject matter;
5. Published journal papers from 2015 to 2020 are included in the review; and
6. Article carries information pertaining to the identified se of keywords;

Data collection and analysis

Considering the objectives of this project, various data were collected from the literature as given below:

- Explanation, application, and examples of traditional infrastructure used for flood control in river floodplains and their tidal marshes ;
- Description, application, and examples of green infrastructure used for flood control in river floodplains and their marshes and tidal channels;
- Literature was sorted to collect information on fish movement, water quality parameters, species richness and abundance, migratory behavior, passage efficiency, and hydrological connectivity. The literature was used to compare the environmental impacts of traditional and fish-friendly flood control retrofits and their benefits to fish habitat;
- To assess greenhouse gas emissions/sequestration, data were collected on carbon accumulation, CO_2 capture potential, GHG efflux, CH_4 efflux, and carbon sequestration rates related to various stages of structure’s lifecycle; and
- Cost-effectiveness and other related benefits of green and traditional flood control infrastructures were recorded to compare economic costs.

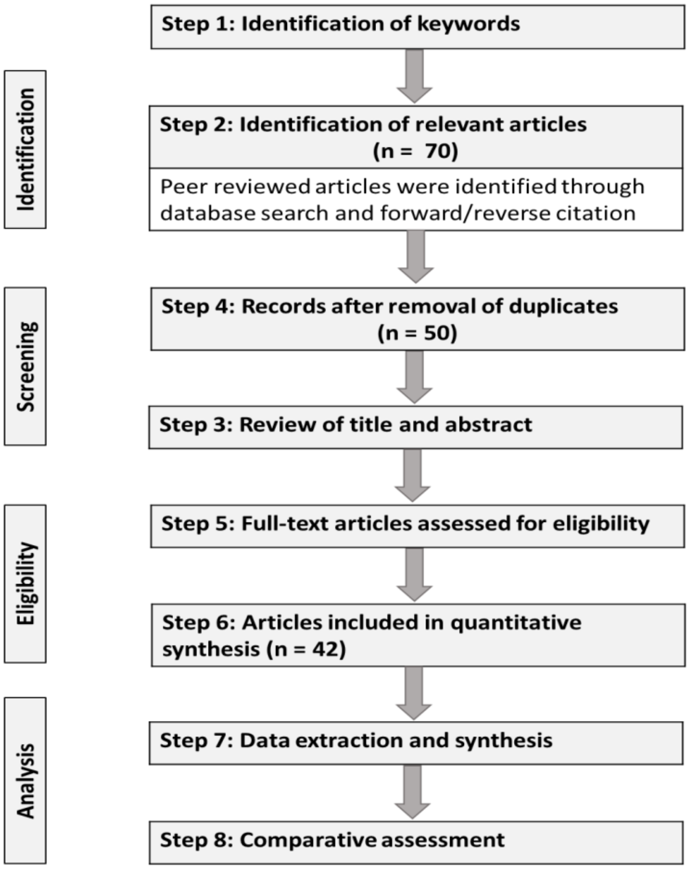


Figure 1 Steps of the systematic literature review.

Virtual Tour

Considering the travel restrictions due to COVID19, a virtual tour was organized on Jan 28, 2021 and Dan Straker from Resilient Waters and Lina Azeez from Watershed Watch Salmon Society guided this activity. This activity aimed to provide context for the project, including clarification on the possible range of flood control solutions in the lower Fraser/ BC, and a description of the kinds of ecological restoration that might accompany different types of flood control solutions. The agenda items discussed in that tour included the following:

- Brief background on the origins and purpose of this project;

- Clarify the difference and overlap between fish-friendly (FF) and nature-based flood control solutions as they apply in the lower Fraser and other parts of BC
    - Fish-friendly flood gate
    - Fish-friendly pump station
- Set back dikes and dike breach overview case studies of FF tide gates and flood boxes;
- Discuss the kinds of nature-based solutions that might be possible in the lower Fraser and other areas of BC
    - Pitt Addington Marsh
    - Backwash Ferry Island
- Describe projects identified through Resilient Waters that include nature-based solutions and/or ecological restoration that would sequester carbon
- Share photos / google earth images of priority fish-friendly and nature-based projects (or projects in other jurisdictions) to clarify the range of fish friendly and nature-based options in BC.
    - Maple Creek, Port Coquitlam
    - Katzie Slough, Pitt Meadows (2 sites)
    - Yorkson Creek, Township of Langley
    - Colony Farm, Coquitlam
    - Zeits Slough, Nicomen Island
    - Tilbury Slough, Delta
    - Chillukthan, Delta

Results

Traditional and Green flood control infrastructure

Based on the literature review, a summary of grey (traditional) and green infrastructure was gathered and is presented in Tables 3 and 4 and Figure 2.

Table 3 Description of grey flood control infrastructure.

Infrastructure	Description	Potential Impacts	Location of study
Floodgate	Floodgates are culverts that consist of a flap gate mounted on the downstream side that allow drainage out to the main river while preventing the water from collecting behind the protective dikes. The operation of the floodgate requires a hydraulic head difference across the gate where upstream accumulated water exerts pressure, pushes the gate to open, and allow passage of water and fishes.	In general, the operation of floodgates are known to affect the water quality and restrict fish passage during migration. Unavailability of unimpeded access along waterways hamper survival and reproduction leading to localized extinction of native fish.	Lower Fraser River British Columbia, Canada
Tide gates	Tide gates are similar to flood gates and close during rising tidal inflow into estuaries and open to release accumulated water on the upstream side into the water body. Commonly, the use of tide gates restricts access to the estuary and converts tidal marshes into agricultural lands and pastures.	Tide gates are effective to maintain low water levels on the upland side of a coastal barrier. The presence of these gates prevents the circulation of water between both sides of barrier and alter water temperatures, soil moisture level, sediment movement, and channel design.	River Stiffkey, North Norfolk, UK

Sluice gate	A sluice is a water channel or canal regulated at its head by a barrier or gate. Traditionally, sluice gates are made up of wood or metal and slide in grooves that are designed in the sides of water channel. In majority of the cases, sluice gates are raised during the rising tide to allow water to flow in. These gates are lowered with the returning tide and water may spill over the top of gates, in which situation the gates act as weir.	Sluice gates impart negative environmental impacts with change in the water flow pattern in the canal, riverine habitat, fish diversity, and livelihood stability.	River Dee, North Wales, UK
Low head dam	A low head dam is a barrier built across the width of a river to alter the height of the water level and to control the flow. The main purpose of a low head dam is to impound water behind a wall and raise the water level upstream.	From a fish perspective, the negative impacts include being a barrier to fish passage, as well as potentially affecting the quality of the flooded habitat upstream, and sediment movement downstream. In many instances, these dams are considered a threat to human lives because the water falling over the dam recirculates back on itself at the base of the dam and forms a deadly trap, which is difficult to escape.	Qingyi River, China
Dikes	A dike or levee is an elongated embankment that runs parallel to the course of a river in its floodplain or along low-lying coastlines. Dike may occur naturally or constructed artificially to control water levels in the area.	Most importantly, dikes are useful to mitigate flood frequency and severity, thus reduce the chances of floodplain inundation.	Mississippi levee system

Shoreline armouring structures	Shoreline armouring structures include seawalls and riprap structures for protection against scour and water and wave erosion. A seawall is a static structure that prevents the sediments' exchange between land and sea and works to protect areas of human settlement, conservation, and leisure activities. In addition, shoreline armouring also includes the construction of overwater structures, such as piers, docks, that facilitate the use of waterfront area.	The construction of a solid structure, such as a seawall, eliminates shoreline habitat, causes erosion, and is expensive to build and maintain. Curved seawalls reflect or dissipate energy of incoming wave and creates turbulence, which may lead to the erosion of structure.	Puget Sound, Washington, USA Hudson River, New Jersey and New York, USA

Table 4 Description of green flood control infrastructure.

Structure	Description	Potential Impacts	Location of study
Mangroves	Mangroves are salt-tolerant shrubs that are adapted to grow in anoxic conditions prevalent in intertidal coastal areas. Worldwide, mangrove plantations are found in the tropic and subtropics regions and are known to protect coastal areas from soil erosion, hurricanes, and tsunamis.	Considering climate change, coastal mangroves exceed most other forests in their capacity to store carbon and are recognized as the most important carbon sinks in the world.	Florida, USA Hanjiang River Estuary, Guangdong province, China
Wetlands and Marshes	A wetland is low-lying area that provides a transition zone by connecting land and water. A wetland can be saturated with water permanently because the water table is close to the land surface for most part of the year. Due to the presence of a high water table, the wetlands nourish a broad diversity of aquatic plants, animals, and insects thus, are considered a highly productive ecosystem of the world. Marshes are a type of wetland that form the transition zone between aquatic and land ecosystems and have herbaceous plants such as grasses, rushes, or sedges. In general, marshes are quite shallow and provide habitat and nourishment to a variety of aquatic invertebrates. Based on the location and salinity contents, marshes can be divided into three types: tidal freshwater marshes, tidal saltwater marshes and inland freshwater marshes. Tidal freshwater marshes are affected by tides but, these are further inland from the coast area and contain fresh water whereas, tidal saltwater marshes are close to the coast and have high salt	From an environmental perspective, wetlands play a crucial role to prevent flooding, filter pollutants, and reduce soil erosion. Preserving and protecting wetlands is critically important to reduce storm damage. The use of wetlands for flood control may vary, and depends on the size, slope, location of the wetland, type and condition of plants, and the saturation level of soils before flooding. Trees, shrubs and other wetland plants help reduce the speed of floodwaters.	New Orleans, USA Humber estuary, UK San Francisco Bay, California Wadden Sea, The Netherlands New Orleans, USA Dover, Delaware, USA Port Phillip Bay, Victoria, Australia

	contents. Inland freshwater marshes are shallow in nature and occur in lake basins and low-lying depressions.		
Beach Nourishment	Beach nourishment, often called beach filling, is an artificial process of adding large quantities of sediment to a beach that offers recreational and aesthetic benefits and enhances the original shoreline. Contrary to hard structures, it is a soft engineering alternative that protects infrastructure and buildings from storm surge, creates and restores natural environments, and stabilizes the shoreline.	Beach nourishment may negatively impact vegetation and animals as they are buried by the sand placement. If the nourished beach is too steep, turtles cannot use it for laying eggs.	Coney Island, New York
Vegetated Dune	Dunes are a natural coastal feature formed by sand, which blows inland from the beach and deposits in an area behind the coastline. Vegetation plays an important role in dune stabilization. The leaves of grass and other beach plants on a dune functions as a collector for blowing sand, which stays where it lands and starts to pile up. Also, the growth of plants sends out roots in the soil that further trap and stabilize the sand particles thus making the dune stronger and resistant to erosion.	Dunes act as a flexible barrier that protect the area from erosion and flooding.	North Carolina
Living dikes	Living dikes are a nature-based system that consists of soft foreland and a mobile dike made up of sands, gravel, and dune grasses. As opposed to static structures, living dikes imitate the natural shoreline with the ability to move and self-heal in response to high water and changes in sea level.	Regarding benefits to environment, living dikes provide necessary flood protection and preserve the shoreline and nearshore areas in response to sea levels rise and climate change.	Boundary Bay, BC

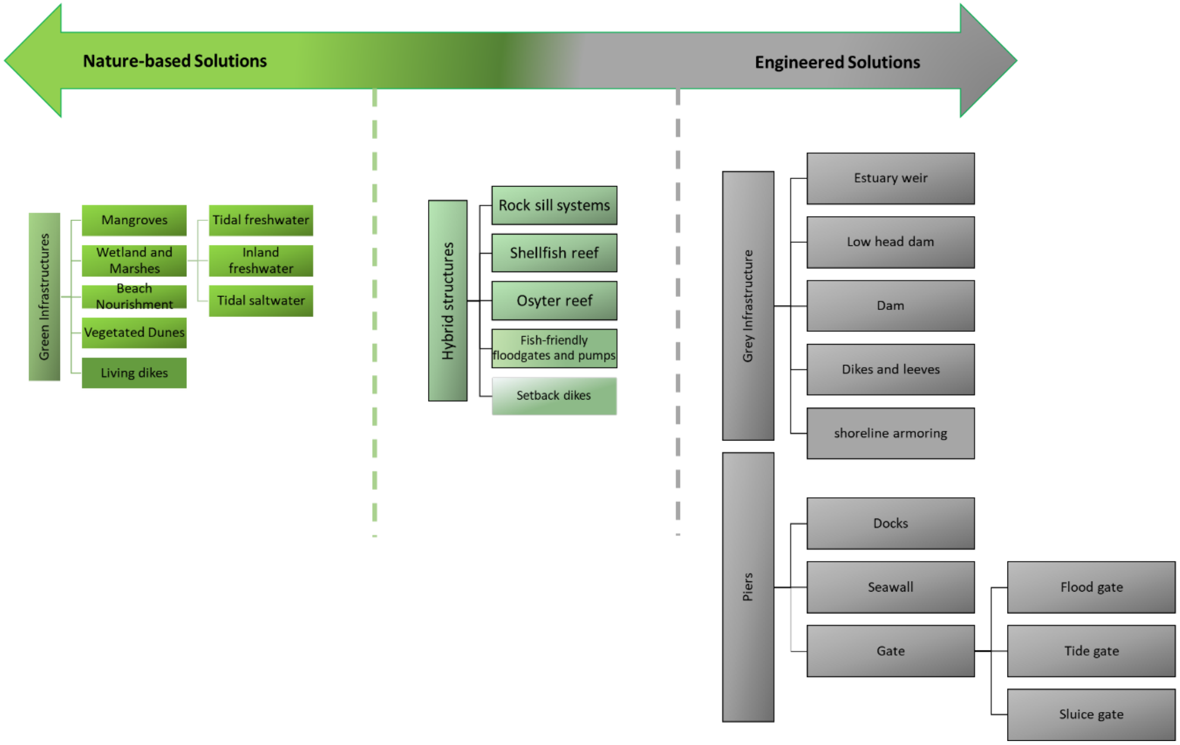


Figure 2 Green and grey flood control infrastructure included in this study.

Impacts of Grey Flood Control Infrastructure on Fish and Aquatic Habitat

The impacts and fish responses for “small grey” flood control infrastructure (sluice gates, flood gates and tide gates) are identified in Figure 3. The literature shows that sites with floodgates are known to alter water quality, restrict fish passage, and reduce fish diversity. Considering water quality, floodgates obstruct exchange of water, which reduces the concentration of dissolved oxygen and increases the levels of nutrients, fecal coliforms, and turbidity in the stagnant upstream habitats (Scott et al., 2016). Previous research has demonstrated that the presence of floodgates physically inhibits the upstream movement of brown trout, and these fish took six times longer to pass these gates compared to unobstructed passages (Wright et al., 2016). Similarly, the presence of the tide gate at the River Stiffkey, UK, are observed to delay upstream migration of endangered European eel (Anguilla Anguilla) compared to an unimpeded fish passage (Wright et al., 2015). The presence of floodgates contributes to the modification of fish communities, which is evident with an increase in invasive fish species and a decrease in native species (including salmon species) as seen in lower Fraser River (Seifert and Moore, 2018).

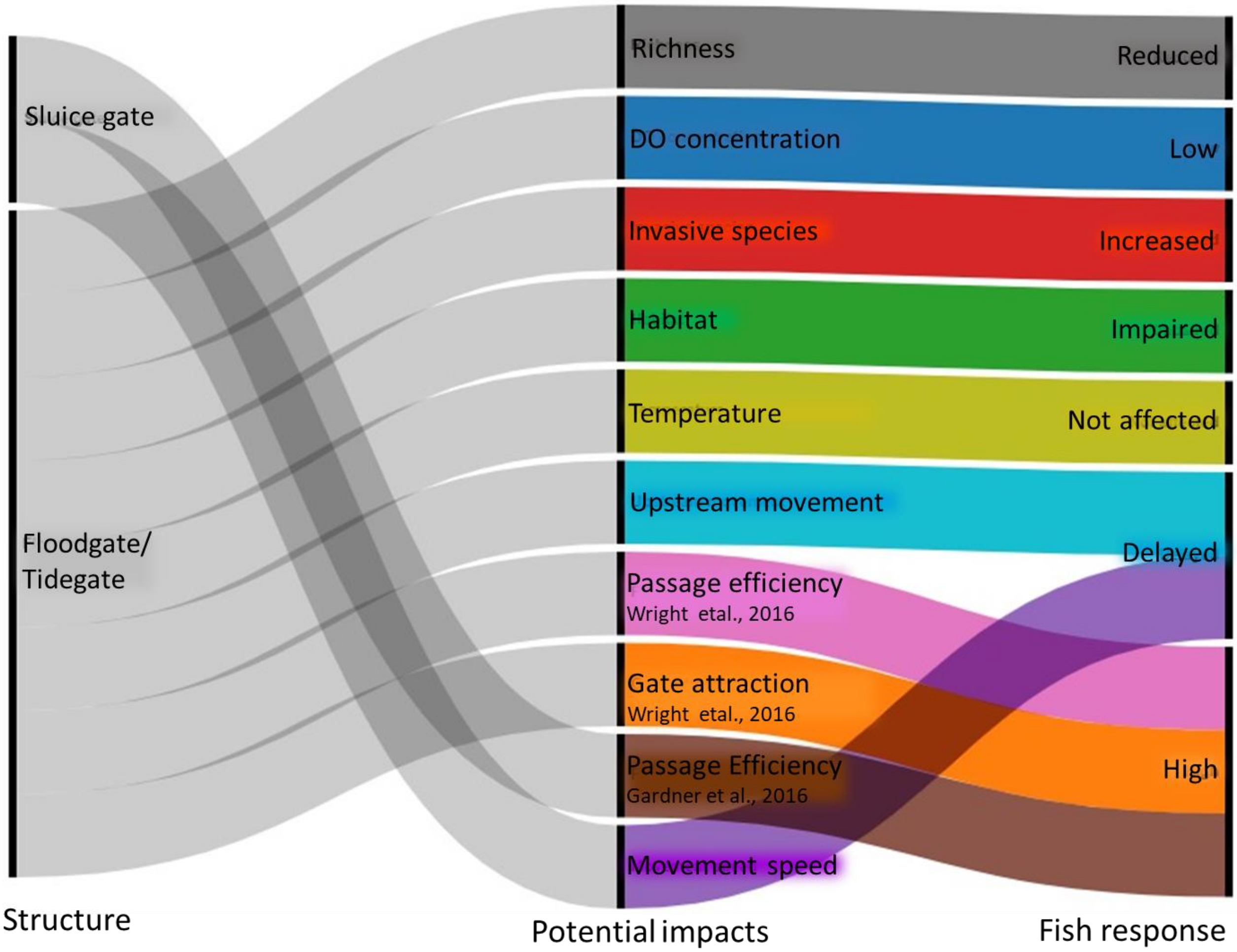


Figure 3 List of small grey FCI and their potential impacts and fish responses.

The impacts and fish responses for "large grey" flood control infrastructure (FCI) (such as dams, and shoreline armouring structures) are identified in Figure 4. An evaluation of impoundments of low-head dams at the Qingyi River, China, revealed that dam height and substrate heterogeneity are correlated to richness of indigenous fish, whereas fish species assemblages were influenced by invasive fishes. Habitat homogenization due to dam building may affect endemic fish assemblages by reducing the suitability of the habitat for native fishes (Chu et al., 2015). In addition, shoreline modifications affect aquatic habitats by altering or removing feed sources, habitats for reproduction, and by replacing productive shallow habitats with deep water habitats. Large overwater shoreline infrastructures alter fish assemblages, beach spawning, and consumption of epibenthic and terrestrial prey. These structures provide shade and a high-density environment that constrains localized movements of fish and impairs habitat value for visually oriented fish (Munsch et al., 2017).

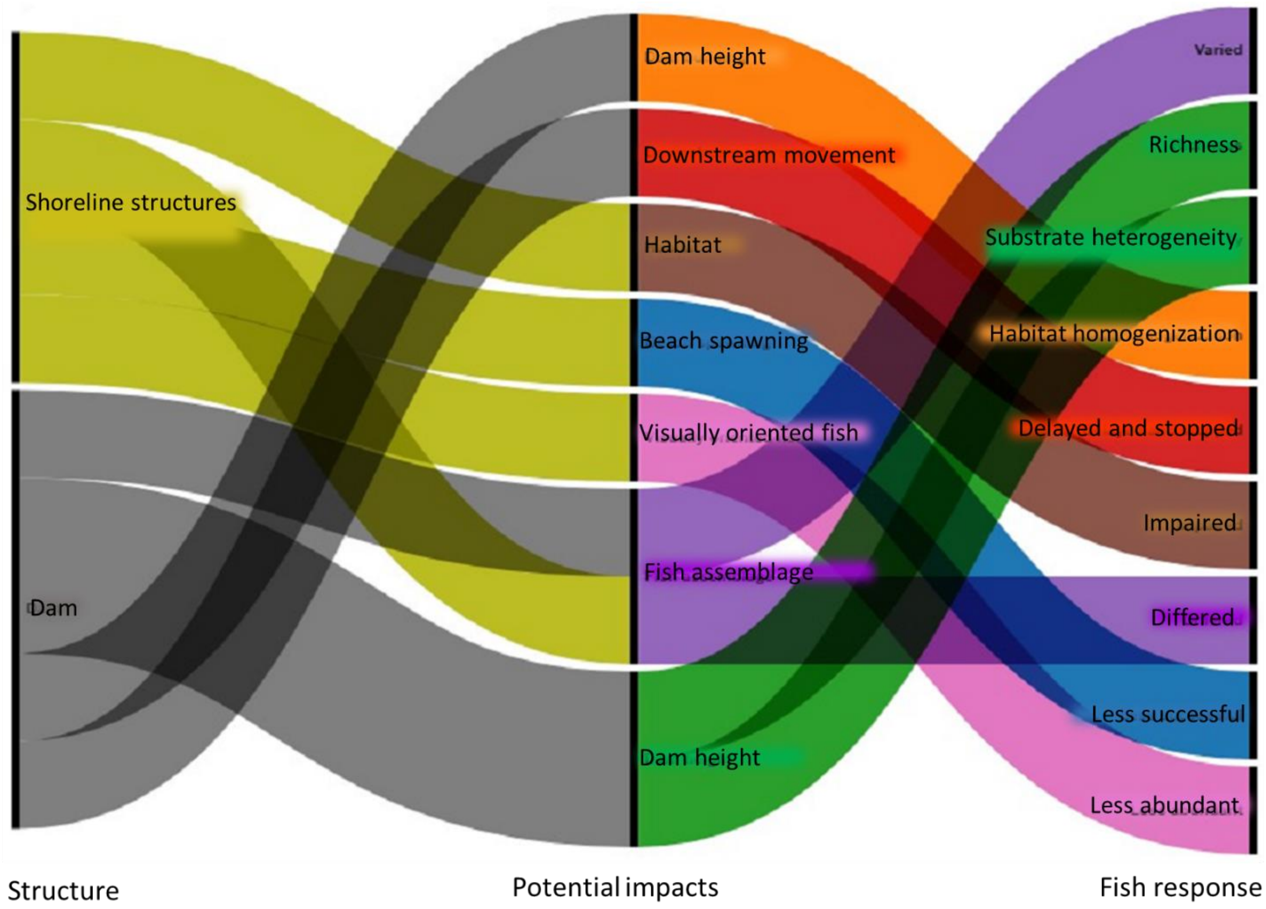


Figure 4 List of large grey FCI and their potential impacts and fish responses.

Impacts of Green Flood Control Infrastructure on Fish and Aquatic Habitat

The impacts and fish responses for green FCI are identified in Figure 5. Recently, nature-based FCI is becoming recognized as a sustainable solution to combat flood risks and reduce damage to fish habitat (Moudrak et al., 2018). These flood control structures are usually developed at locations where sufficient space is available between urban centers and the shoreline to accommodate the creation of natural ecosystems of mangroves, salt marshes and other floodplain habitats. Mangroves are important to reduce water flow and they attenuate storm waves by 31% (Morris et al., 2018). In tropical regions of southeast Asia, mangrove forest plantations provide protection against coastal hazards and storm events (Schmitt et al., 2013). In Florida, one study showed that mangrove forest reduced hurricane surge levels by 40 to 50 cm per kilometer of forest width (Zhang et al., 2012). The rate of wave reduction varies with the area of the plantation and can be as high as 20% per 100 m of mangrove forest (Mazda et al., 1997) and mangrove forests are effective for coastline protection over a larger range of water depths (Morris et al., 2018). For saltmarsh, the wave height attenuation from a meta-analysis is estimated to be 70% and is positively affected by width, vegetation density and growth, and marsh elevation. Additionally, subtidal habitats formed in these structures cause localized water shallowing, which encourages wave breaking (Narayan et al., 2016). The development of coastal vegetation and shellfish reefs promote sediment deposition, reduce erosion and sediment movement thus, stabilize shorelines (Spalding et al., 2014). The sediment deposition over time due to coastal vegetation can increase the height of the land in relation to sea level, thus reducing the probability of flooding during storm surges and extreme tidal events (Shepard et al., 2011).

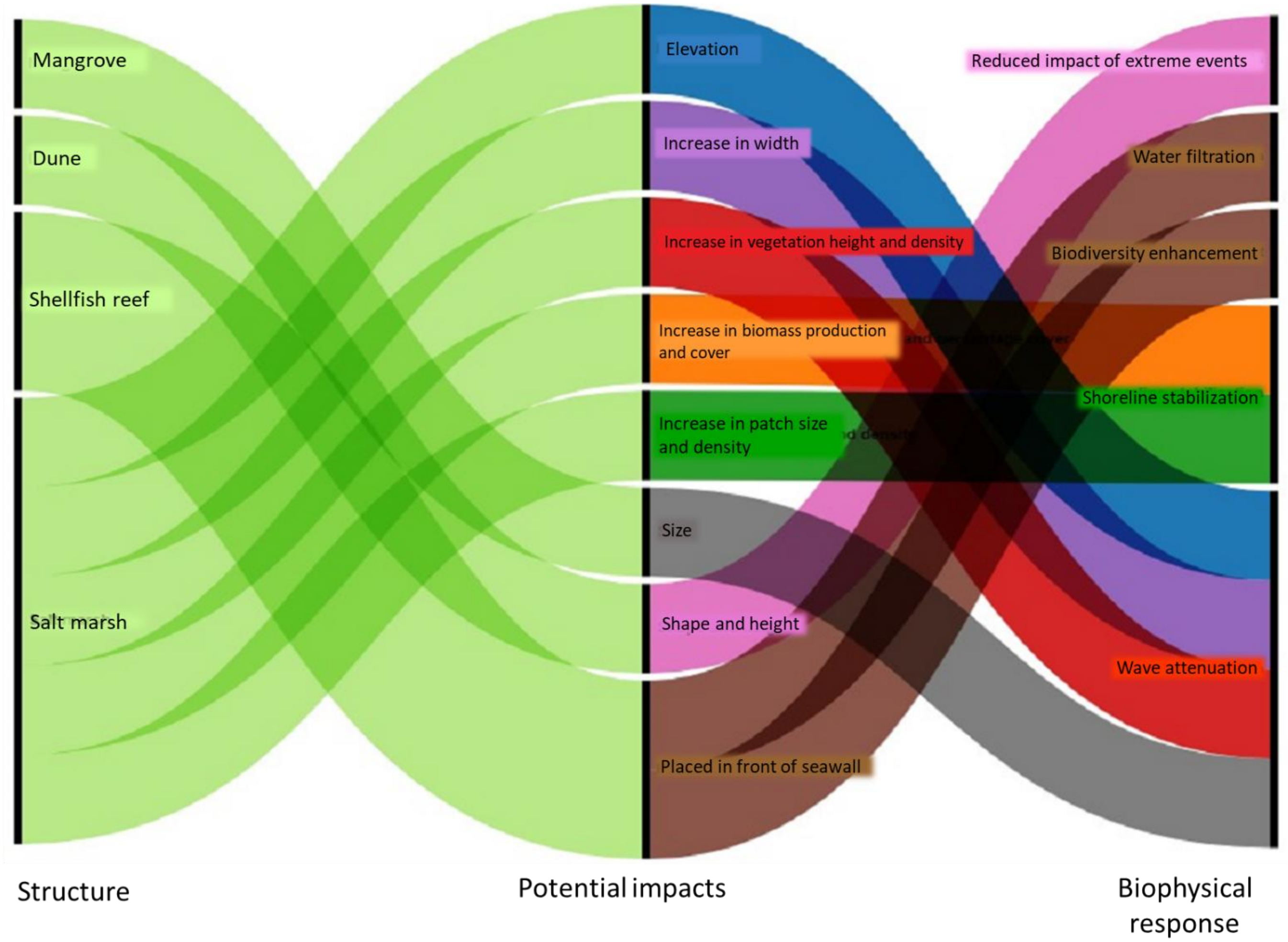


Figure 5 List of green FCI and their potential impacts and biophysical responses.

GHG Emissions from Grey FCI

Very little information is available on the climate costs of grey FCI, i.e., the life-time greenhouse gas emissions of dikes, floodgates and other hard infrastructure. However, a large number of studies are available on life cycle GHG emissions per kilo-watt-hour for different types of hydropower (HP) dams (Table 5). While these studies do not present carbon emissions in a way that can be directly compared to the carbon emissions/sequestration of grey or green flood control infrastructure, they do offer some information on the greenhouse gas emissions of the dam construction phase. Dams are constructed to stop or control the flow of water for a variety of purposes such as water supply, flood control, power generation, and others. A life cycle assessment for hydropower dams provides estimates of the GHG emissions, their long-term impacts on the environment (up to 100 years) and helps to identify gaps and potential improvements in the production cycle to make production more sustainable with respect to the GHG emissions (Denholm and Kulcinski, 2004). Typically, the construction phase of a dam is considered a major contributor of GHG emission because this phase includes extensive processes of raw material extraction, transportation, and actual building of the structure. This is the phase that is most relevant to grey flood control infrastructure such as dikes, as these also require raw material excavation and transport, construction materials and structure design. The studies reviewed showed a range of greenhouse gas emissions for the construction phase from 4.3 to 645 g CO2 eq./ kWh (Table 4). The major factors influencing GHG emissions at the construction and building stage are mainly related to diesel fuel and electricity consumption by on-site equipment usage (Zhang et al., 2015).

Table 5 Carbon emission during construction phase of various Hydropower (HP) dams.

Grey FCIs	**Location**	**Carbon emissions (g CO_2 eq./ kWh)**	**References**
Weir (Diversion HP)	Thailand	52.7	Pascale et al., 2011
Weir (Diversion HP)	UK	8.9	Gallagher et al., 2015
Mass concrete weir (Diversion HP)	Thailand	16.5	Suwanit et al., 2011
Concrete gravity dam (Diversion HP)	China	28.4	Pang et al., 2015
Concrete dam (Diversion HP)	India	31.2	Varun et al., 2010
Canal-based (Diversion HP)	India	74.9	Bhat and Prakash, 2008
Canal-based (Diversion HP)	India	35.4	Varun et al., 2010
Concrete dam (Diversion HP)	Japan	11.3	Hondo et al., 2005
Concrete dam (Reservoir-based HPs)	India	11.9	Varun et al., 2010
Rock-fill concrete (Reservoir-based HPs)	China	44	Zhang et al., 2007
Concrete arch dam (Reservoir-based HPs)	US	76.3-227.3	Pacca, 2007
Concrete arch dam (Reservoir-based HPs)	US	35.4-62.6	Pacca and Horvath, 2002

Earth-core rock dam (Reservoir-based HPs)	China	8.4	Zhang et al., 2015
Dam (Reservoir-based HPs)	Brazil	4.3	de Miranda Ribeiro and Da Silva, 2010
Pumped-storage HP	Belgium	25-645	Oliveira et al., 2015
Earth/rock-fill dam (Pumped storage HPs)	US	5.6	Denholm and Kulcinski, 2004

GHG Emissions and Sequestration in Green FCIs

In contrast to grey coastline defenses, nature-based, green approaches are useful to increase shoreline biodiversity, ecological connectivity, and biogeochemical cycling. These structures require less energy to build and maintain, and consequently have less GHG emissions and impact on the environment (Temmerman et al., 2013). Estimates of methane emissions, a major GHG gas, by vegetated coastal ecosystems (such as mangrove, salt marsh, seagrass) are measured to be 0.33–0.39 Tmol CH_4-C/year (Al-Haj and Fulweiler, 2020). In parallel, these infrastructures are responsible for carbon sequestration, which reduces the amount of CO_2 by capturing it from atmosphere and storing it. The assessment of carbon sequestration rates of Chinese tidal flat sediments ranged from 35 to 361 g C m^{-2} yr^{-1} (Chen et al., 2020). Similarly, a recent study has shown that restoring seagrass could remove 0.42 tCO_2e ha^{-1} yr^{-1} from the atmosphere (Oreska et al., 2020). The investigation of the CO_2 capture potential of seaweed aquaculture is estimated to be 0.68 Tg C per year and carries a potential to stimulate the bio-economy along the extensive coastline (Duarte et al., 2017). An example of such interventions has been presented by Norway where the surface area occupied by seaweed cultivation has increased by three times in only 3 years (Stévant et al., 2017). It is important to note that these data for GHG emissions and carbon sequestration are obtained from a variety of sources using a wide range of units of measurement. Comparative assessment of these infrastructures cannot be completed without unit standardization of data that ensures a level of consistency and accuracy, which is beyond the scope of this review. A summary of recent estimates on carbon sequestration and accumulation is given in Table 6.

Table 6 Carbon sequestration and emissions from different types of floodplain ecosystems and nature-based flood control solutions.

Green FCIs	**Environmental Impacts**	**References**
	Carbon accumulation	
Tidal marsh	0.54 tons C/ha/ yr	Gulliver et al., 2020
Mangrove *(Kandelia obovata)*	106.6±1.4 Mg/ha	He et al., 2020
Mangrove *(Sonneratia apetala)*	36.6±1.3 Mg/ha	He et al., 2020
Mangrove (mixed plantations)	46.0±3.0 Mg/ha	He et al., 2020
Mangrove peat	1,130± 128 Mg/ha	Ezcurra et al., 2016
Wetland soils	11.52 Pg C	Nahlik and Fennessy, 2016
Tidal marshes	0.55±0.02 Mg C/ha/yr	Macreadie et al., 2017
	Carbon sequestration	
Tidal flat sediments	78.07 Tg C	Chen et al., 2020
Tidal marshes	0.75 Tg C/yr	Macreadie et al., 2017
Mangrove	15.51 Pg CO_2	Jakovac et al., 2020
Seagrass restoration	0.42 tCO2e/ha/yr	Oreska et al., 2020
Seaweed aquaculture	0.68 Tg C/yr	Duarte et al., 2017
Tidal flat sediments	35 to 361 g C/m^2/yr	Chen et al., 2020
Forest canopy (Temperate mixed and Coniferous forest)	0.8 tons C/hr/yr	Wilson, 2010
Non tidal wetlands	0.2-0.3 tons C/hr/yr	Wilson, 2010
	Carbon emission	
Freshwater ponds	71–149 Tg C/yr	Butman et al., 2016

Life Cycle Cost-Effectiveness of Grey and Green FCI

In addition to the greenhouse gas emissions, a life cycle analysis can review costs to identify if a particular infrastructure is economically viable or if another type of infrastructure will be more cost effective over time. Considering grey FCI, the economic cost to build hard infrastructure is substantially higher for coastal protection as compared to nature-based flood control solutions (Powell et al., 2019). For example, the installation of a seawall that requires huge quantities of concrete can be as high as $32,800/ meter and typically ranges between $6,500 - $9,800/meter

(Sutton-Grier et al., 2018). The construction of surge barriers can be more expensive as they cost >$10,000/ft of barrier (Cunniff and Schwartz, 2015). Moreover, these built structures often require emergency repair and replacement and incur maintenance costs over their lifetime. The literature indicates that unit costs for strengthening dikes in The Netherlands ranges between 6.47 and 26.38 million USD per km for every 1 m of increased dike height for urban areas, and between 5.30 and 14.60 million USD for rural areas (Jonkman et al., 2013). For New Orleans, the unit cost of strengthening the levees is relatively low, between 2.945 and 5.88 million USD / km per m raising for earthen levees, and between 2.66 and 5.77 million USD / km 1.per m height for constructing concrete floodwalls. In contrast to grey FCI, nature-based defenses are more sustainable, comparatively low cost, and offer essential ecosystem services. For United States, the construction cost of typical beach nourishment varies between 2,000 to 5,000 USD and annual operational and management cost lies between 100 to 500 USD for a 50-year project life (Cunniff and Schwartz, 2015). The cost-effectiveness of nature-based FCI is due to cheaper raw materials, versatility, and durability. Also, the provision of additional ecosystem services potentially makes green FCI the preferred choice over grey FCI (Heery et al., 2020). For example, seaweeds are considered beneficial for a wide range of applications extending from biofuels production to food products and textiles (Morris et al., 2018). Since these plants are grown locally, they exhibit a high potential to support local food security, energy autonomy, and low carbon economies in coastal cities while providing a platform for community engagement (Heery et al., 2020). The detailed comparison of cost for different types of grey and green FCIs is given in Table 7.

Table 7 A summary of construction and maintenance costs for different types of grey and green infrastructure.

Infrastructure	**Cost/foot**	
Grey FCI	**Construction**	**Annual O&M**
Groins	$2-5K	$0.1-0.5K
Breakwaters	$5-10K	>$0.5K
Seawall	$5-10K	>$0.5K
Revetments	$5-10K	$0.1 - 0.5K
Bulkheads	$2-5K	$0.1 - 0.5K
Surge Barriers	>$10K	n/a
Green FCI		
Beach Nourishment	$2.0K-5.0K	$0.1K -0.5K
Restored Mangroves Forest	$0.23K - 216K /ha	n/a
Restored Wetland	$0.81K - 36.4K/ha	n/a
Restored Oyster/Shell-fish Reefs	$0.23K - 0.24K	n/a
Restored/Created Coral Reefs	$0.2K – 508K	n/a
Vegetated Dune	$0.03K - 5K	$0.1K -0.5K
Barrier Island Restoration	$0.76K - $1.1K	n/a

(Ref: Cunniff and Schwartz, 2015)

Cost-effectiveness represents an important component of decision-making and is controlled by three key factors. First, the type of structure required; for example, saltmarshes, are less costly where they are an appropriate solution, compared to foreshore areas that require a high zone or disconnected breakwater and thus a different kind of flood control solution. The second factor is the necessary costs for the construction, maintenance, and repair of the infrastructure. Continuous operational and maintenance costs make hard engineering structures the less attractive option to manage flood risk. Thirdly, the decision-making process must ask whether the infrastructure has additional economic benefits, such as the increasing fisheries profitability and maintenance of biological diversity, which in turn sustains a community (Vuik et al., 2019) Importantly, nature-based green FCI provides the benefits of habitat conservation and restoration, thus these structures play an important role in maintaining ecosystem services. For example, there is much interest in the economic valuation of fisheries provision and nutrient cycling related to restored mangroves, saltmarsh, seagrass, and shellfish reefs (Morris et al., 2018).

Knowledge Gaps and Recommendation for Future Work

This analysis of the literature highlighted a number of limitations related to understanding the climate mitigation potential of green FCI. At present, the relative climate impacts of grey and green FCI cannot be understood accurately because data are lacking. Also, the lack of uniformity in the units of measurement for the studies that do exist prevents any quantitative comparisons It is hoped that this review encourages comparative assessments of the life cycle greenhouse gas impacts of grey and green FCI under similar conditions so that the climate mitigation benefits can be understood, and decision-making processes can be supported. This assessment is particularly important to overcome uncertainties about the implementation and comparative life cycle costs of nature-based FCI at a time when governments need to design and replace coastal defenses to provide adequate flood protection and climate resilience.

Recommendations

In order to understand the climate mitigation properties of the different types of green FCI and how they compare to grey FCI, life cycle assessment studies should be performed. The steps below could be used to compare green and grey FCI options or to compare existing structures.:

- identify type, location, and age of existing or proposed structure;
- collect data on material, energy, and cost related to construction, operation, maintenance, replacement, and disposal of selected FCIs;
- assess long-term life cycle impacts of selected FCIs using software such as Simapro’s life cycle assessment software package.,

- use a cost model (e.g. net-present value) to determine life cycle cost of the infrastructure; and
- perform cost-benefit analysis (i.e. reduction in CO_2 per unit cost) to compare environmental and economic benefits of selected grey and green FCIs.

Conclusions

Increased flooding due to climate change has aggravated the risks related to aging built infrastructure and reduced the service life of existing and future built structures along shorelines (Powell et al., 2019). Adopting green FCI in coastal areas has the capacity to fulfill the needs of coastal defense in the face of environmental change. Investing in nature-based, green FCI offers more resilience to disasters, better protection to environmental resources, while also being cost-effective to construct and maintain over the long term. Although beneficial, a key challenge in assessing the performance of green FCIs includes gathering of data on GHGs emissions and sequestration, long-term environmental impacts, and performance evaluation relative to grey FCIs. It is clear that for most of the FCI reviewed, the data are currently unavailable on their effectiveness for carbon sequestration and these results would be helpful for appropriate environmental management. Furthermore, implementation of green FCI will benefit society by supporting cost-effective strategies that protect coastal communities, as well as offer opportunities of economic importance not provided by traditional coastal defenses.

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