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The grey – green spectrum: A review of coastal protection interventions

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ABSTRACT

In the face of uncertainties around coastal management and climate change, coastal engineering interventions need to be able to adapt to changing conditions. Nature-based solutions and other non-traditional, integrated interventions are gaining traction. However, system-based views are not yet embedded into coastal management strategies. Moreover, the differences in coastal interventions, ranging from hard ('grey') to nature-based ('green') infrastructure remain understudied. In coastal management it is therefore challenging to work with the grey-green spectrum of interventions with clarity and focus, and to produce results that can be evaluated. The objective of this paper was to examine whether there is a common understanding of: the characteristics and differences between grey and green infrastructure, where interventions sit on this spectrum, and the resilience of grey versus green infrastructure. We conducted an integrative literature review of the grey-green spectrum of coastal infrastructure. We examined 105 coastal protection case studies and expanded the double-insurance framework to ensure an integrative approach, looking at both external and internal factors of resilience. Our review showed that external factors are typically used to characterise the grey-green spectrum. However, although useful, they do not facilitate a holistic comparison of alternative interventions. The additional consideration of internal factors (response diversity, multifunctionality, modularity and adaptive, participatory governance) bridges this gap. The review showed that dikes, reefs, saltmarshes, sand nourishment and dunes span a wider segment of the grey-green spectrum than they are generally categorised in. Furthermore, resilient solutions for adaptation are unlikely to be exclusively engineered or natural, but tend to be a mix of the two at different spatial scales (micro, meso, macro and mega). Our review therefore suggests that coastal planners benefit from a more diverse range of options when they consider the incorporation of grey and green interventions in the context of each spatial scale. We propose that internal resilience should be accounted for when infrastructure options are comparatively evaluated. This consideration brings attention to the ways in which the grey-hybrid-green spectrum of infrastructure enhances value for people.

1. Introduction

Climate change has resulted in changing weather patterns combined with rising sea levels, exacerbating the risks of coastal erosion and flooding. In parallel, urbanisation is increasing global demand for built environments to provide a high quality of life. Nearly a quarter of the world's population resides within 100 km of a shoreline (Zanuttigh et al., 2014), meaning that a large share of the demand for safe and sustainable living environments is linked to an increasingly vulnerable area.

A range of measures (e.g. dikes, revetments, dunes) can be considered to protect these coastal, densely populated areas and reduce the risks of hazards. Both in science and practice, these measures are generally conceptualised as a spectrum, ranging from 'hard' to 'soft' interventions, 'grey' to 'green' infrastructure, or 'engineered' to 'nature-based solutions'. An increasing variety of literature recommends decision makers to conduct a holistic comparison of alternative systems when deciding on interventions to protect both people and land (de Alencar et al., 2020). However, it is not yet common practice to include a system-based view and ecosystem knowledge into coastal management strategies (Van Wesenbeeck et al., 2014). The focus tends to be on a single function for comparison, particularly when examining

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nature-based versus conventional alternatives (Engström et al., 2018). Considering urban coastal development and the expected coastal squeeze (Mills et al., 2016), looking beyond single functions is expected to become a key issue for future coastal management (O'Shaughnessy et al., 2020).

In the last decade, interest for nature-based solutions has increased considerably, both in research and policy making (EC, 2015; EU, 2013; UN, 2017). This trend necessitates a better understanding of the interrelations between the natural environment, built environment and their wider social context, i.e. taking an social–ecological–technical system perspective to coastal engineering. In line with this, Oberndorfer et al. (2007) state that considering aggregate benefits is crucial in the search for ameliorating urban environments. In addition, Andersson (2018) states that design, planning and governance requirements should extend beyond biophysical elements and components, and that there must be a recognition of the interconnections between the natural and built environment, and formal and informal governance arrangements. This is particularly important as we face an increasingly uncertain future (Walker et al., 2013), and therefore need interventions that are resilient to changing conditions.

This review examines case studies along the grey-green spectrum of coastal protection. The objective of this paper is to examine whether there is a common understanding of: the characteristics of and differences between grey and green infrastructure, where interventions sit on this spectrum, and the resilience of grey versus green infrastructure. We conducted an integrative literature review (Torraco, 2016), thereby systematically collecting and synthesizing previous research, examining the current state of science and practise and collecting a wide variety of global case studies. Based on the review findings, we propose important aspects that could be considered by coastal managers and planners in the design, implementation and governance of coastal protection interventions.

2. Method

2.1. Conceptual framework

The extent to which an intervention can provide long-term insurance against coastal hazards depends on its quality as well as its context (Andersson et al., 2017). In agreement with this view, we accommodate a systems approach to this review. A systems approach to engineering involves considering a system in parts and describing the interactions and relationships between the parts, the system and its environment (Meadows and Wright, 2008). A systems approach to coastal protection requires that social and ecological aspects are considered for each intervention, in addition to technical elements (McPhearson et al., 2016). To incorporate this view into our review, we expanded the 'double-insurance' framework by Andersson et al. (2017), to be used as a lens for reviewing literature about coastal management, and finding the characteristics that distinguish different types of infrastructure.

The double insurance framework defines two levels of resilience that should be considered in a nature-based intervention (Fig. 1). It aligns with a systems approach because it considers the elements of the system, as well as how they react with each other and the consequent characteristics. The first level of resilience is **external**; it involves the capacity of the intervention to protect the larger system, based on how the system fits functionally, spatially and in size into a vulnerable area (i.e. physical characteristics, location and scale). The second level of resilience is **internal**; the intervention must be able to weather disturbances *and* lag times between events. In other words, it must be perceived as valuable even when its protective services are not actively in use. This is especially important in densely populated urban landscapes, with constant competition for economic functions, land-use and space. Internal resilience characteristics (i.e. response diversity, multifunctionality, modularity, and participatory and flexible governance) are emergent properties following from the relationships between the ecological, technical and social components of coastal interventions.

We expanded the double insurance framework by broadening the scope for each factor so it could be used to assess the grey-green range of coastal protection interventions, rather than solely nature-based interventions. Only examining green spaces and their services would be an oversight of how the grey-hybrid-green continuum of infrastructure enhances value for people (Depietri and McPhearson, 2017; Grimm et al., 2015). We therefore studied literature on each factor from a wider range of disciplines than coastal engineering (e.g. architecture, urban planning, ecology) and distilled the relevant characteristics of each factor in grey and hybrid systems (Supplementary Material A). External factors describe the physical characteristics of interventions, and internal factors describe the characteristics that emerge from the interaction of ecological, technical and social components (Fig. 1). The literature was therefore analysed in two parts: first to study the external factors and their relation to 'grey' or 'green' characteristics, and second to study the internal factors of specific coastal interventions to understand whether the literature holds a converging view of where each

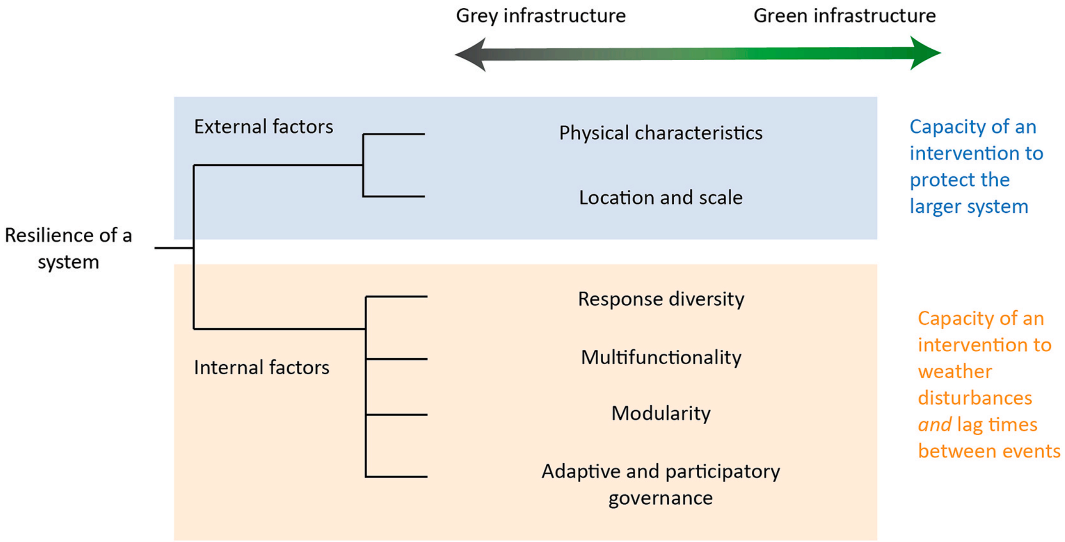

Fig. 1. Expansion of the double insurance framework as used in this review. We expanded the framework by Andersson et al. (2017) to include grey and hybrid infrastructure, rather than solely considering nature-based solutions.

intervention sits on the grey-green spectrum.

2.2. Literature review

This literature review targeted a representative sample of the literature that explicitly considers the grey-green spectrum of coastal interventions, in order to understand and clarify their distinguishing characteristics. We searched for English-language literature from 2000 to 2020 in the Web of Science with the following search strings:

- hard soft engineer* coast* AND (flood* OR ero*)
- grey green* coast* AND (flood* OR ero*)
- nature-based* coast* AND (flood* OR ero*)
- ecological* engineer* coast* AND (flood* OR ero*)

These strings served to find literature that discusses grey-green infrastructure in its various conceptualisations, specifically in relation to coastal protection (i.e. flood* for flood protection and/or ero* for erosion) from the last two decades. This query yielded 242 peer-reviewed articles in total (on February 11, 2020). We then evaluated each article for relevance based on the following criteria:

- Titles that indicated geomorphological processes or plants/animals that were too specific were removed, case studies were kept
- Abstracts that did not indicate that the paper would characterise grey or green interventions were removed.

This resulted in 104 publications (with 105 case studies), published in journals spanning disciplines including environmental sciences, water resources, geosciences, oceanography, ecology, civil engineering, urban studies and public administration (Supplementary Material B). We then formulated a question for each factor from the expanded double-insurance framework, to collect data from the literature about external factors and internal factors (Table 1). The information collected from each article was: *Year of publication, Cases study, Case country, Type of coast, Measure, Function of coast, Proximity to population, Coastal hazards, Aim of protection infrastructure, Typology of infrastructure, Scale, Type of intervention, Material, Ecological consideration, Multifunctionality, Response diversity, Modularity, Adaptiveness to changing boundary conditions* (Supplementary Material B).

3. Results

In the reviewed literature, grey infrastructure is viewed as hard, conventional, engineered infrastructure that has traditionally been used to manage the coastal zone. On the other side of the coastal protection spectrum, there are 'green' or 'natural' concepts such as *building with nature, natural barriers, green adaptation, working with natural processes, greening flood protection, nature-based solutions, natural infrastructure, living shorelines and ecosystem-based infrastructure*. Grey and green infrastructure are generally presented as distinct forms but these are not systematically defined. The reviewed literature published between 2000 and 2010 predominantly mentioned 'hard/soft engineering' or 'working with natural processes'., 'ecological engineering' became popular in 2011, and from 2013 onwards started to diversify in terms of approaches and characteristics. Increasing interest in 'nature-based' became apparent from 2010, which may be explained by institutions such as the World Bank and the IUCN highlighting the importance of biodiversity in mitigating and adapting to climate change (IUCN, 2009; MacKinnon et al., 2008). In 2013, the European Union published a report about greening infrastructure (EU, 2013), and in 2015 the European Commission published a research agenda for nature-based solutions (EC, 2015). Since 2017, published papers have increasingly been referring to 'nature-based' interventions in contrast to grey interventions.

Table 1
Data collection question per factor, based on Andersson et al. (2017).

Factor	Data collection questions
Physical characteristics	Does the publication mention ecological aspects of the intervention? What kind of material is the intervention constructed from?
Location and scale	What urban function does the coast have? Is proximity to population mentioned? What is the scale (micro, meso, macro, mega) of the intervention?
Response diversity	Does the publication mention components that are diverse in their response to disturbances?
Multifunctionality	Does the publication mention ecological, social, and/or economic functions in addition to coastal protection?
Modularity	Does the publication mention components that can be replaced, restored or renovated without disturbing the entire system?
Governance	Does the publication mention flexible and/or participatory processes?

We examined 105 coastal protection case studies to clarify the grey-green spectrum of coastal protection. The three types of interventions that were referred to most often were: sand nourishment (11 cases), saltmarshes (7 cases) and dunes (9 cases). In this section we present the findings of our review in two parts. First, we describe the results of studying the external factors and their relation to 'grey' or 'green' coastal infrastructure characteristics. Second, we present the results of studying the internal factors of coastal interventions.

3.1. External factors

Although specific typologies are often referred to (i.e. nature-based, living shorelines, ecological engineering), our review shows that none have categories and definitions that are widely accepted, agreed upon or consistently used. Interventions that incorporate ecological features within the coastal protection function cannot be characterised as a homogenous group. In addition, ecological features are not the sole characteristic to distinguish between grey and green infrastructure, as the construction material, location and scale also play a role. The clearest distinction can be made based on function. Grey interventions derive their entire coastal protection function from an engineered structure, whereas green interventions derive that function from ecosystems and their functional characteristics (e.g. roots, functional traits, material, physical structure). Numerous coastal interventions exist in between green and grey, which makes an absolute distinction challenging.

3.1.1. Ecological aspects of intervention

There is broad agreement that nature-based interventions integrate ecological processes into coastal protection (Pontee et al., 2016; van der Nat et al., 2016). However, the meaning of 'nature' in 'nature-based' varies widely and is applied inconsistently; a notable difference lies not in the system type of the intervention (i.e. dunes, wetlands, reefs), but in the biodiversity-related motives that underlie the choice of intervention or non-intervention (i.e. restoration, enhancement, conservation). Most interventions were newly built ecosystems (58 cases), as opposed to restored systems (20 cases) and conserved systems (5 cases). The other cases involved renovated, restored or enhanced systems. The aims of the interventions varied too; the primary objectives were coastal protection, management, defence, risk reduction or resilience against hazards. In a few cases, protection was the secondary objective of an intervention; the primary objective was ecosystem conservation, increasing touristic value or contributing to knowledge development.

3.1.2. Material

Abiotic materials such as cement, steel or rock were related to infrastructure described as 'grey', 'conventional', 'hard' and/or 'engineered' (in 15 cases). Biotic materials such as sand, vegetation and wood primarily featured in infrastructure described as 'building with nature' and 'nature-based solutions' (52 cases). 'Hybrid' or 'combined' interventions made use of a mix of biotic and abiotic material (46 cases). Only five cases mentioned the origin of the material (i.e. locally sourced or not), all of which are biotic materials.

3.1.3. Location (socio-economic context)

Socio-economic context (e.g. population density, resources of its city, urban zoning of coastal areas) were rarely defined for case studies in this selection of literature. There was insufficient data to support this analysis, a spatial analysis would be better suited to reveal findings on this factor.

3.1.4. Scale

When distinguishing grey from green infrastructure, scale was found to play a key role. When disaggregating the integration of ecosystem by scale (i.e. micro, meso, macro or mega (Borsje et al., 2011)), classically grey interventions can be 'greened' on a micro scale (e.g. concrete structures with barnacle settlements on the surface) (Coombes et al., 2015). Vice versa, green infrastructure may be supported by a grey core on the meso level (e.g. sand dune with a rocky seawall at the core) (Almarshed et al., 2020). A pattern found in the literature was that natural ecosystems required more space to provide protective services than engineered interventions (Morris et al., 2018; Sutton-Grier et al., 2015). This limits the application of natural systems as a coastal protection feature to locations with sufficient space between urban and coastal areas.

3.2. Internal factors

Internal factors are characteristics that emerge from the interaction of ecological, technical and social components (Section 2.1). In this section, we synthesize management and design considerations that contribute to response diversity, multifunctionality, modularity and adaptive, participatory governance, respectively (Andersson et al., 2017). As these interactions were found to vary per type of intervention, we present our results for four types: dikes, reefs, saltmarshes, and sand nourishment and dunes combined. This section explores whether the literature shows a common view of where each intervention sits on the grey-green spectrum, and how this relates to its resilience. Resilience is understood as the capacity of an intervention to weather disturbances and lag times between events, by enhancing value for people in both times (Andersson et al., 2017).

3.2.1. Dikes

Dikes are man-made structures designed to protect low-lying areas from flooding. They are designed to withstand and resist wave action and water overtopping. They are generally designed as a ridge or mound parallel to the waterfront. The shape, size, slope of walls and structural material of dikes vary (Masria et al., 2015). There were 15 cases describing dikes in the reviewed literature, from which the following insights were found.

Using diverse building materials can encourage **response diversity**, such as within the structure of the dikes in Katwijk (Almarshed et al., 2020). Allocating 'sacrificial' land parcels for managed flooding also facilitates response diversity (Krishnan et al., 2019; Pontee et al., 2016). In some cases, a dike is incorporated within multiple lines of defence. For example, in Louisiana, USA, a marshland, flood gate, levee pump station, elevated buildings and evacuation route created diversity in the coast-land interface (Arkema et al., 2017). Furthermore, using **modular elements** such as concrete blocks and tiles, geotextile sandbags and rocks with niches, it is possible to contain the impact of a disturbance to one area of a system rather than the entire system, thereby reducing the need for structural and functional changes at a larger systems level (Desjardins et al., 2015). Local building knowledge and resources have a significant impact on the simplicity and modularity of how hard infrastructure is practised in different places (Naylor, 2015).

Multifunctionality, the addition of functions other than coastal protection, is encouraged through the integration of ecological elements. For instance, dike-in-dunes enhance the natural qualities of the area and provide spatial development options (Almarshed et al., 2020), and barnacle encrustation on hard infrastructure creates habitats and reduces the rate of deterioration of intertidal concrete and rocks (Coombes et al., 2017). Multifunctionality is also achieved through the integration of societal services in the dike; including a parking garage inside a dike to optimise the use of space near the coastal boulevard (Almarshed et al., 2020), or designing the structure to provide access to beaches, space for selling souvenirs, leisure and exercise (Mycoo and Chadwick, 2012). The literature describes various cases in which grey infrastructure integrates functions related to nature, sustainable energy, mobility, economy, landscape values and tourism (Janssen et al., 2020; Mycoo and Chadwick, 2012).

Dikes are considered grey infrastructure, as are seawalls, levees, revetments and groynes. They tend to be characterised as fixed, monofunctional and non-adaptive structures, in contrast to green infrastructure, which is considered to be multifunctional, adaptive and self-repairing. However, the reviewed literature shows that grey infrastructure increasingly ensures internal resilience by incorporating ecological processes and societal functions on varying scales. Concrete can become self-repairing through the incorporation of 'self-repairing' barnacles on concrete on a micro scale (Coombes et al., 2017), or the incorporation of various ecosystems in the foreshore on a macro scale. This combined use of ecological and technical elements requires a joint exploration of visions by designers, engineers, ecologists etc. (Krishnan et al., 2019), however references to **participatory and adaptive governance** were seldom found in the reviewed literature (11 case studies).

3.2.2. Reefs

Broadly speaking, reefs are submerged structures on the seabed of marine environments (Reguero et al., 2018b). They can be biogenic, artificial or a hybrid; biogenic reefs grow themselves such as coral reefs and oyster reefs, whereas artificial reefs are any solid manmade structure submerged into the natural environment, such as waste tires or car wrecks. A total of 13 cases described reefs in the reviewed literature, from which the following factors were found to influence internal resilience.

Adjusting the reef cover, diversity, structure of community and/or spatial configuration affects its **response diversity** (Morris et al., 2019a; Zhao et al., 2019). Artificial reefs may be designed in 'units' of modular gabion steel baskets that can be grouped into variable heights, widths and alignments (Reguero et al., 2018a). **Modularity** of reefs allows the system to adapt to varying depths and seabed configurations, and facilitates easier on-site assembly and stability, and suitability for local implementation in smaller communities (Reguero et al., 2018a). Due to their profile, position and spacing, biogenic reefs can adapt to optimise their survival (Pontee et al., 2016), but this does not necessarily optimise coastal protection.

Reefs may be incorporated into a system with multiple lines of defence to ensure **multifunctionality**. For instance, along the coast of Belize, multiple habitats (coral reef, seagrass and mangroves) were combined to diversify the number and type of species that contribute to reduction of erosion and flood risk (Arkema et al., 2017). Reefs can have multiple functions (i.e. ecosystem services) other than coastal protection, such as food provision, recreation opportunities and building materials (Zhao et al., 2019); shelter and habitat for algae and fish (Mitsova et al., 2018; Reguero et al., 2018a); and improved surfing conditions (Ng et al., 2014). Altogether, these touristic, cultural and recreational services may play a vital role in identifying and prioritizing restoration and conservation priorities from a socio-economic perspective (Reguero et al., 2018b).

Participatory planning can be achieved by incorporating reef monitoring into educational programs and subsequent promotion of citizen science (do Carmo et al., 2010), as well as the installation of reefs with the help of volunteers (Pontee et al., 2016). In addition, Zhao et al. (2019) suggest that the development of eco-tourism may introduce incentives for the preservation and restoration of existing coral reefs.

The reviewed literature shows that reefs span the entire grey-green spectrum of interventions for coastal protection. Reefs not only vary widely in their physical characteristics such as material, location and scale, but they also vary in internal resilience. The factors for internal resilience look different in biogenic, artificial and hybrid reef systems, but can exist in all of them. This shows that adaptiveness is not restricted to the green side of the coastal engineering spectrum of reefs.

3.2.3. Saltmarshes

Saltmarshes are a type of wetland, characterised by small plants and grasses in a low, wet muddy area that is periodically or continuously shallowly flooded by salt water (Van Coppenolle et al., 2018). This saturation by water influences plant, soil and animal communities. Saltmarshes protect coasts from erosion and flooding by buffering wave actions, trapping sediments and absorbing water. A total of 19 cases referred to saltmarshes in the reviewed literature, from which the following factors were found to influence internal resilience.

Response diversity in saltmarshes is difficult to control; it is affected by complex interactions between mount spacing and water depth in tidal flat-wetlands profiles (Reed et al., 2018). In many cases, it is supported by combining saltmarshes with grey infrastructure such as dikes. **Modularity** is ensured by positioning and spacing of species when manipulated by people, but this is unlikely to occur naturally (Pontee et al., 2016). In designed saltmarshes, plantings may be done on a grid (Mitchell and Bilkovic, 2019), areas can be zoned for resting, breeding and growing (Brière et al., 2018), and trees may be clustered (Borsje et al., 2011; Hegde, 2010). Furthermore, saltmarshes may be integrated into the foreshore of dikes, or other grey infrastructure to make them one of multiple lines of defence (Rahman et al., 2019; Stark et al., 2016; Vuik et al., 2019). This is especially relevant considering that seasonal changes affect the ability of a saltmarsh to protect against flooding and erosion (Chowdhury et al., 2019; Schoutens et al., 2019).

Saltmarshes can be **multifunctional**, providing a range of benefits: biodiversity support, groundwater level and soil moisture regulation and contaminant retention (Thorslund et al., 2017), carbon storage and sequestration, denitrification, biodiversity conservation, recreation (Möller, 2019), nursery, nesting and feeding habitat; filtering of sediments and nutrients from waterways; and reduction of wave energy (Mitchell and Bilkovic, 2019). As well as design considerations, their multifunctionality depends on **governance practises**. The development of knowledge networks, where roles and responsibility are distributed among roles and responsibility gives entrepreneurial actors more decision-making autonomy, which in turn support innovation in the use of ecosystems (Rahman et al., 2019). Furthermore, evaluation of large investments in marsh restoration in terms of sediment transport pathways helps ascertain critical information about the viability and lifespan of projects (Ganju, 2019). Multifunctionality and response diversity are further supported by discussions across disciplines and funding of transdisciplinary research, which can be supported through the creation of virtual forums (Mitchell and Bilkovic, 2019).

Saltmarshes, and by extension wetlands, are generally typified as natural or nature-based interventions for coastal protection. However, the reviewed literature shows that in many cases, the saltmarsh provides protection in combination with grey infrastructure. This increases the ability of the entire system to adapt to changing conditions by building internal resilience through the combination of grey and green elements. Furthermore it illustrates the move from a 'line' of defence to a 'zone' of defence (Van Veelen et al., 2015), which exemplifies 'low--regret'/'safe-to-fail' design principles.

3.2.4. Sand nourishment and dunes

Sand nourishment is the supply of sand to a beach to secure it against erosion. The material is natural but the process of nourishment requires human intervention. Dunes are ridges or mounds of loose, wind-blown sand that can be vegetated. Both are used on sandy shores for protection against erosion and flooding, often in combination with each other. A total of 22 cases referred to these sand-based interventions in the reviewed literature, from which the following factors were found to influence internal resilience.

Variation in dune profiles, surface sand grain size (Lin and Liou, 2013), sedimentary cohesion (Feagin et al., 2015), slope (Hanley et al., 2014) and adding notches (Castelle et al., 2019) can increase **response diversity**. Furthermore, gradients of dune successions that are dominated by young successional stages create high species diversity (Van der Biest et al., 2017). Dune vegetation plays an important role in increasing resilience, specifically the characteristics of plant structure (Feagin et al., 2015), functional richness (Maximiliano-Cordova et al., 2019), and vegetation density and cover (Jenks and Brake, 2001). Additionally, beach nourishment and dunes tend to be one of multiple lines of defence for coastal protection, many are combined with grey infrastructure (Almarshed et al., 2020; Ratnayake et al., 2019; Semeoshenkova and Newton, 2015; Tonmoy and El-zein, 2015; Yang et al., 2010). Interesting to note, the literature does not report a significant contribution of **modularity** to the internal resilience of sand nourishment and dunes.

Sand nourishment and dunes inherently provide ecosystem services in addition to coastal protection, which makes them **multifunctional**: water provisioning, water quality regulation, climate regulation (Van der Biest et al., 2017), recreation (Borsje et al., 2018; Janssen et al., 2020), sources for raw materials, grazing land, intrinsic biodiversity (Hanley et al., 2014), tourism, education and research (Morris et al., 2019b; Sauer et al., 2019).

Adaptive governance practises for sandy systems are well-reported within the reviewed literature, with multiple studies especially considering the Sand Motor at Ter Heijde, The Netherlands. The encouragement (and expectation) to monitor and openly report findings from the Sand Motor is a likely explanation for the large number of papers within this literature review that refer to this project. Several socio-political factors are found to support the internal resilience of sand nourishment. First, the framing of the project as a pilot that was a 'safe-to-fail' experiment and objectives that are 'too vague to critically assess' (Janssen et al., 2015). Furthermore, the inherent ecosystem services of sand nourishment were considered an opportunity to realize multiple benefits (coastal protection, nature development, recreational purposes), among which innovation was key (Aukes et al., 2018). And finally, finding alternative funding, instead of using the national coastline maintenance budget opened up avenues for wider goal setting (Janssen et al., 2015).

Dunes are natural, created or restored systems that can be used for coastal protection. Sand nourishment is typically defined as a nature-based system due to its use of natural material, but nourishment requires human intervention. In both systems, the adaptiveness of the system stems from its biophysical characteristics, however its ability to protect coasts tends to require a collaboration with grey infrastructure; beach nourishment and dunes are generally described in the literature as one of multiple lines of defence.

4. Discussion

Our findings result from applying an expanded version of the double insurance framework (Andersson et al., 2017) to coastal management. We expanded this framework from solely considering nature-based solutions to including grey and hybrid infrastructure. This approach provided a fitting lens through which to review literature in an integrative manner, incorporating insights from multiple scientific disciplines, many of which are not commonly considered in coastal management studies. The focus on both internal and external factors of resilience, guided by questions per framework element, provided two levels with which to assess the literature. Based on external factors alone (i.e.

physical characteristics, location and scale), our review would have compiled an ever-expanding list of characteristics of coastal protection interventions, reiterating the traditional approach for comparing and separating grey infrastructure to green infrastructure. The additional consideration of internal factors in our review proved useful in unveiling novel insights, clarifying how different interventions can span the grey-green spectrum and how to distinguish between them. This approach can also be applied to assessing urban and other systems where grey and green infrastructure coexist. In the following paragraphs, we discuss implications and recommended actions for coastal management, and directions for further interdisciplinary research on coastal engineering interventions. Central to the discussion is the question of how, based on our review, the five internal factors of resilience can be embedded in coastal management, and the added value and challenges that would arise.

4.1. Implications for coastal management

Considering the increasing policy and research interest in nature-based solutions in response to climate change (EC, 2015; EU, 2013; UN, 2017), there is momentum for a broader perspective on (environmental) coastal management. No intervention can eliminate all risk, and taking a holistic perspective showcases the meaningful contributions green and hybrid interventions can make to coastal resilience. However, consideration of response diversity, multifunctionality, modularity and adaptive, participatory governance in the practice of environmental management can be challenging (Sellberg et al., 2018).

R**esponse diversity** and **modularity** tend to be reported in combination and assessed in terms of ‘multiple lines of defence’, through the quantity of diverse species or materials used. The issue of scale is important here; combinations of small-scale interventions with different *modi operandi* can combine to achieve the large-scale, overarching aim of coastal resilience. This suggests the utility in considering multiple spatial scales (micro, meso, macro, mega) when planning for response diversity and modularity. Furthermore, it supports the call for coastal defences to not be considered as ‘line’ infrastructures, but as multi-functional coastal defence ‘zones’ consisting of multiple levels and scales of protection (Van Veelen et al., 2015).

Multifunctionality is reported in multiple case studies too, but the evaluation thereof is generally limited (Depietri and McPhearson, 2017). Coastal interventions are found to favour either an economic function or an ecological one, but few combine both. Overall, more studies claim to contribute to multifunctionality than those that provide compelling examples of it, nor are multiple functions evaluated in combination. A lack of elucidation of multiple values may be linked to a lack of indicators for measuring co-benefits. The strength of such indicators is shown by the ecosystem services framework; by relating socio-economic outcomes with biophysical changes in an ecosystem’s structure and functions driven by human intervention (Olander et al., 2018), it becomes possible to evaluate the outcomes of coastal interventions and other nature-based solutions (Borsje et al., 2011).

A lack of recognition of multiple values can also be linked to limited **participation in the governance** of coastal interventions. The policy landscape around coastal intervention tends to be scattered and focused on primary functions (e.g. safety, sometimes nature) rather than multiple functions (Janssen et al., 2020). Furthermore, management and governance of nature-based coastal interventions tend to be separated, which indicates that such interventions remain ‘under the radar’ of policy actors, and do not go beyond pilot cases or scientific experiments (Slinger et al., 2021). However, resilient coastal interventions depend on the participation of multiple stakeholders (including scientists) as well as collaboration of multiple governance actors on different levels, in order to account for diversity, modularity and acceptance of such interventions (Biggs et al., 2012). Evidence is increasing on the utility of multifunctionality for implementing innovative coastal interventions, as the promise of multiple functions can help to get diverse policy and societal actors on board (Aukes et al., 2018; van Oudenhoven et al., 2018).

4.2. Recommended actions for coastal management

Our review suggests that internal resilience should be accounted for when infrastructure options are comparatively evaluated. Its consideration brings attention to how the grey-hybrid-green spectrum of infrastructure enhances value for people. Such system-based views are rarely reported in coastal engineering literature. For practitioners who are increasingly encouraged to conduct a holistic comparison of alternative systems, this leads to a challenging task that is insufficiently backed up by scientific literature. We propose four questions that can aid coastal managers to pinpoint trade-offs and opportunities. The results of the review are translated into subsequent actions that can support the design and management of resilient coastal protection (Table 2).

It is evident that increasing internal resilience entails inherent trade-offs. Structural integration of multiple functions could increase multi-functionality but reduce modularity (e.g. buildings integrated into dikes). The response diversity of ecosystems may be reduced in hybrid systems (e.g. reefs placed in grid structures). Stakeholder involvement is likely to increase organisational complexity. These apparent contradictions can also be seen as a strength, however: the positive connotation of ‘protection’ makes it easy to gain agreement that coastal protection is desirable and necessary, but ‘protection’ means different things to different people. The four proposed questions and subsequent actions (Table 2) can aid coastal planners to pinpoint trade-offs and opportunities, and can serve environmental management by redirecting the

Table 2
Recommended actions for coastal management, based on this literature review.

Questions to consider	Recommended actions for coastal management
Does the intervention consist of components that are diverse in their response to disturbances?	• Diversify the number and type of species performing a certain function • Introduce variation in height, structure, building typologies, sightlines, distribution of built to unbuilt space, ease of access • Introduce diversity through the micro, meso, macro and mega scales • Introduce variation in economic and social activities
Does the intervention incorporate ecological, social, and economic functions in addition to coastal protection?	• Clarify function of the area during the periods between extreme events • Evaluate and improve ecosystem services • Increase the density of functions the built environment • Improve spatial heterogeneity (i.e. mix different land use functions in one location)
Does the intervention consist of components that can be replaced, restored or renovated without disturbing the entire system?	• Add redundant features that are disaggregated (i.e. multiple components in the system that provide similar functions) • Add decentralized elements to the intervention • Introduce modular features through the micro, meso, macro and mega scales
Has the planning of the intervention incorporated adaptive and participatory processes?	• Use the promise of multiple functions to get diverse policy and societal actors on board • Facilitate discussion of practitioners (engineers, ecologists, spatial planners, policymakers, etc.) from multiple domains • Use interventions as opportunities for experimentation and innovation • Encourage ‘learning by doing’ and create ‘safe-to-fail’ design experiments

conversation on coastal engineering from ‘grey vs. green’ to resilient interventions. Our review of 105 case studies suggests that resilient solutions for adaptation are unlikely to be exclusively engineered or natural, but rather a diverse mix of options (Reguero et al., 2018b).

4.3. Further research

This review followed a deductive approach, in which we analysed whether six factors from the double-insurance framework were explicitly considered (Andersson et al., 2017). The articles considered in the review represented multiple scientific disciplines (i.e. approached from different angles), but few studies were truly interdisciplinary. Cases were often approached either from a predominantly ecological or engineering point of view, and few intended management outcomes related to these disciplines were evaluated, let alone the co-benefits. Moving forward, the application and evaluation of internal and external resilience requires case-by-case evaluation conducted through spatial, social, economic and environmental analysis. The rapidly emerging field of nature-based solutions (UN, 2017) has the potential to generate momentum for true interdisciplinary approaches, especially considering its promising interest in governance and financing issues (e.g. Seddon et al., 2020).

Furthermore, elements that are limited in this review could be considered more deeply, such as attention for geographical context to take into account differences in the global north/south. In addition, integration with existing research (e.g. principles of resilience: flatness of hierarchy, high flux, homeostasis (Wardekker et al., 2010)) can reveal links between socio-economic context and the grey-green spectrum, thereby strengthening the framework’s systems perspective. This also opens the door for evaluation methods and indicators that go beyond either biophysical or economic evaluation, for instance through integrative cost-benefit analyses or multi-criteria decision analysis (e.g. Tonmoy and El-zein, 2015). Such integrated methods will signify progress towards better evaluation and, hence, better insights in the potential outcomes and goals of coastal infrastructure.

5. Conclusions

This review examined case studies along the grey-green spectrum of coastal protection. The objective was to examine whether there is a common understanding of: the characteristics of and differences between grey and green infrastructure, where interventions sit on this spectrum, and the resilience of grey versus green infrastructure. We expanded the double-insurance framework (Andersson et al., 2017) by broadening the scope for each factor so it could be used to assess the grey-green range of coastal protection interventions, rather than solely nature-based interventions. This was applied as a lens to examine 104 multidisciplinary publications related to coastal engineering, comprising 105 case studies. Our systematic collection and synthesis of previous research and a wide variety of global case studies led to the following findings.

Our review showed that external factors are typically used to characterise the grey-green spectrum. The additional consideration of internal factors (response diversity, multifunctionality, modularity and adaptive, participatory governance) revealed novel insights. It showed that interventions like dikes, reefs, saltmarshes, sand nourishment and dunes span a wider segment of the grey-green spectrum than they are generally categorised in. They cannot be characterised as a homogeneous group of interventions, nor can a clear line be drawn between grey and green interventions. Perhaps the clearest distinction can be made based on function; with grey interventions, the entire coastal protection function is derived from engineering, with green interventions that function is derived from ecosystems. However, grey infrastructure increasingly incorporates ecological processes at varying scales, inspired by the inherently resilient qualities of nature. Similarly, natural and nature-based infrastructure tend to be one of multiple lines of defence for coastal protection, often in conjunction with grey interventions. Characteristics that are generally attributed to green interventions (i.e. environmentally sensitive, multifunctional, adaptive, self-repairing, low-regret) were not found to be unique to the green side of the spectrum; the combination of response diversity, multifunctionality, modularity and adaptive governance practises that leads to internal resilience could be found across the entire spectrum of grey-green interventions.

Our findings were the result of employing an adapted version of the double insurance framework (Andersson et al., 2017), in order to take a systems perspective to coastal protection. We expanded this framework from solely considering nature-based solutions to also include grey and hybrid infrastructure, and applied it to coastal protection. The review showed that most studies do not explicitly consider coastal protection interventions from a systems perspective, i. e do not take both internal *and* external factors into account. Some factors feature prominently in the literature (e.g. ecological consideration, multifunctionality), whereas others are rarely mentioned unless it is the goal for a study (e.g. adaptive governance practises, socio-economic context). The bias towards ecological consideration and multifunctionality reflects the prominence of scientific disciplines studying coastal protection from a biophysical and functional point of view. Location, in terms of urban density or proximity to population, was rarely specified. This followed from a general lack of attention for socio-economic context and its consequences for internal factors.

Incorporating a systems-based view into coastal management strategies would support coastal managers and planners in conducting holistic comparisons of alternative systems when deciding on interventions to protect both people and land. A meaningful discussion, and undertaking the recommended actions (Table 2), requires the participation of practitioners (engineers, ecologists, spatial planners, policymakers, etc.) from multiple domains, approaching the same design from multiple perspectives. Interdisciplinary research may be organisationally more complex, but it allows the integration of methodologies across different domains, encourages long-term learning and reduces redundancies and mistakes in later stages of a process. In the face of an increasingly uncertain future, coastal protection needs to add value to its surroundings beyond reduction of flood and erosion risk. Interdisciplinary research and practise play a key role in achieving this. We propose that internal resilience should be accounted for when infrastructure options are comparatively evaluated. This consideration brings attention to the ways in which the grey-hybrid-green spectrum of infrastructure enhances value for people beyond protection.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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