Salt marsh construction as a nature-based solution in an estuarine social-ecological system

Martin J. Baptist [a,g,*], P. Dankers [b], J. Cleveringa [c], L. Sittoni [d,i], P.W.J.M. Willemsen [d,e,f], M.E.B. van Puijenbroek [a], B.M.L. de Vries [b], J.R.F.W. Leuven [b,h], L. Coumou [c], H. Kramer [j], K. Elschot [a]

[a] Wageningen Marine Research, 1781 AG Den Helder, the Netherlands
[b] Royal HaskoningDHV, Nijmegen, the Netherlands
[c] Arcadis, Zwolle, the Netherlands
[d] Deltares, Delft, the Netherlands
[e] Royal Netherlands Institute for Sea Research, Yerseke, The Netherlands & Utrecht University, Utrecht, the Netherlands
[f] Twente University, Enschede, the Netherlands
[g] Aquatic Ecology and Water Quality Management, Wageningen University and Research, Wageningen, the Netherlands
[h] Hydrology and Quantitative Water Management, Wageningen University and Research, Wageningen, the Netherlands
[i] EcoShape – Building with Nature, Dordrecht, the Netherlands
[j] Earth Observation and Environmental Informatics, Wageningen University and Research, Wageningen, the Netherlands

ARTICLE INFO

ABSTRACT

Constructed salt marshes as a Nature-Based Solution for coastal defense offer additional benefits over conventional engineering, but project realization is often hampered by practical and governmental obstacles. We assessed the execution of a local-scale salt marsh construction project as a Nature-Based Solution (NBS) with respect to the regional-scale Social-Ecological System (SES) in an explicitly linked NBS-SES framework. A local municipality came up with various plans to develop its waterfront but these proved unrealizable without wider stakeholder participation. Crucial for success was that the local initiative was turned into an NBS integrating livability, biodiversity and flood safety, and that it was linked to the governance systems and actors in a regional SES. The chosen NBS consists of a city beach and two salt marshes, a salt marsh park that is open to the public and a pioneer salt marsh that is only accessible for research. The pioneer salt marsh was constructed by raising the seabed to around mean high tide with sand obtained from a capital dredging project. It was used as a large-scale natural experiment in salt marsh construction. To test the effect of enrichment with silt and clay on initial salt marsh development, six hectare-scale compartments were created in which mud was mixed with sand in the top 1.0 m of the bed to three mud contents of on average 8%, 25% and 48%. Heavy machinery was needed to mix mud through the upper meter of the sandy bed. Mixing mud was softening the sediment causing the machines to sink into the 48% mud enriched bed. To test whether seeding with a pioneer plant species accelerates salt marsh development, fragments of *Salicornia procumbens* plants were seeded in half of three compartments. Field observations between November 2018 to September 2020 showed that seeding of *Salicornia* plant fragments resulted in significant differences in vegetation cover and species richness in the first growing season. Mud content showed significant positive effects on vegetation cover and species richness in the two monitored growing seasons, where the compartments with on average 7–9% mud had the lowest vegetation cover and species numbers. When constructing a salt marsh by raising sand and mixing mud, a mud content of 25% is practically feasible and results in high vegetation cover and species richness.

1. Introduction

Coastal wetlands provide many ecosystem services valued up to US$ 193,845 ha^{-1}yr^{-1} [1]. Depending on the rate of climate change and adaption measures, between 0 and 30% of global coastal wetland area may be lost by 2100 [2] on top of high historical global losses [3,4]. The historical loss of coastal wetlands has been dominated by human alterations, such as the conversion of wetlands to agriculture and by engineering measures such as coastal flood defences, damming and dredging. However, nature-based coastal defense is gaining momentum as means of coastal protection while supporting nature and its biodiversity, addressing causes and consequences of climate change and secur-

ing ecosystem services for human wellbeing. Upscaling of nature-based coastal defense offers potential for an increase in coastal wetland area [5], on landscape scale instead of the generally patch-specific approach used at present [6]. With increasing risks of flood disasters for many coastal societies, nature-based coastal defense offers many additional benefits over conventional engineering [7], although we should focus on finding synergies among green and gray solutions [8]. Disregard the advantages, execution of nature-based projects are often hampered by practical and governmental obstacles.

Nature-based coastal defense is a component of Nature-Based Solutions (NBS), which were coined by the World Bank as part of their biodiversity portfolio and as a contribution to its work on climate change and adaptation [9]. NBS are defined by the IUCN as "actions 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" [10]. The concept of NBS is rooted in the ecosystem services framework and preceding concepts of NBS were amongst others ecological restoration, ecosystem-based management and ecological engineering [11]. NBS go beyond former approaches by providing an umbrella framework, with new insights on how ecological solutions can work at larger scales, towards policy coherence, and in synergy with more traditional methods [12]. The IUCN Global Standard for Nature-based Solutions is made up of eight interconnected Criteria. Criterion 1 is to effectively address the societal challenge to which the solution will respond. Criterion 2 guides the design of NBS to recognize the complexity of regional-scale land/seascapes. Criteria 3, 4 and 5 correspond to three key dimensions of sustainable development; ecosystem integrity, economic viability and social equity. Criterion 6 addresses trade-offs that are inherent in most natural resource management decision-making. Criterion 7 promotes an evidence-based adaptive management approach in which learning and action complement each other. Criterion 8 promotes mainstreaming within the appropriate jurisdictional context and linking to sustainability targets [13].

An umbrella framework that shares resemblance with NBS is that of a Social-Ecological System (SES). The SES framework is rooted in policy analysis and was developed as a diagnostic method for studying the complexity of variables that affect the incentives and actions of actors under diverse governance systems in multivariable, non-linear, cross-scale ecosystems [14]. An SES is a nested, multilevel system combining social, economic, governmental and ecological systems that provide ecosystem services to society [15,16,14]. On the highest hierarchical level, seven first-tier categories define an SES. First and foremost, an SES consists of four core subsystems: (i) Resource Systems, e.g., a lake or an estuary; (ii) Resource Units, e.g., types of wildlife, and amount and flow of water; (iii) Governance Systems, e.g., the policy area and rule-making organizations; and (iv) Actors, e.g., individuals who use the system in diverse ways for sustenance, recreation, or commercial purposes. Within such a core system actors extract or make use of resources that deliver ecosystem services and at the same time they provide for the maintenance of the resource system. Actors follow procedures determined by the governance system but also in the context of (v) Related Ecosystems, and embedded in broader (vi) Social, Economic and Political Settings. Central in the SES framework are the (vii) Focal Action Situations in which actors interact with each other, leading to outcomes that could be differentially valued. The actors work within the context of social dilemmas and biophysical constraints, as well as within cultural contexts [17]. The SES framework has been applied in studying complex dynamic systems (e.g. [18–20]) and adaptive governance systems (e.g. [21–24]).

The conceptual attributes of the NBS and SES frameworks share many similarities, such as utilizing ecosystem services, linking governmental processes to natural resources and taking account of political support and willingness. The main difference between both frameworks is in visualizing and explaining interconnectedness. The eight Criteria of the IUCN Global Standard are presented as circular rings that are all interconnected [13]. The SES framework is presented as an organized, decomposable structure of subsystems and variables with explicit links

and feedbacks [14]. This structural approach is important for understanding complexity [25]. We therefore link both frameworks and evaluate them using an evidence-based example of a project that deals with flood safety, biodiversity and livability in an estuarine environment. The first objective of this paper is: 1) to evaluate the stakeholder processes in the realization of a project in which a city beach and two salt marshes were constructed. We assess how the proposed local solution was accomplished with respect to the regional SES. We subsequently zoom in on a field experiment for constructing a salt marsh. The field experiment focusses on hectare-scale processes of mixing mud and sand in different ratios, and stimulating vegetation development. The second objective of this paper is: 2) to present the practical knowledge and lessons learned from constructing this salt marsh. Three research questions were identified: i) to what mud content should the original sandy bed be enriched in order to achieve suitable conditions for salt marsh vegetation? ii) to what extent does bed composition affect the formation of tidal creeks in a constructed marsh? and iii) to what extent can seeding with pioneer species kick-start vegetation development?

2. The Ems estuary as a social-ecological system

The Ems estuary is located in the north-eastern part of The Netherlands and the north-western part of Germany (Fig. 1). The most upstream boundary of the Ems estuary is fixed by the man-made weir at the German village Herbrum, which determines the tidal limit of the estuary. The downstream boundary is generally defined by the barrier island Borkum. The length of the Ems estuary, including the tidal river, is approximately 100 km and the surface area is approximately 460 km^2 excluding the ebb-tidal delta seaward of the island of Borkum [26].

The estuary is a prime example of a social-ecological system (SES) that fulfills all four core subsystems: (i) it is a large estuarine natural resource system, (ii) it contains estuarine habitats and wildlife with natural and commercial value, as well as major waterways, (iii) it is managed by various institutions under local, national and European legislation and (iv) it is used by industry and shipping, and to a lesser extent, by fisheries and tourism.

The Ems estuary is one of the major estuaries in the related ecosystem of the Wadden Sea. The estuarine food web of the Ems is rich in habitats for shellfish, seagrass, shrimp, fish, birds, and seals [27–33]. The management of the transboundary Ems estuary is embedded in broader social, economic and political settings and carried out jointly by the Netherlands and Germany under various legal frameworks [34]. Maritime affairs have been agreed in the Ems-Dollard Treaty of 1960 [35] and later treaties. Nature protection, water quality standards and non-maritime management issues fall under the EU Habitats Directive (HD; 92/43/EEC), the EU Birds Directive (BD; 79/409/EEC) and the EU Water Framework Directive (WFD; 2000/60/EC), which have been translated into national legislation such as the Dutch Nature Conservation Act.

The major waterway of the Ems estuary forms an important navigation route. There are three large ports for sea-going vessels, Eemshaven, Delfzijl and Emden. Two towns along the Ems river, Leer and Papenburg, have smaller ports. The latter holds a shipyard for large cruise ships. The navigation channels to these ports have been deepened a number of times in the past decades leading to physical changes of the Ems estuary (e.g. [36,37,26,38,39]). Moreover, this resulted in a chain of physical process reactions increasing the turbidity in the Ems (e.g. [36,40–42]). The Ems river has become hyperturbid in the 1990s [42] with silt concentrations up to 200 g L^{-1} near the river bed [43]. The breakdown of organic matter in this so-called fluid mud layer leads to a strong decline in dissolved oxygen levels (< 2 mg L^{-1}) in summer [44]. On top of this, various human activities caused habitat loss [45]. The physical changes in the estuary have led to a deprived ecological state compared with the 1950s [46].

Because the deterioration of the ecological quality of the estuary was a regional concern, a focal action situation formed in which governmen-
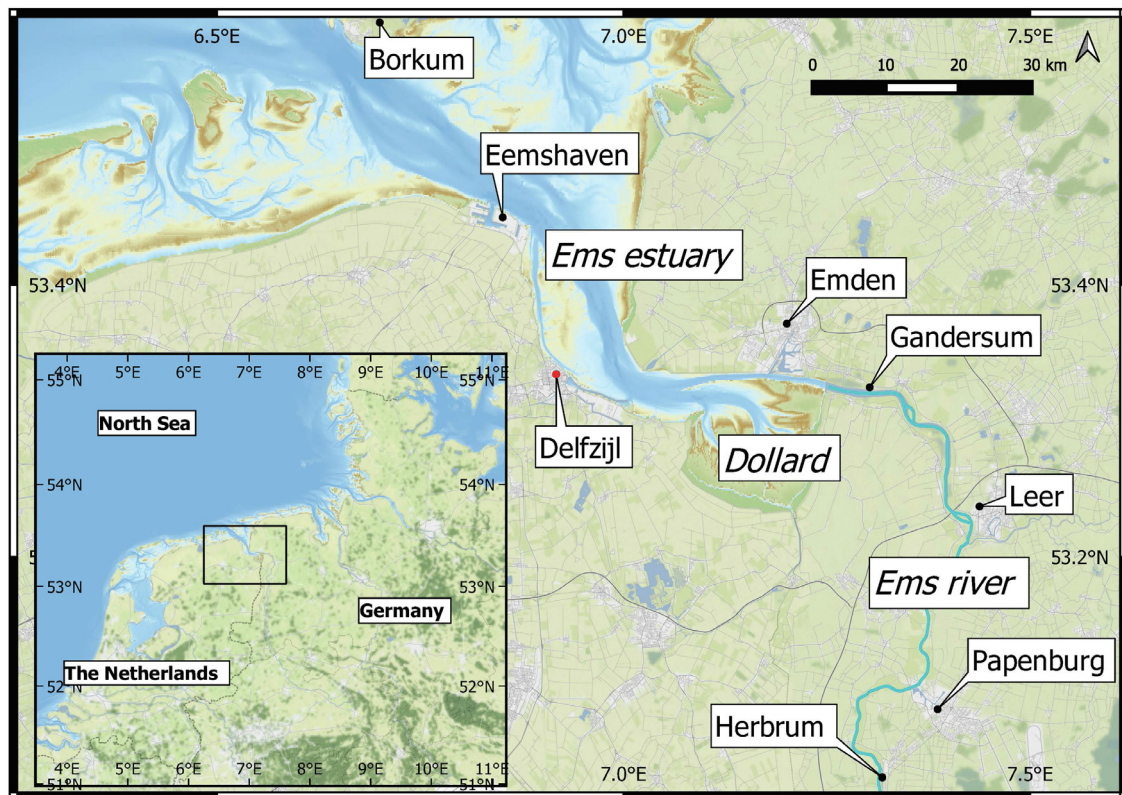
Fig. 1. Map of the Ems estuary on the border between the Netherlands and Germany. Topographic names mentioned in the text. Sources: bathymetry Wadden Sea from Rijkswaterstaat, terrestrial background map showing built environment and roads from Stamen Terrain.

tal, non-governmental and commercial actors proposed a series of measures for ecosystem restoration. One of the measures is to build new habitats acting as sediment sinks along the coastline, in combination with dike reinforcements [47], to contribute to the ambition to withdraw 1 Tg dry weight of fine sediment annually from 2022 onwards [48].

3. Merging the IUCN global standard for NBS into the SES framework

3.1. The merged NBS-SES framework

We placed the eight criteria of the IUCN Global Standard for NBS inside the core framework for Social-Ecological Systems (Fig. 2). Here we outline their relationships, where we refer to the IUCN criteria with numbers between brackets and to the SES components with letter codes between brackets. One or more *Societal challenges* (1) are usually the entry point to start looking for a nature-based solution. Societal challenges are typically formulated by Actors (A), either individuals or collective actors of organizations. The IUCN explains that the area where the societal challenge is addressed is often a part of a larger geographical system. The designer should therefore be aware of the bigger ecological, human and economic aspects of the dynamic land- or seascape. In the SES framework we place the IUCN criterion *Design at scale* (2) at the Resource System (RS), emphasizing the scale of an entire land/seascape but realizing that it also adheres to the economic and policy systems of the land/seascape and to the Related Ecosystems (ECO). An NBS should have a *Biodiversity net-gain* (3) by enhancing ecosystem integrity and health. This criterion adheres to the Resource Units (RU) of the SES. An NBS should also have *Economic feasibility* (4); it should be affordable within conditions of rights and rules that are set by the Governance Systems (GS) towards the actors and focal action. Moreover, an NBS should

show *Inclusive governance* (5) in formal, legal or informal regulations and processes that make the Governance Systems (GS). Often trade-offs need to be determined and made in optimizing ecological, economic and stakeholder gains. The IUCN criterion *Balance trade-offs* (6) must balance the Resource Units (RU) as well as the Actors (A) and is placed in the feedback relations for both. Because ecosystems are complex dynamic systems, an NBS intervention could show unintended, unforeseen and undesirable effects. Consequently, *Adaptive management* (7) is required to iteratively learn and adapt the NBS. This criterion is placed in the feedback loop to the Governance Systems (GS). Last, but not least, for *Mainstreaming & sustainability* (8) of the concept of NBS, it should be embedded into policy or regulatory frameworks as well as linked to national targets or international commitments. This criterion is placed at the Social, Economic and Political Settings (S) bordering the box of the regional SES.

3.2. Application of the merged NBS-SES framework to the salt marsh construction project

Delfzijl, the Netherlands, is a town with 46,000 inhabitants on the bank of the Ems estuary. Delfzijl is at a remote location in the Netherlands and is facing major demographic changes and a decreasing livability. The town is protected from flooding by a vertical sheet pile wall that blocks the town inhabitants' connection with the sea both physically and emotionally. A first Societal challenge (1) in Delfzijl was to make the town attractive to residents and visitors. In the beginning of this century the municipality made plans to regain its former maritime character and to reconnect the port town with the estuary. The municipality came up with various plans to develop its waterfront focusing on their desire to enlarge and widen the city beach. However, the plans failed multiple times, as they proved unrealizable without wider stakeholder participation or, in the case of beach extension, were in breach
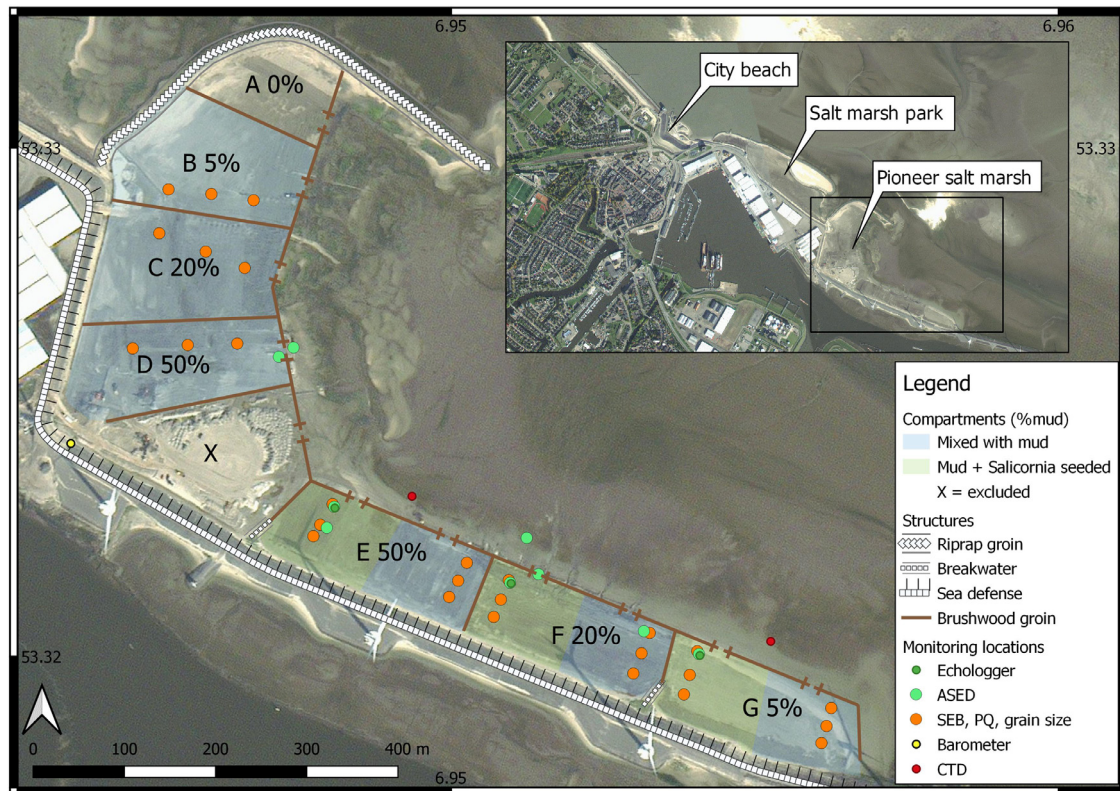
Fig. 2. The IUCN Global Standard for NBS Criteria (eight numbered labels in blue) added to the Social-Ecological System (SES) framework. Figure adapted from Mcginnis and Ostrom [17]. NBS Criteria numbers 1 to 8 and SES codes between brackets link to the text.

of the Nature Conservation Act. A second Societal challenge was to provide coastal safety. The existing flood protection had to be strengthened in face of a risky mix of land subsidence and earthquakes due to gas mining, accelerated sea level rise, and increasing storminess and wave energy. The municipality chose to see this as a chance to make the most of a large investment by the regional water authority.

To explore the possibilities for ensuring flood safety while improving the living environment for people, the municipality invited many Actors (A): ministries, the province, water boards, knowledge institutions, inhabitants, the port authority, nature conservation groups and representatives of industry, recreation and business. As a result, a multi-level, multi-organization Steering Group was established and given the call sign 'Marconi'. The Steering Group formed an alliance with two water boards, a neighboring municipality, the executive agency of the Ministry of Infrastructure and Water Management (Rijkswaterstaat), the province of Groningen, the regional landscape expertise center, and the regional alliance of sea ports. Citizen participation was not a formal part in the Steering Group, instead the project manager informed locals through the newspaper [49]. In March 2012, a spatial vision of the Delfzijl waterfront was published on their behalf and at the end of that year the parties signed the Marconi Memorandum of Understanding. Crucial for later success was that the vision was adhering to the large-scale (2) regional Ems estuary as a Resource System (RS). The vision, which included a beach and a salt marsh landscape in front of Delfzijl, was showing how this contributes to a biodiversity net-gain (3) for the Resource Units (RU) in the estuary.

The Marconi Steering Group joined ongoing consultations within other Governance Systems (GS) such as public-private partnerships and public-NGO partnerships, thereby involving and responding to a variety of stakeholders in an inclusive governance (5) setting and lining-up objectives with those of the Programme Ems-Dollard 2050. The Marconi project then sought for economic feasibility (4) of their plans by linking to a capital dredging project of the navigation channel from Eemshaven to the North Sea. This project, under the responsibility of the main water management authority Rijkswaterstaat, was able to deliver large volumes of sand to the Delfzijl waterfront for a reduced price. Economic feasibility was further increased through subsidy providers, and through the research consortium EcoShape, which was given the opportunity to carry out a field experiment on salt marsh construction delivering evidence-based monitoring needed for adaptive management (7).

A balance of trade-offs (6) needed to be made, involving Actors (A) and Governance Systems (GS). The design for a beach and salt marsh landscape at the waterfront of Delfzijl had to comply to strict environmental regulations for the protected nature of the Natura 2000 area, so more trade-offs were made to safeguard ecosystem integrity. In combination with dike reinforcements the municipality and the water board agreed to move the existing sea defense inland by 100 m, making room for a large city beach that lies outside the Natura 2000 nature protected area. Last, but not least, mainstreaming & sustainability (8) was sought for by adhering to the international policy and regulatory frameworks but also by giving EcoShape room for studying ways to scale up and scale out the chosen Nature-Based Solution. Incorporating this scientific element in the Nature-Based Solution increased project feasibility.

Because the Marconi Steering Group sought for integrated solutions to problems of livability, flood safety, and water management, and because they explicitly included biodiversity, suggestions for a Nature-Based Solution were made. And only because the local initiative was explicitly embedded into the regional social-ecological system of the Ems estuary, the execution of this Nature-Based Solution became possible.

The chosen Nature-Based Solution in Delfzijl combines flood safety with biodiversity and livability. It consists of a city beach and two salt marshes, a salt marsh park that is open to the public and a pioneer salt marsh that is only accessible for research (Fig. 3). The presence of a wave attenuating salt marsh in combination with an alongshore dam forms a hybrid flood defense [50,51] and provides a good basis to protect part of the town center of Delfzijl. Model calculations showed that the presence of the salt marsh leads to a reduction of the significant wave height of 25% for wave overtopping over the dike at a flood level of 7 m above mean sea level and of 60% reduction at a flood level of 4 m above mean sea level, when compared to the original situation without the salt marsh [52]. Moreover, the two salt marshes soften the transitional zone between land and sea, and invoke gradients between freshwater and salt water as well as gradients in grain sizes. The salt marsh park of 13 ha lies adjacent to the city beach and has a bird breeding island for terns and small waders. This part is accessible for nature recreation via a boardwalk and has a bird hide. The salt marsh park and the beach enrich the nature experience and livability for inhabitants and tourists. The pioneer salt marsh of 15 ha has been designed as a field experiment on salt marsh construction and development.

Fig. 3. Lay-out of the pioneer salt marsh experimental site with six compartments with mud mixed in the top meter and their intended mud content. In three compartments half of the area was seeded with *Salicornia* plant fragments. The monitoring locations are indicated: six transects (orange dots) with Sedimentation-Erosion Bars (SEB), Permanent Quadrants for vegetation composition (PQ) and grain size sampling, nine locations (light green dots) with Acoustic Surface Elevation Dynamics sensors (ASED), three locations (small green dots) with Echologger instruments adjacent to three ASEDs, two locations (small red dots) with conductivity, temperature and pressure sensors (CTD) and one location (small yellow dot) with a barometer. Inset: the three components of the Marconi project showing the position of the experimental site. Background image: Triplesat panchromatic composite image from September 2018 (during salt marsh construction).

4. Set-up and design of a large-scale field experiment on salt-marsh construction

A field experiment on salt-marsh construction was carried out in the form of a Large-scale, Unreplicated Natural Experiment (LUNE). Despite their lack of replication, LUNEs have a unique power, not attainable in any other way, namely to test hypotheses at large scales and in complex systems [53]. Field measurements were carried out by partners in the EcoShape consortium, a network of organizations and individuals working together to advance the application of Nature-Based Solutions in hydraulic engineering related societal issues. The field experiment assessed the most effective way of constructing a salt marsh by executing large-scale field tests on mixing mud and sand and by stimulating vegetation development by seeding pioneer plants.

The estuarine environment near Delfzijl consists of sandflats and mudflats, but land-water boundaries are abrupt and rock protected and therefore lack salt marshes. Salt marshes are important coastal habitats that provide nature-based protection against waves [54], sequester carbon [55,56], and facilitate growth with sea level rise thereby sustaining their rich biodiversity [57]. In the Netherlands there is ample experience with methods that stimulate salt marsh development for land reclamation [58]. These consist of drained sedimentation basins delineated by permeable brushwood groins placed in environments where fine sediment accretion already occurs [59]. However, in the Marconi project the aim was to construct salt marshes in a location that had too much wave exposure for accretion of mud and lay too low for vegetation development.

The design of the salt marsh was based on best practices for creating new salt marshes in an estuarine setting [60]. Two rockfill dams, one for each salt marsh, were built to provide wave shelter. Subsequently, the bed level at the site of the projected salt marshes was raised with sand obtained from capital dredging in the estuary. The new bed level was set to 1.20 m above Dutch Ordnance Level (NAP) sloping upwards towards to 1.70 *m* +NAP. The optimal inundation height for pioneer species is around mean high water level [57], which is at 1.40 *m* +NAP at this location. The local mean semi-diurnal meso-tidal range is 3.06 m and the mean annual suspended sediment concentration is 90 mg/l. The raised bed initially consisted of sand with a mud content smaller than 0.5% (particles <63 μm; silt and clay). Although natural siltation during inundation will gradually enrich the bed with fine sediment, a nutrient-poor sandy bed will not evoke fast vegetation development [61], which was an explicit aim of the project. Moreover, a vegetation covered salt marsh is more attractive to inhabitants and tourists, and it also prevents nuisance from drifting sand. Mud was mixed through the sand to speed-up biogeomorphological evolution of the salt marsh.

4.1. Mixing mud through the bed in different contents

In existing man-made salt marshes along the Dutch coast the mud content generally increases in a horizontal gradient from 5% mud in the most exposed seaward sedimentation basins to 50% mud higher on the marsh in the landward sedimentation basins [62]. The mud content also increases vertically going from the top to the bottom of salt marsh deposits, showing that in the beginning of marsh formation mineral sedimentation dominates and the organic contribution to salt marsh growth

increases with age and succession of vegetation [63,64]. The content of cohesive sediments in the bed affects the initial formation of tidal creeks in a young salt marsh [65]. To test the effect of mud enrichment on the morphological and biological salt marsh development we designed a field experiment in which the top 1.0 m of the bed was mixed with mud. In the 15 ha experimental site we created six compartments delineated with permeable brushwood groins in which mud was mixed with sand in two duplicated blocks of three intended mud contents of 5%, 20% and 50% (Fig. 3). Three compartments B, C and D located in the west differ in shape but all have a surface area of 2.3 ha. Each of these has one opening in the permeable dams on the seaside, in order to stimulate creek development. The three compartments E, F and G in the south along the alongshore dam were designed to have equal shapes, slopes and sizes. These compartments are 1.8 ha (216 × 85 m) in size and have two openings in the permeable groins. Compartment A was not included in the experiment because of its divergent position with respect to the riprap groin. Compartment X was not included because it was temporarily in use as sand depot.

Mud was brought in from a land depot where dredged material was stored that came available at a land reclamation port extension into the estuary about forty years ago. The dredged sediment had been consolidated to a rather firm dry soil that was transported by trucks to the experimental site. From August to October 2018 trucks, bulldozers and excavators brought fine sediments on top of the sandy base layer. Mixing of the soil through the top 1.0 m of the sandy bed was achieved with a deep spader (Imants 135SX265PL) pulled by a tractor. For the 5% compartments a layer of 8 cm of soil was placed on top of the sand and mixed through. For the 20% compartments a layer of 30 cm of sand was removed and replaced with soil and subsequently mixed through. For the 50% compartments a layer of 1 m of sand was removed, replaced with 80 cm of soil and covered with a bearing layer of 20 cm of sand for the heavy machines, and subsequently mixed through. The deep spader mixed 0.5 ha per day at 10 working hours per day. In total 35,000 m³ of soil was applied. In the compartments with half mud half sand the heavy machinery sank into the softened soil making project execution complicated and leaving deep tracks. A track-laying vehicle was applied to flatten the surface after mixing.

4.2. Seeding with pioneer plant fragments

Recent field experiments showed that the availability of viable seeds in the sediment can form a threshold for pioneer vegetation establishment even with a source population nearby [66]. Marsh restoration sites may therefore benefit from adding seeds to expedite marsh development [67]. To test whether seeding with a pioneer plant species was needed in this site to accelerate salt marsh development, we seeded fragments of *Salicornia procumbens* plants in half of the three southern compartments: E, F and G (Fig. 3). First, a total of 13,500 *Salicornia* sp. plants were manually collected in autumn 2017 from a nearby salt marsh. The plants were stored over winter for vernalization; the induction of a plant's flowering process by exposure to prolonged cold. One week before seeding, the plants were cut in pieces of 2 cm length, approximately 100 fragments per plant, by use of a hand-driven antique straw cutting machine. The 1.35 million plant fragments were soaked in freshwater for three days to start the germination process of the seeds. Sawdust was added to increase volume. A set of experiments carried out in climate chambers showed that a combination of vernalization and pre-germination in freshwater had the highest success rate with most seedlings establishing. Because washing away of seeds and seedlings by waves and currents has been found to be the cause of substantial seedling mortality [68,66,69], we chose a time window with low spring tide and quiet weather to maximize successful rooting of seedlings. In May 2019 the mixture of wetted plant fragments and sawdust was manually spread out in the western half of compartment E, F and G with a density of approximately 50 plant fragments per m².

4.3. Field observations

A field observation program was carried out from November 2018 to September 2020. The program was designed to determine the spatial and temporal development of the (interaction between) morphology and vegetation. Hereto, sedimentation and erosion rates, sediment composition, development of tidal creeks, bed height, flooding frequency, vegetation cover, and density of salt marsh plants were monitored. Biogeomorphodynamic developments were analyzed with respect to heights, slopes, mud contents, and vegetation cover. Instruments used in the field were a LiDAR drone, RTK-DGPS, CTDs in combination with a barometer, Sedimentation-Erosion Bars (SEB), and Acoustic Surface Elevation Dynamics (ASED) sensors and echologgers, Fig. 3.

4.3.1. Water level

The water level was determined by averaging readings from two submersible dataloggers for conductivity, temperature and pressure (CTD-Diver, Van Essen instruments). Both loggers were placed at the seaward side of the brushwood groins at a few centimeters above bed level. The measuring interval was set at five minutes. The water depth and corresponding inundation characteristics were calculated by correcting for atmospheric pressure, which was measured with a barometer installed well above maximum water level at the study site.

4.3.2. Sediment composition

The grain size composition was determined by laser diffraction (Malvern Mastersizer). Samples were taken in nine transects perpendicular to the sea defense structure at three sampling locations landward, middle and seaward, totaling 27 sample locations. In the first measuring campaign of Nov-2018 one meter deep cores were sampled each 20 cm to obtain a vertical sediment composition profile. In later campaigns in May-2019, Nov-2019, Apr-2020 and Sep-2020 surface samples of the mobile top layer of 1 cm were obtained.

4.3.3. Bed level changes

Salt marsh bed level changes were measured with in-situ instruments, i.e. Sedimentation-Erosion Bars and Surface Elevation Dynamics sensors, with RTK-DGPS and with a LiDAR-drone. Sedimentation-Erosion Bars (SEBs) consist of two horizontally aligned poles inserted into the ground until they reach a stable horizon. During measurements, a 2 m-long bar with 17 holes 10 cm apart is placed on the poles and a ruler is placed through these holes to measure the distance to the soil surface. Through repeated measurements the accuracy of the time series is about 1.5 mm vertically [70]. In the study area 27 SEB-stations were aligned in nine transects perpendicular to the dike. The surface elevation change was determined every two to three months. To measure soil subsidence of the deeper sediment layers, the height of the poles relative to Dutch Ordnance Level NAP (~mean sea level) was measured every 2 – 3 months with an RTK-DGPS (Trimble R6 Model 3 with Trimble TSC3 controller). The bed level changes of the tidal inlets were determined by measuring cross-sections with the RTK-DGPS.

Short-time surface elevation changes were determined with Acoustic Surface Elevation Dynamics (ASED) sensors, successors of the SED sensors [71,72] at nine locations from September 2019 to September 2020. An ASED sensor is downward looking with the measuring head aimed vertically at the bottom. It collects measurements of relative bed height by sending an acoustic signal when the head is fully inundated. A burst of eight measurements was stored every 5 to 15 min. The ASEDs were checked every two to three months to ensure data collection, clean the sensors and retrieve the data. Collected raw data from the sensors were converted using a well-documented Python script following up on Willemsen et al. [72].

The elevation of the entire salt marsh was mapped twice a year with a LiDAR scanner mounted to a drone (RIEGL RiCOPTER with VUX-1UAV, see Brede et al. [73] for system specifications). The absolute positioning

of the point cloud was improved by applying georectification with approximately 20 ground control points (GCPs). The horizontal and vertical position of the GCPs were measured in the field using an RTK-DGPS (Trimble R6) or by applying GCPs with built-in GPS (Propeller Aero-Points). Due to the sparse vegetation cover of small plants, height filtering to separate ground versus non-ground vegetation returns was not necessary. The LiDAR point cloud was converted to a raster with a grid cell size of 0.1 m x 0.1 m delivering a digital terrain model (DTM).

4.3.4. Salt marsh vegetation cover and composition

In situ measurements of vegetation diversity and density were performed annually in September at 27 permanent quadrats (PQs) located adjacent to the salt marsh SEB-stations (Fig. 3) in combination with 34 (2019) or 30 (2020) random vegetation plots. In each 2 m x 2 m plot and PQ total vegetation cover and plant species cover was estimated with the decimal scale of Londo [74]. We analyzed all vegetation data (PQ and random plots) with a linear model having compartment, seed treatment, year and surface elevation as explanatory variables. PQ plots were separately analyzed with a linear model having compartment, seed treatment, year, inundation frequency and sediment dynamics as explanatory variables.

Salicornia sp. abundance and growth were measured at 120 additional plots of 1 m^2 during the growing season of 2019. In the seeded parts of compartments E, F and G, 25 plots (aligned in 5 transects perpendicular to the dam with each 5 plots) were established, and in the non-seeded part 15 plots (3 transects perpendicular to the dike with 5 plots) were established as a control. In each of the 120 plots the number of *Salicornia* sp. plants was counted every two weeks between May 29 and Aug 26. Since it is not possible to distinguish different *Salicornia* species in the field shortly after germination, no further distinction was made.

5. Results of field observations

5.1. Field observations on salt marsh morphology and sediment composition

Vertical cores of 1 m with 20 cm interval subsampling for grain composition sampled in November 2018 showed that mixing mud with sand was accomplished throughout although the mud was present in the form of peds. Mud content (volume%) was determined with laser diffraction for sediment particles smaller than 63 μm. The resulting mud contents in compartments B, C and D through the top 1.0 m of the sandy bed were on average ±standard error 9 ± 6%, 25±14% and 47±11% respectively. Compartments E, F and G had on average 48±12%, 25±14% and 7 ± 8% mud mixed through the sandy bed.

Disregard the efforts in flattening the surface, the tire tracks of the heavy machines were clearly visible in the field and in the DTM, showing local elevation differences ranging from several to more than 20 cm. The tire tracks were most evident in the muddy compartments (D and E), and almost absent in the sandy compartments (B and G) (Fig. 4).

The average elevation of the salt marsh was above Mean High Water (MHW) (Fig. 5). During field observations between November 2018 and September 2020 complete inundation of the salt marsh occurred approximately 70 times. The seaward monitoring plots were flooded once every day on average and the inundation frequency decreased to once every four days for the landward plots.

Unexpectedly, sand bars had formed during construction in compartments E, F and G and continued to develop in later stages (Fig. 4,Fig. 5). The bars formed just above the MHW-line. Furthest away from the wave protecting riprap groin, the bar in compartment G was continuous, while the closer-by bar in F was interrupted and in E only two lobes of sand were present. The sand bars or lobes generally were about 10–20 cm higher than the surrounding bed level and had a steep landward edge and gentle slope towards the brushwood groins. The highest bars formed at the wave-exposed part of the salt marsh, whereas no lobes of sand were deposited in the wave sheltered compartments B and C, and only

Table 1
Mud content (volume%) of the top 1 cm of the bed in six compartments, mean and standard error (SE).

	May 2019		November 2019		April 2020		September 2020	
	Mean	*SE*	*Mean*	*SE*	*Mean*	*SE*	*Mean*	*SE*
B	8	9	17	20	23	12	23	4
C	33	34	46	30	53	28	45	23
D	58	14	64	20	66	9	63	9
E	26	24	40	NaN	32	24	37	28
F	13	12	9	9	11	10	15	15
G	4	5	2	4	3	5	8	13

small lobes of sand were present in D. The sand bars thus formed due to wave action, implying that the semi-permeable brushwood groins were not dissipating all wave energy. Bed level changes over two years measured with Sedimentation-Erosion Bars in 27 locations confirmed that the largest changes resulted from sand bar development, order 10–20 cm, whereas remaining changes were small, order 1–2 cm. Overall there was no significant effect of mud content on bed level change ($F_{2,26} = 1.33$, $p = 0.28$), nor was there a significant effect of flooding frequency on sedimentation ($F_{1,240} = 0.15$, $p = 0.70$).

We estimated consolidation of the subsurface, i.e. a soft sediment mudflat, with RTK-DGPS measurements of the height of the SEB-poles and wooden poles of the brushwood groins. The data did not show a consistent consolidation trend over time within the 2 cm measurement inaccuracy.

Between May 2019 and September 2020 the grain size composition of the top 1 cm of the bed showed a trend towards finer sediments in compartments B, C and D, i.e. smaller median grain sizes and higher mud contents (Table 1). These compartments are sheltered from waves, hence these trends can be explained by an import of fine sediment and reduced erosive forces. No clear trends in grain size composition over time were observed in compartments E, F and G other than resulting from the migration of sand bars.

Tidal creeks formed at the seaward end of the compartments. Creek formation started before the brushwood groins were placed, hence some creeks crossed the permeable groins and remained active. Compartment G lacked tidal creek formation. A tidal creek formed intendedly through the inlet in the brushwood groins in compartments B and D (Fig. 5). The latter is one of the deepest (0.3 m) and most actively migrating creeks in the analyzed compartments of the salt marsh. Because of a lack of creek formation in the inlets we could not establish a significant relationship between creek dimensions, mud content of the bed or any other parameters.

Measurements with ASEDs showed that, locally, the bed level increased in the growing season (April - September) with sedimentation in the order of 1 to 2 cm, but erosion was observed in the order of 2 to 6 cm outside the growing season (October – March). Bed level dynamics inside the different compartments (dynamics of creeks and sand bars excluded), where vegetation was able to establish, was limited during the 2-year measurement period.

5.2. Field observations on salt marsh vegetation

The soil that was mixed through the sandy base layer contained seeds of high numbers of glycophytes typically found on fresh non-saline soils. Halophytes growing in the salt marshes were either seeded or seeds came naturally by wind or flowing water.

After seeding with plant fragments of *Salicornia* sp. in May 2019, the seeds did not germinate immediately, despite our freshwater treatment to evoke germination. The number of *Salicornia* sp. plants started to increase mid-July, 1.5 month after seeding (Fig. 6). Seeding significantly increased the number of plants (Seed treatment × Date: $\chi^2_{(1,N = 870)} = 98.14$, $p < 0.001$). The highest mud content showed highest number of *Salicornia* plants ($\chi^2_{(2,N = 870)} = 27.42$, $p < 0.001$).
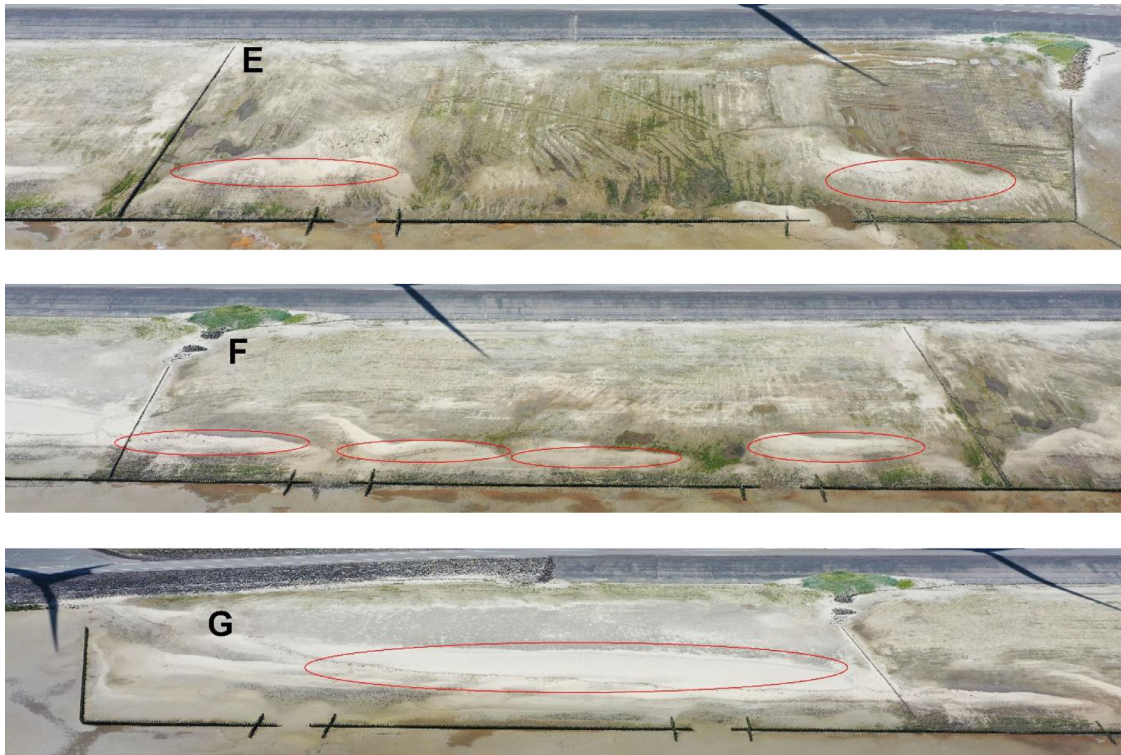
Fig. 4. Oblique aerial pictures of compartments E (top), F (middle) and G (bottom) in June 2020. Red ellipses indicate locations of sand bars. Photo source: Eemsdelta Drones.
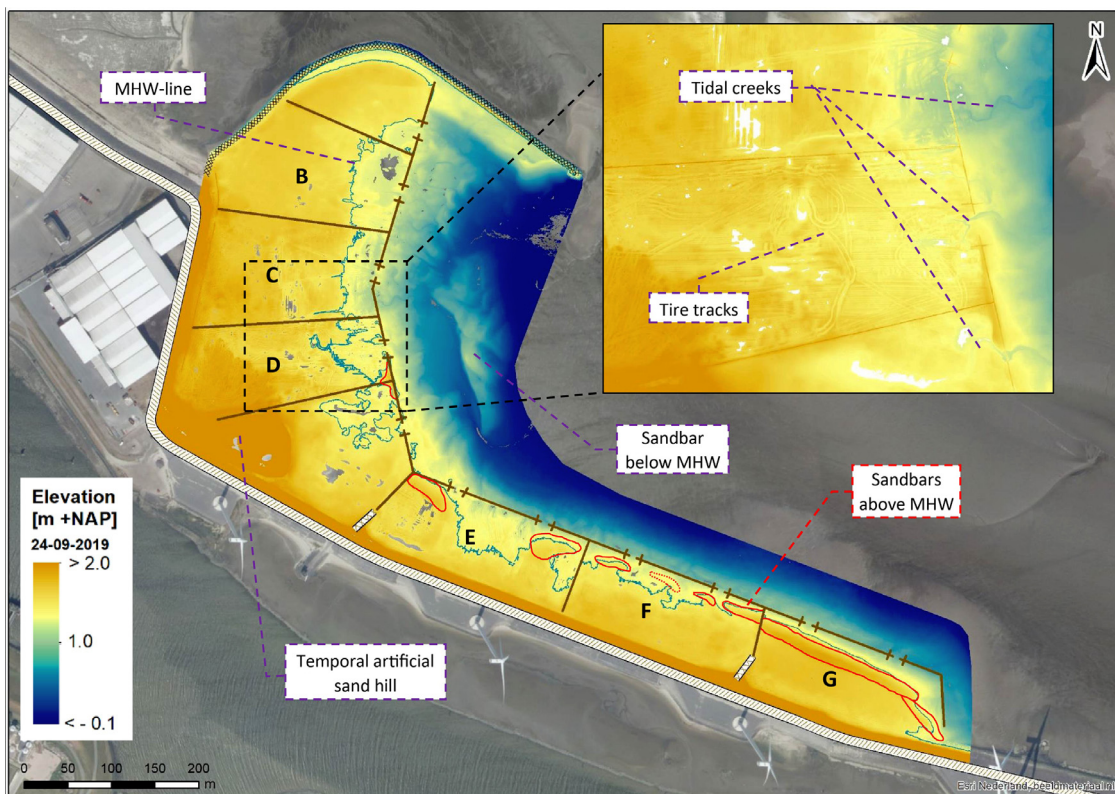

Fig. 5. Digital Terrain Model of the experimental salt marsh based on LiDAR measurements at 24 September 2019. MHW = Mean High Water (1.4 *m* +NAP). Background: aerial photograph of the Netherlands 2019 (beeldmateriaal.nl).
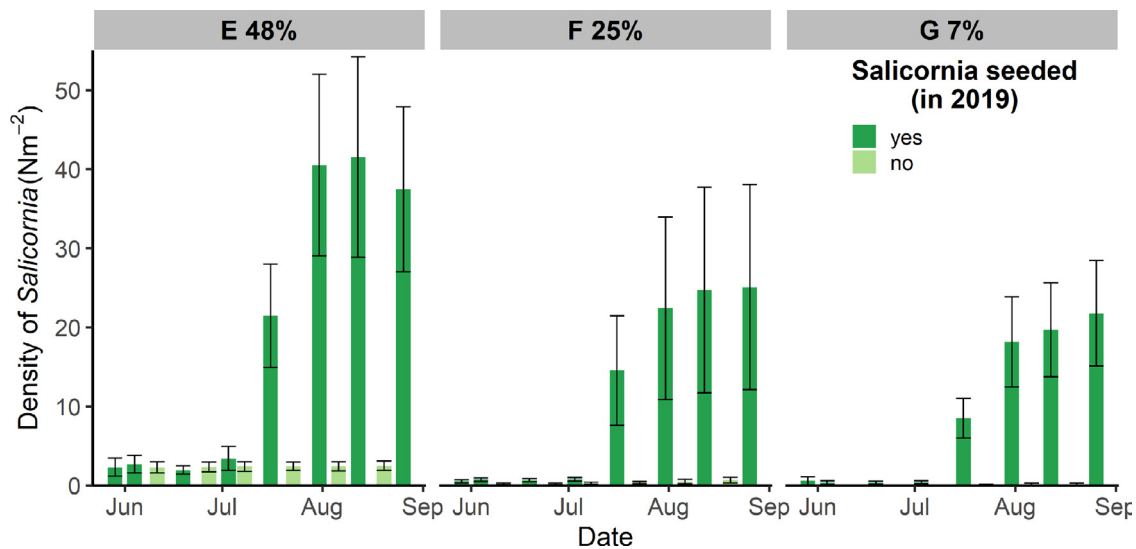
Fig. 6. The density of *Salicornia* sp. plants over time in the first growing season (2019) in compartments E, F and G and for seed treatment.
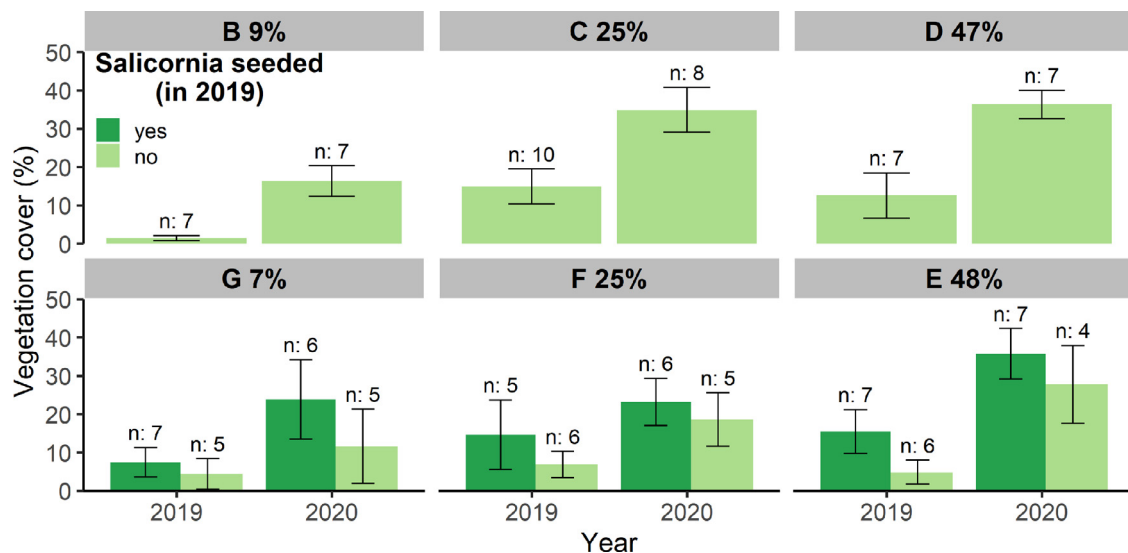
Fig. 7. Vegetation cover in September 2019 and September 2020 for each compartment with (dark green) and without (light green) *Salicornia procumbens* seeding treatment, based on observations in 27 PQ-plots plus random plots.

The total vegetation cover on the salt marsh increased from $10.7 \pm 1.6\%$ in September 2019 to $29.0 \pm 2.6\%$ in September 2020 (Fig. 7). Contrary to our expectation, seed treatment resulted in a significant difference in vegetation cover only in the first year between 2018 and 2019 and only in our PQ plots (Table 2). This indicates that the effect of seeding was temporary and natural seed input was high. The mud content mixed through the bed showed a significant positive effect on total vegetation cover. Pairwise comparisons for mud content showed significant differences for all pairs and were most significant for pairs that included the lowest mud content (50% - 5%: $p < 0.001$, 50% - 20%: $p = 0.036$, 20% - 5%: $p = 0.013$). The compartments with a realized mud content of on average 7 - 9% had lowest vegetation cover, while the differences in cover between compartments with on average 25% or 47 - 48% mud were less outspoken. Photographs of vegetation cover in PQ-plots, comparing seeded with not seeded compartments are shown in the supplementary material. Surface elevation did not show a significant effect on vegetation cover, indicating that the complete landscape was at suitable height for initial salt marsh vegetation development. Sedimentation/erosion dynamics showed a significant effect on vegetation cover in 2020. This was explained by plots lacking vegetation at high erosion rates (>2.5 mm/month) in compartments F and G.

The seeding with plant fragments of *Salicornia* in May 2019 resulted in a significantly higher species richness in September 2019, but the effect was no longer significant in September 2020. Species richness was significantly related to mud content and elevation, both in 2019 and 2020. A higher species richness was found at higher mud contents, where especially the compartments with on average 7 - 9% mud had lowest species numbers. A higher species richness was found at higher surface elevations, likely due to lower inundation frequencies diminishing abiotic stress. The relationship between surface elevation and species richness became stronger in 2020, which indicates that the higher parts of the salt marsh showed vegetation succession from a pioneer salt marsh stage towards a lower salt marsh stage (Petersen et al. 2014).

6. Discussion

6.1. Merging a local NBS into a regional SES

Recently, a conceptual model of the social-ecological system of Nature-Based Solutions in urban environments has been published [75], but the authors did not link to the SES framework explicitly, as

Table 2

Statistical models for the vegetation cover in 27 PQ plots and vegetation cover and species richness in PQ plots plus random plots, for September 2019 and September 2020. Models used for vegetation cover are anova models for which the F-values are shown. Models used for species richness are generalized linear models with a poison distribution for which chi-squared values are shown. Seed treatment is with or without seeding. Mud% is the measured volume percentage of sediment particles smaller than 63 μm in each PQ averaged over the top meter of the bed. Elevation is the measured bed level relative to Dutch ordnance level. SEB dynamics are sedimentation/erosion bed level changes in mm/month.

Factors	Vegetation cover PQs		Vegetation cover PQs + Random		Species richness	
	2019	2020	2019	2020	2019	2020
Seed treatment	7.44*	0.01	2.35	0.75	5.56*	0.15
Mud%	9.23**	35.81***	2.89*	4.54**	24.69***	18.65***
Elevation	0.13	2.96	1.87	1.41	10.55***	34.96***
SEB dynamics	0.99	8.41**	–	–	–	–
Nr. samples	27	27	61	57	61	57

Abbreviation: * < 0.05, ** < 0.01, *** <0.001.

we did. Our merged NbS-SES framework exemplifies that identified shortfalls in the earlier defined NbS principles [10], such as adaptive management and governance, ecosystem complexity and monitoring [12], are now convincingly dealt with in the redefined IUCN Global Standard for Nature-based Solutions [13]. Similar to the IUCN NbS-criteria the EcoShape consortium in The Netherlands developed six 'enablers' to make the development process of a Nature-Based Solution project or initiative practicable [76]. The six enablers are all interlinked with overlap between the different components and should be approached collectively. The six enablers, without particular order, are: -Technology and system knowledge, -Multi-stakeholder approach, -Adaptive management, maintenance, and monitoring, -Institutional embedding, -Business case and -Capacity building. In comparison with the IUCN NbS-criteria, the EcoShape enablers emphasize technological concepts that are using the driving forces of nature over an explicit aim in prevailing ecosystem degradation. Further, a balance between ecosystem services trade-offs [77] seems to be lacking, or is implicitly formulated.

The IUCN Global Standard for Nature-based Solutions [13] is presented semi-structurally as circular rings that are all interconnected. Their visualization implies that the Societal Challenges are central to the approach, followed by a first ring around the center, which is that of Design at scale. The criteria of Biodiversity net-gain, Economic feasibility and Inclusive governance are then lumped together within the second ring for Balance trade-offs. This visually explains the coherence between the three key dimensions of sustainable development (ecosystem integrity, economic viability and social equity) and the fact that trade-offs are to be made between these dimensions. Next, there is a ring for Adaptive management and the outer ring is for Mainstreaming & Sustainability, implying that these are in the final, and longer-term, implementation of a Nature-Based Solution. The IUCN NbS-framework is not meant to be a scientific framework but should facilitate users to apply NbS interventions. It was deliberately not designed as a rigid normative framing tool [13]. Scientific progress often has been achieved by structuring complex economic, ecological and social systems into partially dec omposable systems [78,79]. This is also what Ostrom [14] strived for when designing the SES-framework, emphasizing that decomposability of complex subsystems is important for achieving a better system understanding. Our merged NbS-SES framework helped us in placing the IUCN NbS criteria in the complexity of a social-ecological system and in understanding better which core subsystems were involved in which stages of the realization of the project. Although Nature-Based Solutions by definition aim at solving societal challenges [11], our case study showed that as long as the initiative for an NbS was kept local, project initiators ran into financial, judicial and governmental obstacles. Only when the initiative was embedded into a larger scale regional SES, enough support could be found to execute the project. In view of

the IUCN NbS-framework their criterion *Design at scale* (2) proved to be decisive.

6.2. Mixing mud and sand in salt marsh construction

The chosen Nature-Based Solution in this study example is the construction of a salt marsh by applying dredged sediment. Already by 1987, more than 130 freshwater and saltwater marshes have been purposely created using dredged material substrates in U.S. waterways [80]. These case studies involve the placement of dredged sediment directly onto the desired location and sometimes include artificial propagation of marsh plants. Transplanting or seeding of marsh vegetation has been a common practice in salt marsh restoration and construction projects in the USA, but almost exclusively with *Spartina* spp. [81]. Case studies are known from the Mississippi River delta, such as studies on spray disposal [82,83] and salt marsh raising with dredged material [84–87]. Based on tens of case studies, lessons learned on elevation, soils and planting of *Spartina* spp. in salt marsh construction projects were given for the lower Chesapeake Bay [88], San Diego Bay [89], Texas [90] and San Francisco Bay [91]. In Europe the application of dredge material for salt marsh construction is not as widely applied as in the USA. The most applied technique is de-embankment, also known as managed realignment [92–94]. Recently, beneficial use of dredged sediment to enhance salt marsh development has been tested by applying a semi-continuous source of mud in front of an accreting marsh [95].

The Marconi project in this study is unique for its six experimental hectare-scale compartments in which muddy soil was mixed in different contents down to a meter depth. We found that the mud content mixed through the bed showed a significant positive effect on vegetation cover, and mixing to 25% mud was showing high vegetation cover, while still being practically feasible. A mud content over 20% results in cohesive sediment and reduces erosion by a factor 6 to 8 [62], although our measurements on sedimentation-erosion rates could not confirm this. Soils with higher mud content have a higher soil moisture [96,97]. Seeds germinate more quickly at high soil moistures [98]. Because the summers of both 2019 and 2020 were relatively dry, a high soil moisture in higher mud contents was likely giving an advantage to *Salicornia* sp. germination and growth. Moreover, bringing in natural muds also adds available nutrients, which increases plant growth [84].

6.3. Seeding with plant fragments

Seeding with freshwater soaked plant fragments of *Salicornia* sp. was not unique but the latest attempts were made decades ago. Seeding of *Salicornia* sp. has been tested and applied in early land reclamation projects in Germany [99], later followed in the Netherlands [59]. At first, both authors tried to remove the seeds from dried plants, which

turned out to be cumbersome. An improved technique was invented by Wohlenberg [99] and tested by Kamps [59], to separate the seeds with a strong jet of water, thus mimicking the natural rotting of the parenchymatic tissue. The seeds were subsequently air-dried, but not too dry, stored in a cool place and regularly turned to prevent mold, which was a labor-intensive treatment. Seeds were at first sown by hand but later a seed-sowing machine was built. Finally, Kamps [59] found out that cutting the plants in pieces of 2 cm length and sowing these out in bare parts immediately after harvesting was a more efficient technique. We improved this method by harvesting plants in autumn before seeds naturally dispersed and storing the harvested plants instead of the delicate seeds. We applied storage in a cold open shed during winter for vernalization, which is improving germination capacity. And prior to seeding we tried to commence germination by applying freshwater to the plant fragments. Germination of *Salicornia* spp. seeds is best in water up to 100 mM NaCl [100–102]. Despite this treatment, our field measurements revealed that the number of rooted seedlings only started to increase 1.5 months after sowing. It was not expected that the seeds would remain dormant for so long in the growing season. In May and June 2019 there were no flood events inundating the entire salt marsh so we expect that there was no, or at least limited, water-driven dispersal of the plant fragments into the non-seeded compartments before rooting. This assumption is corroborated by the large difference in the number of *S. procumbens* plants over time in the first growing season between seeded and non-seeded compartments (Fig. 6). In the second growing season there were no significant differences in total vegetation cover (Fig. 7). We expect that this results from dispersal and successful germination of seeds from plants growing in nearby salt marshes. The salt marsh closest to our study site is at 10 km distance. This distance does not seem to be a problem for seed dispersal. This is in agreement with Wolters et al. [94] who found that even in de-embanked salt marshes with a seed source distance of 80 km, 30% of the species in the local species pool had established. In our experiment the seeding with *Salicornia* sp. plant fragments resulted in a kick-start of vegetation establishment in the first growing season, but the effects were limited to the first season only.

6.4. Tidal creek formation

One of the goals of the pilot was to monitor tidal creek formation for different contents of sand-mud mixtures. For this reason mixing was carried out in the top one meter of the subsurface, deeper than necessary for vegetation development. It was furthermore decided to let nature take its course in forming tidal creeks. We observed that the storage volume of each compartment, wave-formed sand bars, infilling of creeks and the presence of fine sediments all played a role in tidal creek formation and development. Earlier studies have shown that tidal creeks are able to develop in two years in a newly restored salt marsh (e.g. [103]). However, our two year monitoring period proved too short to draw firm conclusions about tidal creek development. The relative high elevation of the salt marsh probably slowed down the morphological developments because of the small volumes of water flowing in and out of the salt marsh compartments each tide. In due time the tidal creeks might evolve towards larger and more interconnected tidal creek networks.

7. Conclusions

Nature-Based Solutions offer potential to increase coastal wetland area worldwide. Nature-based coastal defense is supporting nature and its biodiversity, and can secure ecosystem services for human wellbeing. Disregard its advantages, the execution of Nature-Based Solutions is often hampered by practical and governmental obstacles. In this study we show how we can build back coastal wetlands through large-scale salt marsh construction. We demonstrate that mixing sand with 25% mud boosts vegetation cover and species richness. Mixing to higher mud contents will hamper the heavy machinery needed for constructing a muddy

marsh. Seeding with Salicornia plant fragments kick-starts colonization. Moreover, we show that embedding a local Nature-Based Solution into a regional social-ecological system with its associated actors and policy objectives, greatly enhances the chance of project execution.

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.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.nbsj.2021.100005.

References

[1] R. Costanza, R. de Groot, P. Sutton, S. van der Ploeg, S.J. Anderson, I. Kubiszewski, S. Farber, R.K. Turner, Changes in the global value of ecosystem services, Glob. Environ. Chang. 26 (2014) 152–158, doi:10.1016/j.gloenvcha.2014.04.002.

[2] M. Schuerch, T. Spencer, S. Temmerman, M.L. Kirwan, C. Wolff, D. Lincke, C.J. McOwen, M.D. Pickering, R. Reef, A.T. Vafeidis, J. Hinkel, R.J. Nicholls, S. Brown, Future response of global coastal wetlands to sea-level rise, Nature 561 (2018) 231–234, doi:10.1038/s41586-018-0476-5.

[3] N.C. Davidson, How much wetland has the world lost? Long-term and recent trends in global wetland area, Mar. Freshw. Res. 65 (2014) 934–941, doi:10.1071/MF14173.

[4] H.K. Lotze, H.S. Lenihan, B.J. Bourque, R.H. Bradbury, R.G. Cooke, M.C. Kay, S.M. Kidwell, M.X. Kirby, C.H. Peterson, J.B.C. Jackson, M. Bay, Depletion, degradation, and recovery potential of estuaries and coastal seas, Science (80-.) 312 (2006) 1806–1809.

[5] J. Thorslund, J. Jarsjo, F. Jaramillo, J.W. Jawitz, S. Manzoni, N.B. Basu, S.R. Chalov, M.J. Cohen, I.F. Creed, R. Goldenberg, A. Hylin, Z. Kalantari, A.D. Koussis, S.W. Lyon, K. Mazi, J. Mard, K. Persson, J. Pietro, C. Prieto, A. Quin, K. Van Meter, G. Destouni, Wetlands as large-scale nature-based solutions: status and challenges for research, engineering and management, Ecol. Eng. 108 (2017) 489–497, doi:10.1016/j.ecoleng.2017.07.012.

[6] N.J. Waltham, M. Elliott, S.Y. Lee, C. Lovelock, C.M. Duarte, C. Buelow, C. Simenstad, I. Nagelkerken, L. Claassens, C.K.C. Wen, M. Barletta, R.M. Connolly, C. Gillies, W.J. Mitsch, M.B. Ogburn, J. Purandare, H. Possingham, M. Sheaves, UN Decade on ecosystem restoration 2021–2030—what chance for success in restoring coastal ecosystems? Front. Mar. Sci. 7 (2020) 1–5, doi:10.3389/fmars.2020.00071.

[7] S. Temmerman, P. Meire, T.J. Bouma, P.M. Herman, T. Ysebaert, H.J. De Vriend, Ecosystem-based coastal defence in the face of global change, Nature 504 (2013) 79–83.

[8] N. Seddon, A. Chausson, P. Berry, C.A.J. Girardin, A. Smith, B. Turner, Understanding the value and limits of nature-based solutions to climate change and other global challenges, Philos. Trans. R. Soc. B Biol. Sci. 375 (2020), doi:10.1098/rstb.2019.0120.

[9] K. MacKinnon, C. Sobrevila, V. Hickey, Biodiversity, Climate Change and Adaptation; Nature-Based Solutions from the World Bank Portfolio, World Bank Group, Washington, D.C., 2008.

[10] WCC, 2016. Defining Nature-based Solutions. WCC-2016-Res-069.

[11] Cohen-Shacham, E., Walters, G., Janzen, C., Maginnis, S., 2016. Nature-based solutions to address global societal challenges. Gland, Switzerland: IUCN. xiii + 97pp. https://doi.org/10.2305/iucn.ch.2016.13.en

[12] E. Cohen-Shacham, A. Andrade, J. Dalton, N. Dudley, M. Jones, C. Kumar, S. Maginnis, S. Maynard, C.R. Nelson, F.G. Renaud, R. Welling, G. Walters, Core principles for successfully implementing and upscaling Nature-based Solutions, Environ. Sci. Policy. (2019), doi:10.1016/j.envsci.2019.04.014.

[13] IUCNIUCN Global Standard For Nature-based Solutions: a User-Friendly Framework For the verification, Design and Scaling Up of NbS: First Edition, IUCN, Gland, Switzerland, 2020, doi:10.2305/iucn.ch.2020.08.en.

[14] E. Ostrom, A diagnostic approach for going beyond panaceas, Proc. Natl. Acad. Sci. 104 (2007) 15181–15187, doi:10.1073/pnas.0702288104.

[15] F. Berkes, C. Folke, Linking Social and Ecological systems: Management Practices and Social Mechanisms For Building Resilience, Cambridge University Press, 1998.

[16] C.R. Binder, J. Hinkel, P.W.G. Bots, C. Pahl-Wostl, Frameworks for analyzing social-ecological systems, Ecol. Soc. 18 (2013) 26, doi:10.5751/ES-05551-180426.

[17] M.D. Mcginnis, E. Ostrom, Social-ecological system framework: initial changes and continuing challenges, Ecol. Soc. 19 (2014) 30.

[18] A. Downing, E. van Nes, J. Balirwa, J. Beuving, P. Bwathondi, L. Chapman, I. Cornelissen, I. Cowx, K. Goudswaard, R. Hecky, J. Janse, A. Janssen, L. Kaufman, M. Kishe-Machumu, J. Kolding, W. Ligtvoet, D. Mbabazi, M. Medard, O. Mkumbo, E. Mlaponi, A. Munyaho, L. Nagelkerke, R. Ogutu-Ohwayo, W. Ojwang, H. Peter, D. Schindler, O. Seehausen, D. Sharpe, G. Silsbe, L. Sitoki, R. Tumwebaze, D. Tweddle, K. Van de Wolfshaar, H. Van Dijk, E. Van Donk, J. Van Rijssel, P. Van Zwieten, J. Wanink, F. Witte, M. WM, Coupled human and natural system dynamics as key to the sustainability of Lake Victoria' s Ecosystem services, Ecol. Soc. 19 (4) (2014), doi:10.5751/ES-06965-190431.

[19] L.H. Gunderson, C.S. Holling (Eds.), Panarchy: Understanding Transformations in Human and Natural Systems, Island Press, Washington, D.C., USA, 2002.

[20] B. Walker, C.S. Holling, S.R. Carpenter, A. Kinzig, Resilience, adaptability and transformability in social – ecological systems, Ecol. Soc 9 (2004) 5, doi:10.1103/PhysRevLett.95.258011.

[21] V.N. de Jonge, R. Pinto, R.K. Turner, Integrating ecological, economic and social aspects to generate useful management information under the EU Directives' "ecosystem approach, Ocean Coast. Manag. 68 (2012) 169–188, doi:10.1016/j.ocecoaman.2012.05.017.

[22] C. Folke, T. Hahn, P. Olsson, J. Norberg, Adaptive govenance of social-ecological systems, Annu. Rev. Environ. Resour. 30 (2015) 441–473.

[23] T.M. Koontz, D. Gupta, P. Mudliar, P. Ranjan, Adaptive institutions in social-ecological systems governance: a synthesis framework, Environ. Sci. Policy 53 (2015) 139–151, doi:10.1016/j.envsci.2015.01.003.

[24] H. Österblom, A. Merrie, M. Metian, W.J. Boonstra, T. Blenckner, J.R. Watson, R.R. Rykaczewski, Y. Ota, L. Jorge, V. Christensen, M. Schlüter, S. Birnbaum, B.G. Gustafsson, C. Humborg, C. Mörth, B. Müller-karulis, M.T. Tomczak, C. Folke, H. Österblom, A. Merrie, M. Metian, W.J. Boonstra, T. Blenckner, Modeling social–ecological scenarios in marine systems, Bioscience 63 (2013) 735–744, doi:10.1525/bio.2013.63.9.9.

[25] E. Ostrom, A general framework for analyzing sustainability of social-ecological systems, Science (80-.) 325 (2009) 419–422.

[26] Victor V.N. De Jonge, H.M. Schuttelaars, J.E.E. Van Beusekom, S.aA. Talke, H.E. De Swart, The influence of channel deepening on estuarine turbidity levels and dynamics, as exemplified by the Ems estuary, Estuar. Coast. Shelf Sci. 139 (2014) 46–59, doi:10.1016/j.ecss.2013.12.030.

[27] J. Baretta, P. Ruardij (Eds.), Tidal Flat estuaries: Simulation and Analysis of the Ems Estuary, Springer Verlag, 1988.

[28] F. Colijn, Light absorption in the waters of the Ems-Dollard estuary and its consequences for the growth of phytoplankton and microphytobenthos, Netherlands J. Sea Res. 15 (1982) 196–216, doi:10.1016/0077-7579(82)90004-7.

[29] T.J. Compton, S. Holthuijsen, M. Mulder, M. van Arkel, L.K. Schaars, A. Koolhaas, A. Dekinga, J. ten Horn, P.C. Luttikhuizen, J. van der Meer, T. Piersma, H.W. van der Veer, Shifting baselines in the Ems Dollard estuary: a comparison across three decades reveals changing benthic communities, J. Sea Res. 127 (2017) 119–132, doi:10.1016/j.seares.2017.06.014.

[30] V.N. De Jonge, J.E.E. Van Beusekom, Contribution of resuspended microphytobenthos to total phytoplankton in the EMS estuary and its possible role for grazers, Netherlands J. Sea Res. 30 (1992) 91–105, doi:10.1016/0077-7579(92)90049-K.

[31] Jager, Z., 2013. Wax and wane of Zostera marina on the tidal flat Hond-Paap /Hund-Paapsand in the Ems estuary ; examinations of existing data. ZiltWater Report 201302.

[32] Z. Jager, H.L. Kleef, P. Tydeman, Mortality and growth of 0-group flatfish in the brackish dollard (Ems Estuary, Wadden Sea), Netherlands J. Sea Res. 34 (1995) 119–129, doi:10.1016/0077-7579(95)90020-9.

[33] N. Osinga, S.B. Nussbaum, P.M. Brakefield, H.A. Udo de Haes, Response of common seals (Phoca vitulina) to human disturbances in the Dollard estuary of the Wadden Sea, Mamm. Biol. 77 (2012) 281–287, doi:10.1016/j.mambio.2012.02.005.

[34] K. Van der Werf, H.K. Gilissen, M. Kleinhans, M.VanV. Rijswick, On dynamic naturalness, static regulation and human influence in the Ems-Dollard estuary, Int. J. Water Resour. Dev. 00 (2020) 1–20, doi:10.1080/07900627.2020.1826293.

[35] Eems-Dollardverdrag, 1960. Verdrag tussen het Koninkrijk der Nederlanden en de Bondsrepubliek Duitsland tot regeling van de samenwerking in de Eemsmonding, met Bijlagen en Slotprotocol (Eems-Dollardverdrag).

[36] V.N.deD. De Jonge, Relations between annual dredging activities, suspended matter concentrations, and the development of the tidal regime in the ems estuary, Can. J. Fish. Aquat. Sci. 40 (1983) s289–s300, doi:10.1139/f83-290.

[37] V.N. De Jonge, Importance of temporal and spatial scales in applying biological and physical process knowledge in coastal management, an example for the Ems estuary, Cont. Shelf Res. 20 (2000) 1655–1686, doi:10.1016/S0278-4343(00)00042-X.

[38] E.G. DeGroodt, V.N. De Jonge, Effects of changes in turbidity and phosphate influx on the ecosystem of the Ems estuary as obtained by a computer simulation model, Hydrobiologia 195 (1990) 39–47, doi:10.1007/BF00026812.

[39] H.M. Schuttelaars, V.N. de Jonge, A. Chernetsky, Improving the predictive power when modelling physical effects of human interventions in estuarine systems, Ocean Coast. Manag. 79 (2013) 70–82, doi:10.1016/j.ocecoaman.2012.05.009.

[40] V.N. De Jonge, H.M. Schuttelaars, J.E.E. Van Beusekom, S.A. Talke, H.E. De Swart, The influence of channel deepening on estuarine turbidity levels and dynamics, as exemplified by the Ems estuary, Estuar. Coast. Shelf Sci. 139 (2014) 46–59, doi:10.1016/j.ecss.2013.12.030.

[41] Talke, S.A., De Swart, H.E., 2006. Hydrodynamics and morphology in the Ems/Dollard estuary: review of models, measurements, scientific literature, and the effects of changing conditions. Utrecht.

[42] D.S. Van Maren, J.C. Winterwerp, J. Vroom, Fine sediment transport into the hyper-turbid lower Ems River: the role of channel deepening and sediment-induced drag reduction, Ocean Dyn. 65 (2015) 589–605, doi:10.1007/s10236-015-0821-2.

[43] S. Papenmeier, K. Schrottke, A. Bartholomä, B.W. Flemming, Sedimentological and rheological properties of the water–solid bed interface in the Weser and Ems estuaries, North Sea, Germany: implications for fluid mud classification, J. Coast. Res. 289 (2013) 797–808, doi:10.2112/JCOASTRES-Dd-11-00144.1.

[44] S.A. Talke, H.E. De Swart, V.N. De Jonge, An idealized model and systematic process study of oxygen depletion in highly turbid estuaries, Estuaries Coasts 32 (2009) 602–620, doi:10.1007/s12237-009-9171-y.

[45] Elliott, M., Hemingway, K., Cutts, N., Burdon, D., Perez-Dominquez, R., Allen, J., Thomson, S., De Jonge, V., Breine, J., Van den Bergh, E., Stevens, M., Simoens, I., Jager, Z., Twisk, F., 2008. Chapter 7: habitat Loss, in: estuarine Ecosystem Functioning, Restoration and Health. Final Report (Harbasins WP2). pp. 375–466. doi:10.1016/S0022-3913(12)00047-9.

[46] D. Bos, H. Büttger, P. Esselink, Z. Jager, V. De Jonge, H. Kruckenberg, B. Van Maren, B. Schuchardt, The Ecological State of the Ems estuary and Options For Restoration, Leeuwarden/Veenwouden, 2012.

[47] Lenselink, G., Taal, M., Hommes, S., Oost, A., Maren, B.van, Baptist, M., Tamis, J., Brinkman, B., 2015. Ecologisch perspectief Eems-Dollard 2050; MIRT-onderzoek Eems-Dollard fase II.

[48] ED2050, 2015. Innovatieprogramma Nuttig Toepassen Slib. Groningen, Provincie Groningen en het Ministerie van Infrastructuur en Milieu (in Dutch).

[49] L. Egberts, S. Riesto, Raise the dikes and re-use the past? Climate adaptation planning as heritage practice, Marit. Stud. (2021) 2021 1–12, doi:10.1007/S40152-021-00226-1.

[50] V. Vuik, S.N. Jonkman, B.W. Borsje, T. Suzuki, Nature-based flood protection: the efficiency of vegetated foreshores for reducing wave loads on coastal dikes, Coast. Eng. 116 (2016) 42–56, doi:10.1016/j.coastaleng.2016.06.001.

[51] V. Vuik, S. Van Vuren, B.W. Borsje, B.K. Van Wesenbeeck, S.N. Jonkman, Assessing safety of nature-based flood defenses: dealing with extremes and uncertainties, Coast. Eng. 139 (2018) 47–64, doi:10.1016/j.coastaleng.2018.05.002.

[52] Van Lente, J.-.W., Vuik, V., 2020. Wave load reduction on salt marshes: a case study based on Marconi Delfzijl. HKV Report PR4265.10.

[53] S.C. Barley, J.J. Meeuwig, The power and the pitfalls of large-scale, unreplicated natural experiments, Ecosystems 20 (2017) 331–339, doi:10.1007/s10021-016-0028-5.

[54] M.D. Spalding, A.L. Mcivor, M.W. Beck, E.W. Koch, I. Möller, D.J. Reed, P. Rubinoff, T. Spencer, T.J. Tolhurst, T.V. Wamsley, B.K. van Wesenbeeck, E. Wolanski, C.D. Woodroffe, Coastal ecosystems: a critical element of risk reduction, Conserv. Lett. 7 (2014) 293–301, doi:10.1111/conl.12074.

[55] C.M. Duarte, I.J. Losada, I.E. Hendriks, I. Mazarrasa, N. Marbà, The role of coastal plant communities for climate change mitigation and adaptation, Nat. Clim. Chang. (2013), doi:10.1038/nclimate1970.

[56] E. McLeod, G.L. Chmura, S. Bouillon, R. Salm, M. Björk, C.M. Duarte, C.E. Lovelock, W.H. Schlesinger, B.R. Silliman, A blueprint for blue carbon: toward an improved understanding of the role of vegetated coastal habitats in sequestering CO2, Front. Ecol. Environ. 9 (2011) 552–560, doi:10.1890/110004.

[57] J.D. Bakker, De Leeuw, K.S. Dijkema, P.C. Leendertse, H.T. Prins, J. Rozema, Salt marshes along the coast of The Netherlands, in: Netherlands-Wetlands, Springer, Dordrecht, 1993, pp. 73–95.

[58] K.S. Dijkema, Changes in salt-marsh area in the Netherlands Wadden Sea after 1600, in: Vegetation Between Land and Sea, Springer Netherlands, 1987, pp. 42–51, doi:10.1007/978-94-009-4065-9_4.

[59] Kamps, L.F., 1962. Mud distribution and land reclamation in the Eastern Wadden shallows. The Hague, Rijkswaterstaat Communications Nr 4.

[60] De Groot, A.V., Van Duin, W.E., 2013. Best practices for creating new salt marshes in an estuarine setting, a literature study. IMARES Report number C145/12.

[61] H. Olff, J.De Leeuw, J.P. Bakker, R.J. Platerink, H.J. van Wijnen, Vegetation Succession and Herbivory in a Salt Marsh: changes Induced by Sea Level Rise and Silt Deposition Along an Elevational Gradient, J. Ecol. 85 (1997) 799, doi:10.2307/2960603.

[62] E.J. Houwing, Morphodynamic development of intertidal mudflats: consequences for the extension of the pioneer zone, Cont. Shelf Res. 20 (2000) 1735–1748, doi:10.1016/S0278-4343(00)00045-5.

[63] M.J. Baptist, A.V. de Groot, W.E. van Duin, Contrasting biogeomorphic processes affecting salt-marsh development of the Mokbaai, Texel, The Netherlands, Earth Surf. Process. Landforms 41 (2016), doi:10.1002/esp.3949.

[64] K. Elschot, J.P. Bakker, S. Temmerman, J. Koppel, Bouma Van De .T.J., Ecosystem engineering by large grazers enhances carbon stocks in a tidal salt marsh, Mar. Ecol. Prog. Ser. 537 (2015) 9–21, doi:10.3354/meps11447.

[65] S. Fagherazzi, D.J. Furbish, On the shape and widening of salt marsh creeks, J. Geophys. Res. 106 (2001) 991–1003.

[66] M. Van Regteren, I. Colosimo, P. De Vries, M.E.B. Van Puijenbroek, V.S. Freij, M.J. Baptist, K. Elschot, Limited seed retention during winter inhibits vegetation establishment in spring, affecting lateral marsh expansion capacity, Ecol. Evol. 9 (2019) 13294–13308, doi:10.1002/ece3.5781.

[67] M. Van Regteren, E.H. Meesters, M.J. Baptist, A.V. De Groot, T.J. Bouma, K. Elschot, Multiple environmental variables affect germination and mortality of an annual salt marsh pioneer: Salicornia procumbens, Estuaries and Coasts 43 (2020) 1489–1501, doi:10.1007/s12237-020-00735-y.

[68] Houwing, E., Duin, W.E.V., Waaij, Y.S.D., Dijkema, K.S., Terwindt, J.H.J., 1999. Biological and abiotic factors influencing the settlement and survival of 197–206.

[69] P.O. Wiehe, A quantitative study of the influence of tide upon populations of Salicornia Europea, J. Ecol. 23 (1935) 323, doi:10.2307/2256124.

[70] S. Nolte, E.C. Koppenaal, P. Esselink, K.S. Dijkema, M. Schuerch, A.V. De Groot, J.P. Bakker, S. Temmerman, Measuring sedimentation in tidal marshes: a review on methods and their applicability in biogeomorphological studies, J. Coast. Conserv. 17 (2013) 301–325, doi:10.1007/s11852-013-0238-3.

[71] Z. Hu, W. Lenting, D. van der Wal, T.J. Bouma, Continuous monitoring bed-level dynamics on an intertidal flat: introducing novel, stand-alone high-resolution SED-sensors, Geomorphology 245 (2015) 223–230, doi:10.1016/j.geomorph.2015.05.027.

[72] P.W.J.M. Willemsen, B.W. Borsje, S.J.M.. Hulscher, D. Van der Wal, Z. Zhu, B. Oteman, B. Evans, I. Möller, T.J. Bouma, Quantifying bed level dynamics at the transition of tidal flat and salt marsh : can we understand the lateral location of the marsh edge ? J. Geophys. Res. Earth Surf. 123 (2018), doi:10.1029/2018JF004742.

[73] B. Brede, A. Lau, H.M. Bartholomeus, L. Kooistra, Comparing RIEGL RiCOPTER UAV LiDAR derived canopy height and DBH with terrestrial LiDAR, Sensors (Switzerland) 17 (2017) 1–16, doi:10.3390/s17102371.

[74] G. Londo, The decimal scale for releves of permanent quadrats, Vegetatio 33 (1976) 61–64.

[75] K. Tzoulas, J. Galan, S. Venn, M. Dennis, B. Pedroli, H. Mishra, D. Haase, S. Pauleit, J. Niemelä, P. James, A conceptual model of the social–ecological system of nature-based solutions in urban environments, Ambio (2020) 1–11, doi:10.1007/s13280-020-01380-2.

[76] E. Van Eekelen, M. Bouw (Eds.), Building With Nature: Creating, Implementing and Upscaling Nature-based Solutions, One Architecture & Urbanism; Rotterdam, Dordrecht, EcoShape; New York, 2020 nai010 publishers.

[77] F. Turkelboom, M. Leone, S. Jacobs, E. Kelemen, M. García-Llorente, F. Baró, M. Termansen, D.N. Barton, P. Berry, E. Stange, M. Thoonen, Á. Kalóczkai, A. Vadineanu, A.J. Castro, B. Czúcz, C. Röckmann, D. Wurbs, D. Odee, M.J. Baptist, E. Preda, E. Gómez-Baggethun, G.M. Rusch, G.M. Pastur, I. Palomo, J. Dick, J. Casaer, J. van Dijk, J.A. Priess, J. Langemeyer, J. Mustajoki, L. Kopperoinen, P.L. Peri, R. Mukhopadhyay, R. Aszalós, S.B. Roy, S. Luque, V. Rusch, When we cannot have it all: ecosystem services trade-offs in the context of spatial planning, Ecosyst. Serv. (2017), doi:10.1016/j.ecoser.2017.10.011.

[78] C.S. Holling, Understanding the complexity of economic, ecological, and social systems, Ecosystems 4 (2001) 390–405, doi:10.1007/s10021-001-0101-5.

[79] S.A. Levin, Complex adaptive systems: exploring the known, the unknown and the unknowable, Bull. Am. Math. Soc. 40 (2003) 3–19, doi:10.1090/S0273-0979-02-00965-5.

[80] U.S. Army Corps of Engineers, 1987. Beneficial Uses of Dredged Material. Washington, DC, USACE Engineer Manual No 1110-2-5026.

[81] S.W. Broome, E.D. Seneca, W.W. Woodhouse, Tidal salt marsh restoration, Aquat. Bot. 32 (1988) 1–22, doi:10.1016/0304-3770(88)90085-X.

[82] D.R. Cahoon, J.H. Cowan, Environmental impacts and regulatory policy implications of spray disposal of dredged material in louisiana wetlands, Coast. Manag. 16 (1988) 341–362, doi:10.1080/08920758809362067.

[83] M.A. Ford, D.R. Cahoon, J.C. Lynch, Restoring marsh elevation in a rapidly subsiding salt marsh by thin-layer deposition of dredged material, Ecol. Eng. 12 (1999) 189–205, doi:10.1016/S0925-8574(98)00061-5.

[84] R..D. Delaune, S.R. Pezeshki, J.H. Pardue, J.H. Whitcomb, W.H. Patrick, Some influences of sediment addition to a deteriorating salt marsh in the Mississippi River deltaic plain: a pilot study, J. Coast. Res. 6 (1990) 181–188.

[85] S.A. Graham, I.A. Mendelssohn, Functional assessment of differential sediment slurry applications in a deteriorating brackish marsh, Ecol. Eng. 51 (2013) 264–274, doi:10.1016/j.ecoleng.2012.12.031.

[86] I.A. Mendelssohn, N.L. Kuhn, Sediment subsidy: effects on soil-plant responses in a rapidly submerging coastal salt marsh, Ecol. Eng. 21 (2003) 115–128, doi:10.1016/j.ecoleng.2003.09.006.

[87] C. Tong, J.J. Baustian, S.A. Graham, I.A. Mendelssohn, Salt marsh restoration with sediment-slurry application: effects on benthic macroinvertebrates and associated soil-plant variables, Ecol. Eng. 51 (2013) 151–160, doi:10.1016/j.ecoleng.2012.12.010.

[88] J.E. Perry, T.A. Barnard, J.G. Bradshaw, C.T. Friedrichs, K.J. Havens, P.A. Mason, W.I. Priest, G.M. Silberhorn, Creating Tidal Salt Marshes in the Chesapeake Bay Creating Tidal Salt Marshes in the Chesapeake Bay, J. Coast. Res. SI27 (2001) 170–191.

[89] J. Haltiner, J.B. Zedler, K.E. Boyer, G.D. Williams, J.C. Callaway, Influence of physical processes on the design, functioning and evolution of restored tidal wetlands in California (USA), Wetl. Ecol. Manag. 4 (1997) 73–91, doi:10.1007/bf01876230.

[90] D.J. Shafer, W.J. Streever, A comparison of 28 natural and dredged material salt marshes in Texas with an emphasis on geomorphological variables, Wetl. Ecol. Manag. 8 (2000) 353–366, doi:10.1023/A:1008491421739.

[91] P. Williams, P. Faber, Salt Marsh Restoration Experience in San Francisco Bay, J. Coast. Res. 27 (2001) 203–211.

[92] J.P. Bakker, P. Esselink, K.S. Dijkema, W.E. Van Duin, Jong De .D.J., Restoration of salt marshes in the Netherlands, Hydrobiologia 478 (2002) 29–51, doi:10.1023/A:1021066311728.

[93] P.W. French, Managed realignment - the developing story of a comparatively new approach to soft engineering, Estuar. Coast. Shelf Sci. 67 (2006) 409–423, doi:10.1016/j.ecss.2005.11.035.

[94] M. Wolters, A. Garbutt, J.P. Bakker, Salt-marsh restoration: evaluating the success of de-embankments in north-west Europe, Biol. Conserv. 123 (2005) 249–268, doi:10.1016/j.biocon.2004.11.013.

[95] M.J. Baptist, T. Gerkema, B.C. Van Prooijen, D.S. Van Maren, M. Van Regteren, I. Colosimo, J. Vroom, T. Van Kessel, B. Grasmeijer, P. Willemsen, A.V. De Groot, J. Cleveringa, E.E. Van Eekelen, F. Schuurman, H.J. De Lange, Beneficial use of dredged sediment to enhance salt marsh development applying a Mud Motor, Ecol. Eng. 127 (2019) 312–323, doi:10.1016/j.ecoleng.2018.11.019.

[96] B.W. Flemming, M.T. Delafontaine, in: Mass Physical Sediment properties. Encyclopedia of Estuaries, Springer, Dordrecht, 2016, pp. 419–432. Encycl. estuaries.

[97] B.W. Flemming, M.T. Delafontaine, Mass physical properties of muddy intertidal sediments: some applications, misapplications and non-applications, Cont. Shelf Res. 20 (2000) 1179–1197, doi:10.1016/S0278-4343(00)00018-2.

[98] L.D. Doneen, J.H. MacGillivray, Germination (emergence) of vegetable seed as affected by different soil moisture conditions, Plant Physiol. 18 (1943) 524–529, doi:10.1104/pp.18.3.524.

[99] E. Wohlenberg, Biologische Kulturmaßnahmen mit dem Queller (Salicornia herbacea L.) zur Landgewinnung im Wattenmeer, Westküste 1 (1938) 52–104.

[100] M. Aghaleh, V. Niknam, H. Ebrahimzadeh, K. Razavi, Salt stress effects on growth, pigments, proteins and lipid peroxidation in Salicornia persica and S. europaea, Biol. Plant. 53 (2009) 243–248, doi:10.1007/s10535-009-0046-7.

[101] M. Ajmal Khan, D.J. Weber, Factors influencing seed germination in Salicornia pacifica var. utahensis, Am. J. Bot. 73 (1986) 1163–1167.

[102] D. Singh, A.K. Buhmann, T.J. Flowers, C.E. Seal, J. Papenbrock, Salicornia as a crop plant in temperate regions: selection of genetically characterized ecotypes and optimization of their cultivation conditions, AoB Plants 6 (2014), doi:10.1093/aobpla/plu071.

[103] A. D'Alpaos, S. Lanzoni, M. Marani, A. Bonometto, G. Cecconi, A. Rinaldo, Spontaneous tidal network formation within a constructed salt marsh: observations and morphodynamic modelling, Geomorphology 91 (2007) 186–197, doi:10.1016/j.geomorph.2007.04.013.