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The development of vegetation and soil stability in salt marshes and their use for coastal defense

MSc Thesis

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The development of vegetation, soil stability and erosion resistance in salt marshes and their use for coastal defense

MSc Research

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Abstract

Using vegetated wetlands as coastal protection has become increasingly popular because of their beneficial characteristics, such as wave action attenuation and sediment trapping. Given the present context of marsh loss due to climate change, rebuilding intertidal lands that were previously reclaimed can offer a chance to create coastal barriers. However, the effectiveness of these barriers depends in part on soil stability and the settling of vegetation. This study aimed to monitor two pioneer salt marshes in the Netherlands by creating time series. The objective was to determine which factors play an important role in the marshes' development using field studies and data elaboration. This was done by measuring vegetation and sediment parameters of one managed realignment site, Perkpolder, and one created salt marsh, the Marconi Project. The objective was reached by analysing how vegetation density, elevation, sediment characteristics, and their interactions influence the sites' vegetation and soil stability. Our findings revealed that: (i) Based on the time series analysis, it is uncertain whether Perkpolder and Marconi can be categorised as established salt marshes. Although both marshes have demonstrated significant stability over time, especially when looking at the elevation, it can be challenging to estimate the exact time required for them to fully transform from a tidal flat into a stable salt marsh. However, the vegetation has been expanding at both sites, and I believe this trend will continue. (ii) Results show that at Perkpolder, there is a strong relation between increasing vegetation density at higher elevations and decreasing vegetation at high surface water content in the sediment. On the other hand, at Marconi Project, we observed a significant difference in vegetation coverage percentages depending on sediment silt content. Therefore, the main factors controlling the sites' vegetation development were sufficient elevation, which reduces inundation times, and sediment characteristics, including moderate silt and moister contents, which affect the sediment's cohesiveness. (iii) Using indirect methods such as penetration resistance and shear vane to measure marsh erosion provides insights into sediment stability. For the managed realignment, there was a positive correlation between elevation and shear strength, suggesting that locations at higher elevations have better surface drainage, which can lead to increased soil consolidation and stability. Furthermore, results showed that Perkpolder exhibited higher shear strength and penetration resistance in sediments with intermediate silt content ranging from 40% to 75% rather than for higher percentages. Similarly, Marconi showed higher erosion resistance in sediments with 20% silt content than those with lower or higher mud content. As expected, shear strength was not higher in soils with the highest silt contents because, at these locations, surface drainage is restricted due to silt particle characteristics and remains wet easier. Finally, at both sites, the effect of vegetation presence on soil stability was not strong. However, shear strength and penetration resistance were higher inside almost every Tussock at Perkpolder than outside the vegetation patch. According to the study, creating a salt marsh by raising the elevation with already established sand-mud mixtures may speed up sediment stabilisation and the growth of pioneer vegetation.

1 Introduction

1.1 Background on Salt Marshes, an example of biogeomorphic environments

Rising sea levels and increasingly frequent and intense coastal storms are two major climate change consequences, posing significant risks to vulnerable coastal and estuarine shorelines. Flooding, erosion, and damage to coastal communities and infrastructure are among the future and present challenges we must address (Temmerman et al., 2023; Zhu et al., 2020). Traditional coastal protection methods, such as hard structures like seawalls and dykes, have significant drawbacks, including high costs and destructive impacts on the natural environment and require regular maintenance (van Zelst et al., 2021). Thus, there is a growing interest in the innovative combination of engineered structures and nature-based coastal defences, which are low-cost and more sustainable (Zhu et al., 2020). In addition, coastal wetlands, like marshes, may be an efficient addition to hard-structured defences alone because they can provide protection and a range of other ecosystem services, including improving water quality and providing coastal fisheries (Bouma et al., 2014; Temmerman et al., 2013).

Salt marshes are intertidal wetlands developed over time by sediment build-up under low-energy circumstances. Marshes have a global geographical distribution, and their elevation depends on the tidal regime (Brooks et al., 2020). Their formation, stability, and size are influenced by horizontal and vertical shallow-water coastal processes over timescales ranging from decades to centuries. Periods of horizontal seaward expansion are followed by lateral erosion in a cyclic pattern. Due to tidal waves, this retreat phase typically occurs shoreward along the marsh edges (Bouma et al., 2016). In addition, when sufficient sediment supply and seaward expansion rates favour it, salt marshes also rise by sedimentation (Lo et al., 2017). Because of this process, generally called accretion, salt marshes can keep pace with sea level rise by building up in elevation (with rates of mm yr^{-1}) (Coleman et al., 2022). Due to their microtopographic variability, vegetation canopy, and channel networks, all at elevations of shoaling waves, salt marshes are effective dissipators of incident wave energy when flooded, even during storm surge conditions (Temmerman et al., 2013).

Salt marshes are "biogeomorphic ecosystems" that evolve due to feedbacks. Such biogeomorphic feedbacks result from hydrodynamics, sediment, and vegetation impacting each other over time through processes and responses (Groot & Duin, 2013). The vegetation in salt marshes traps the sediment with its roots and reduces hydrodynamic energy (flow velocity and waves) with the shoots. The minerals trapped in the soil enhance the growth of the vegetation, and the system becomes more effective at capturing additional sediment. Hence, a positive feedback is generated (Bouma et al., 2016; Fagherazzi et al., 2012). Moreover, "vegetation zonation" typically characterises salt marshes, creating a succession of vegetation species related to elevation and time. Specifically, when vertical accretion exceeds sea-level rise, the marsh becomes less inundated, changing from pioneer species at the low marsh to high marsh species (Bouma et al., 2016). Additionally, salt marsh substrates' physical and mechanical properties have been studied extensively to determine how they contribute to the marsh's ability to resist the erosive forces of waves and currents (Lo et al., 2017; Marin-Diaz et al., 2022; Temmerman et al., 2023).

By analysing historical dike breaches in the Netherlands, Zhu et al. (2020) demonstrated that the presence of a salt marsh in front of or between dikes effectively protects against flooding. Because of their capacity to provide multiple ecosystem services**,** salt marshes have high natural and societal importance. Salt marshes' functions include supporting habitats and biodiversity, mitigating sea level rise (and subsidence) effects and dissipation of incident wave energy, carbon sequestration, and pollutant immobilisation (Barbier et al., 2011; van den Hoven et al., 2022). Combining coastal wetlands and engineered structures provides a cost-effective strategy for sea defence, compared to conventional hard engineering alone (Brooks et al., 2020; Feagin et al., 2015; Zhu et al., 2020). In locations where the sediment supply is sufficient, coastal wetlands can provide a Nature-based Solution because of their combined capacity to build up with ongoing sea level rise by accumulating sediment and their impact on wave dissipation (Zhu et al., 2020; Coleman et al., 2022). Especially in furtherance of climate change effects such as sea level rise and greater storm intensity and frequency, implementing marshes in front of dike breaches is expected to reduce flood propagation and limit the breach dimension and its consequences (Leonardi et al., 2016).

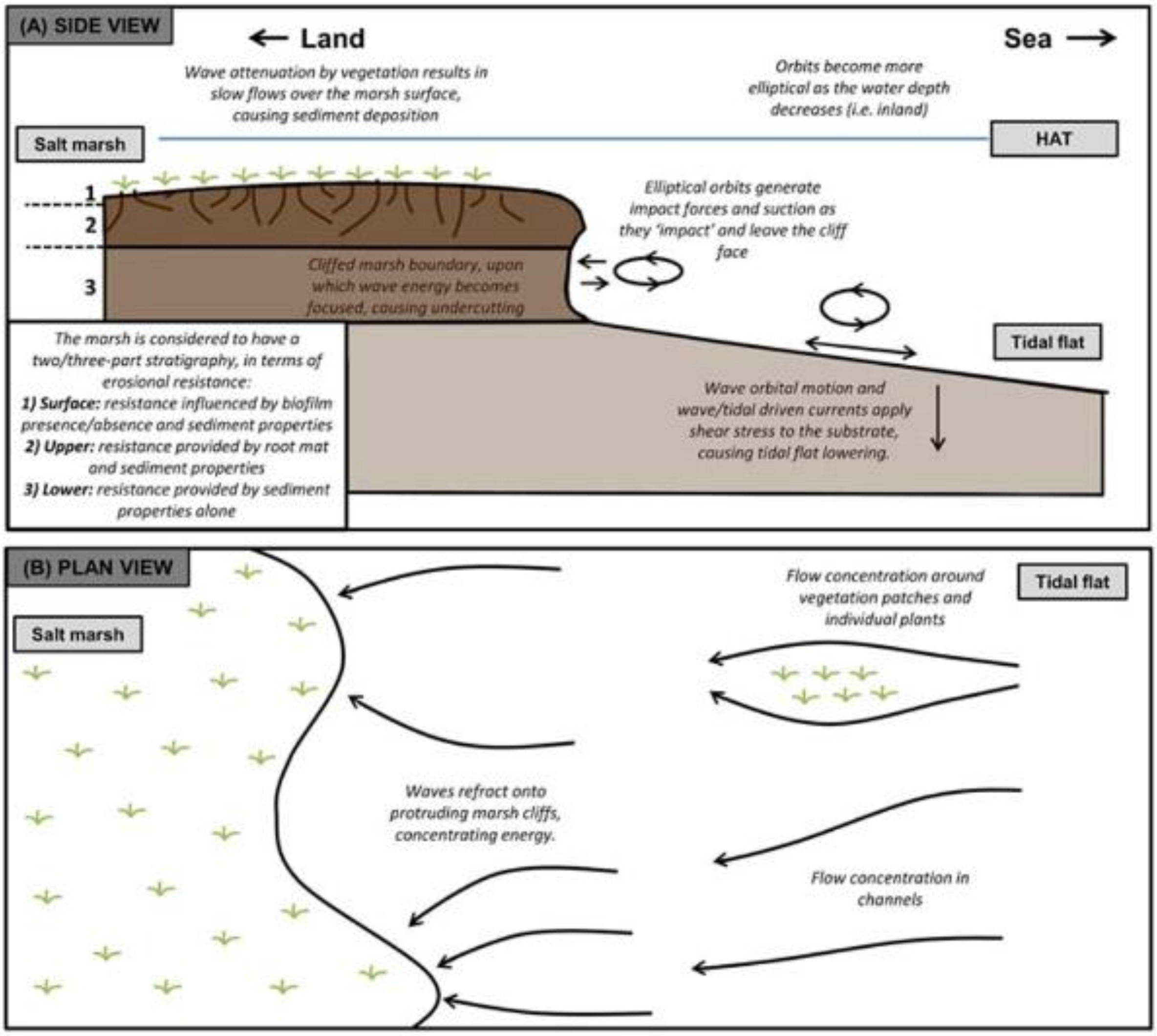


Figure 1 Impact of hydrodynamic forcing on marsh edges (A) and surface (B) scheme (Brooks et al.,2020)

1.2 Salt Marshes as Nature-based coastal defence

Temmerman et al. (2023) reviewed the principal studies that investigated the use of wetlands as storm buffers. Marshes can be considered "effective" depending on their functionality and persistence. The former relates to the capacity of salt marshes to reduce hydrodynamic forces, including flooding and mitigating erosion risks associated with storm waves. The latter refers to the resistance and recovery abilities from disturbance factors of these ecosystems. While many studies confirm we can benefit from marshes' coastal protection capacity, assessing these nature-based solutions' limitations is critical, especially under extreme conditions (Temmerman et al., 2023). The interaction between vegetation properties, like density and stiffness, and hydrodynamics strongly impacts the rate of wave dissipation and, consequently, sediment accretion. At the same time, the change in flow and sediment transport alters the environment, directly impacting plant properties (Bouma et al., 2016; Cao et al., 2018; Temmerman et al., 2012). Field studies and simulations emphasised that marshes must be continuous and wider to affect storm surge height reduction significantly. Also, higher surface elevation and larger vegetation density effectively increase friction (Hu et al., 2015; Sheng et al., 2012).

The mentioned “eco-engineering feedback” strength highly depends on vegetation density, growth and seasonality. Because of global change, the main threats to salt marshes are intensified. The combined effect of sea levels increasing at higher rates and coasts narrowing due to urban coastal land reclamation enhances the risk of salt marshes loss (Billah et al., 2022). State-of-the-art tools like the ecomorphodynamic model introduced by Brückner et al. (2019) aim to unwind the intricate relationship between vegetation density and hydrodynamics. They do it by reproducing newly established salt marshes and predicting 15-year growth trends, cover and spatial patterns. The model’s findings support the positive correlation between salt marsh density and age (represented as life stages) (Adam, 2002). The density of salt marshes rises as they get older, indicating a steady colonisation process. Furthermore, a vegetation density gradient was found: the high marsh has dense and mature vegetation, while the low elevations had sparse cover due to limited seedling survival and lateral expansion. Additionally, the hydroperiod, regulated by water levels and bed elevations, plays a significant part in developing vegetation and sedimentation. In dense marshes, vegetation slows the flow rate, affecting the hydroperiod and increasing the sedimentation rate along the marsh’s edge. Large amounts of vegetation do, however, lengthen the hydroperiod, which restricts salt marsh spread, especially at lower elevations. This negative eco-engineering effect is thought to hamper the marsh's expansion ability (Brückner et al., 2019).

In pioneer marshes, fully submerged plants at higher water depths are less effective because of the decreased drag from vegetation and substrate, providing meagre attenuation rates, especially in winter (Schoutens et al., 2019). Furthermore, attenuation effects are significantly reduced by the degradation of coastal marsh vegetation. Temmerman et al. (2012) demonstrated that tidal marsh patches die off, especially when connected to channels, leading to much faster propagation of flood landwards. Thus, the flood attenuation functionality decreases exponentially in marshes with increasing percentages of die-offs. Overall, these findings emphasise the importance of considering factors like vegetation density, bed elevation and their interaction and relation with the water flow. We aim to consider such findings and compare the predicted ecosystem dynamics with field measurements when monitoring the development of restored or newly created salt marshes. Moreover, because of plants’ capacity to influence hydrodynamics with their above-ground structures and reduce erodibility with their root systems, it is critical to distinguish which specific mechanisms are influencing the flow of water and the stability of the soil and assess the relative role of vegetation density.

Salt marsh erosion is affected by a variety of properties extrinsic and intrinsic to the soil, including wind exposure (impacting on wave force) and soil and vegetation (e.g., grain size, organic content, and belowground biomass) (Wang et al., 2017). Plant roots can directly enhance aggregate soil stability and decrease soil erodibility. Thus, compared to bare mudflats, the soil matrix of vegetated marshes is generally more stable because of the combined effect of root strength and compression (Brooks et al., 2020). Brooks et al. (2020) defined salt marsh stability as the ability of the exposed substrate to resist surface erosion or lateral erosion caused by water-generated forces (like waves and currents, for instance) (Figure 1). Vegetation properties, the composition of the soil matrix and the interaction between these are the main factors controlling the substrate resistance to lateral erosion. Moreover, biota (roots/organisms) and sediment properties govern erosion resistance in the top substrate layers. On the other hand, sediment characteristics and decomposed or decaying organic matter regulate resistance in the lower layers (below the live root). Lo et al. (2017) studied the *Spartina* genus to determine how the presence of this pioneer species and factors like the sediment grain size modified lateral erosion. The *Spartina* genus is characterised by a global distribution and ecoengineering qualities, like the capacity to trap sediment from the water column with the shoots. Hence, it was interesting for coastal protection purposes to see that the presence of *Spartina* reduced 80% of erosion in sandy soils and 17% in silty ones in the Northern Adriatic coastline. Furthermore, erosion resistance was increased mainly by vegetation. Although, when vegetation was absent, erosion resistance significantly increased with silt content, remarking the effect of soil properties on erosion resistance (Lo et al., 2017). Because roots and rhizomes can help increase soil shear strength by enhancing cohesiveness, this raises the question of to what degree, in pioneer marshes, erosion resistance depends on factors like above-ground biomass density and sediment properties like grain size of sand, silt content, soil ageing and compaction, for instance. We aim to investigate the effects of sediment composition on erodibility by looking at the effects of vegetation's presence and absence in salt marshes restoration projects. Investigating this experimentally in the field will contribute to a better understanding of how pioneer species like *Spartina* can indirectly contribute to reducing lateral erosion.

Erosion occurs in sediment when deviation from an equilibrium state occurs, and erosive forces surpass resistive forces, which include cohesiveness (Winterwerp et al., 2012). The erodibility of sediment is determined by its biogeochemical properties, which affect the resistive forces (Grabowski et al., 2011; Winterwerp et al., 2018). Van Ledden et al. (2004) also highlight the importance of understanding how erosion characteristics depend on sediment content. This is especially true if we want to investigate the erosion behaviour of sand-mud mixtures. An equilibrium state between deposition and erosion is common in sand beds and can be disturbed depending on the flow conditions and sediment components. On the other hand, mud is not as available or easily transported as sand. Consequently, achieving an equilibrium phase between mud deposition and erosion is difficult. Hence, erosion in mudflats depends strongly on flow conditions and bed properties (Van Ledden et al., 2004). The challenge of experimentally testing soil stability in the field arises from erosion dynamics drastically changing when sand is introduced to a mudflat or vice versa. Measuring marsh lateral and surface erosion with indirect measurements is common in the field. Indirect measurements comprise various methods, including shear vane, cohesive strength and penetrologger (Brooks et al., 2020). Precisely, we measure the cohesive forces within the sediment bed with penetration resistance by representing the resistance that a cone encounters when penetrating the sediment. Higher penetration resistance in the context of erosion expresses a stronger cohesiveness inside the sediment bed, increasing its resistance to erosion. On the other hand, shear vane measurements determine how strong the sediment bed is under shear. A shear vane instrument is utilised to apply force to the sediment surface and detect the resulting shear stress. The sediment's resistance to deformation caused by shear forces is measured by its shear strength (Box P. and Giesbeek, 2009; Royal Eijkelkamp, 2017). Understanding cohesive sediment is important when managing or monitoring aquatic habitats such as salt marshes (Grabowski et al., 2011). Because sediment sand-mud content and vegetation properties are the main drivers of sediment stability, using penetration resistance and shear vane measurements can help us assess the degree of erosion of soft cohesive sediment beds under shear flow conditions in pioneer marshes (De Battisti et al., 2019; Winterwerp et al., 2012).

1.3 Adaptive coastal management strategies

Traditional coastal defence systems can broadly benefit from salt marsh restoration, conservation, and creation of managed realignments sites (MR) (Wolters et al., 2005). Research on ecological engineering aims to understand the potential and limits of the hybrid approach to coastal defence. Bouma et al. (2014) provide valuable insights into implementing adaptive coastal management. The site-specific coastal protection value under storm conditions and long-term persistence over time (50-100 years) must be assessed to include a coastal ecosystem in the defensive scheme. Willemsen et al. (2022) emphasise the need for long-term analyses to successfully implement salt marshes as nature-based solutions in coastal management. Coastal defence schemes are designed to last for decades, so it is important to understand the long-term dynamics determining the expansion or retreat and the width of salt marshes. Moreover, evaluating the establishment of pioneer vegetation is crucial, as it improves the environment's suitability by locally lowering hydrodynamic energy for eventual plant colonisation and marsh growth (Willemsen et al., 2022). Continuous monitoring of bed-level dynamics is required to assess morphodynamics related to storm event impacts.

Billah et al. (2022) reviewed current literature on the topic and published a list of available salt marsh restoration/creation techniques and strategies used worldwide in their study. One example of assisted abiotic restoration strategy used in the Netherlands is managed realignments. MRs are created after the intentional or natural breaching of the coastal defence structure, which causes the salt marshes' ecological response and biodiversity enhancement. Generally, restoration techniques differ depending on the degradation causes and environmental stressors impacting the ecosystem. There are several recognised and innovative management techniques for managing the (re)creation of salt marshes (Figure 2).

Moreover, ‘soft’ strategies aim to use materials related to the natural environment and participate in the natural processes. These strategies must be repeated often unless they are natural systems able to maintain themselves. On the other hand, ‘hard’ approaches are usually long-lasting and stay fixed over time without following environmental dynamics. Groot & Duin (2013) include a list of soft to hard techniques used in Northwest Europe to create and restore salt marshes:

1. Reduction of hydrodynamics to facilitate sedimentation and establishment of vegetation. Use of brushwood groynes as the preferred material.
2. Increment of elevation of the tidal area surface by applying dredged material to enhance development.
3. Reduction of hydrodynamics using geotubes as a breakwater or to create a basin for dredged material.
4. Reduction of hydrodynamics using shellfish reefs as a breakwater.
5. Increment drainage by creating channels to ease sediment aeration and establishment of vegetation.
6. Reduction of hydrodynamics using stones and concrete dams as breakwaters or to create a basin for dredged material.
7. Reduction of hydrodynamics stone in front of salt marsh edge to protect from erosion.

1.4 Goal of the study and research question(s)

The NIOZ Department of Estuarine and Delta Systems is looking at ways of promoting the restoration or creation of salt marshes. For this research, I participated in a broader PhD study, focusing mainly on how physical and ecological factors (including marsh age and soil and vegetation characteristics) affect the development of soil stability and erosion resistance in salt marshes. This project included fieldwork and experiments at NIOZ Yerseke and theoretical work at Utrecht University.

This research aimed to determine how soil stability and erosion resistance developed over time by comparing the development of these properties in one managed realignment project and one artificial/created marsh. We measured vegetation and soil characteristics and stability to monitor the soil stability of two well-studied experimental sites and evaluate how their development differs between a managed realignment and an artificial system. By monitoring these sites, we also aim to gain generic insight into how fast marsh restoration projects could be deemed successful.

I aim to achieve this broad research goal by answering the following questions:

- How are vegetation and soil stability developing over time at a managed realignment site and a created salt marsh, and how does this depend on location within the sites?
- Which abiotic and biotic properties control vegetation development at the study sites?
- Which abiotic and biotic properties control the development of soil stability at the study sites?

Figure 2 Examples of different salt marsh restoration techniques reported in the literature (Billah et al., 2022). Figures c and e represent the techniques investigated in this study.

2 Methods

This section describes the methodology used to evaluate the development of vegetation and soil stability in created salt marshes and managed realignments by monitoring the state of vegetation and sediment properties. Firstly, the study areas and research set-up are presented. Then I elaborate on how fieldwork and the data collection were conducted. Lastly, the data analysis is explained.

2.1 Study Areas and research set-up

I measured vegetation and soil parameters in 2 experimental sites in the Netherlands and studied as examples of artificial and managed realignment marshes.

2.1.1. Perkpolder

Perkpolder is a managed realignment site in the Western Scheldt (Zeeland, NL), initially agricultural land. In 2015 dikes were breached at this location, causing the basin to be flooded twice a day by sea-water. As a consequence of this transition, erosion and sedimentation processes were directly impacted by the inflow of water, which is still causing morphological changes. *Spartina anglica* tussocks have been planted and monitored since 2016, and it constitutes the entire vegetation measured at Perkpolder. From the start of this project, vegetation was expected to grow over time due to the realignment and eventually increase soil stability. Sediment slowly started accumulating in the low-lying land through natural processes, taking longer than expected yet causing a slight increase in the area’s elevation over time (De Paiva et al., 2019).

Measurements were taken at the 6 locations where vegetation survived (Tussocks 1,2,3,11,13,15) to observe how abiotic and biotic sediment properties develop over time (Figure 3). Four replicates per soil and vegetation measurements were collected. Soil measurements were taken inside and outside each tussock to evaluate the effect of vegetation presence.

2.1.2 Marconi

The Marconi project is located at the port of Delfzijl (North of the Netherlands). Two salt marshes were developed there; one 'salt marsh park' was built for recreation. The second pioneer salt marsh was created for coastal protection (Baptist et al., 2019). The accretion at the site is artificial, as the elevation was increased by applying dredged material in combination with brushwood groynes (Groot & Duin, 2013).

Three blocks defined the main sampling areas at Marconi with different grain size distributions: E (50% silt), F (20% silt), and G (5% silt). I took vegetation measurements in each block at two elevations (higher/land and middle of the Block). Aluminium sticks were used to mark the sampling location and three types of vegetation: one "Control" plot, left with its original vegetation (mostly *Salicornia sp.*), one *Spartina* plot, and one *Puccinellia* plot (Figure 4). I collected data at 24 sampling locations per Block because each plot comprises four replicates along the two elevations. Yet, I considered only the vegetation measurements taken at the Control plots in every block for the final analysis because of less missing data.

Furthermore, soil measurements were taken at the same sampling sites as vegetation measurements, with care not to disturb the sediment. In every block, four replicas of each soil measurement were also collected along the mudflat to test the parameters without vegetation.

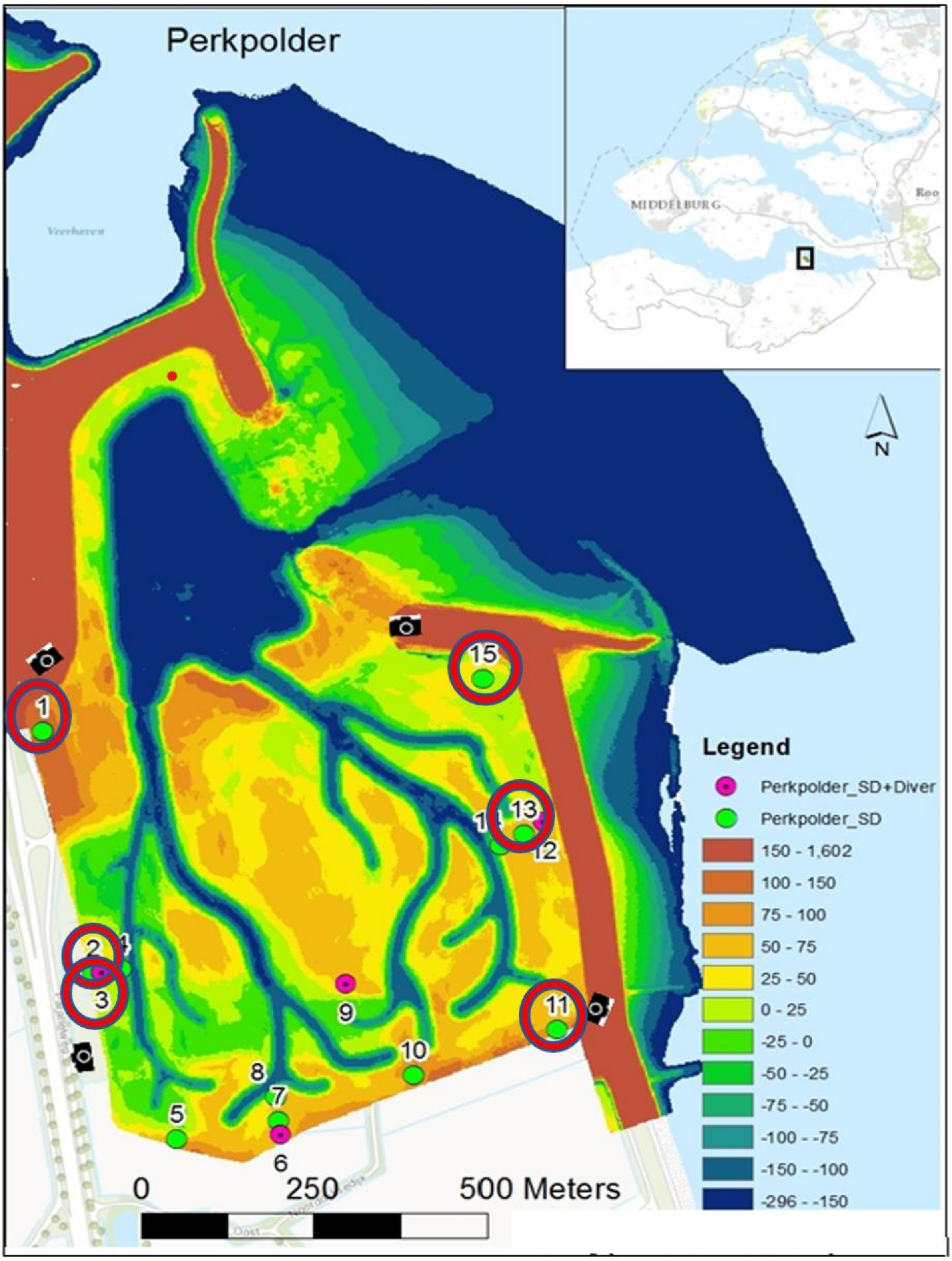


Figure 3 Elevation map of the Perkpolder site with natural sedimentation in the Western Scheldt estuary (NL). The location of survived Tussocks and numbering used in this thesis are indicated by red circles (De Paiva et al., 2019).

Figure 4 Satellite image of the Marconi site made with dredged material in the Ems estuary, close to the port of Delfzijl (NL). Locations of vegetation measurements are indicated in the blocks with different sediment compositions. Vegetation plots were planted at two elevations and are denoted by coloured pixels. Red pixels indicate the sample stations analysed in this study. Source: Maxar Technologies; www.satellietdataportaal.nl

2.2 Data Collection and fieldwork methods

Measurements at Marconi and Perkpolder were collected in September 2021, May 2022 and October 2022. The measurements performed aim to add new observations taken for this study in October and November 2022 to available data in order to create a time series. Table 1 shows the complete list of parameters measured during the fieldwork in autumn 2022 and the measurements already taken in Marconi and Perkpolder during previous field campaigns. Thus, it was possible to compare part of the new observations with the old measurements to monitor how these parameters change over time at various locations. By measuring the following parameters, we aim to gain insight into the vegetation and soil characteristics that lead to a stable marsh soil and, thus, understand the environmental aspects required to successfully implement marsh restoration and managed realignment projects.

Table 1 Parameters measured during the field campaigns

Measured Parameters		**Measured Marconi 2021**	**Measured Perkpolder 2021**	**Measured Marconi 2022**	**Measured Perkpolder 2022**
Vegetation measurements	Elevation	x	x	x	x
	Diameter of the Tussocks	x	x	x	x
	Height of the shoots	x	x	x	x
	Vegetation coverage, count of shoots	x	x	x	x
	Dry aboveground biomass (g)		x		x

Soil Measurements	Erosion resistance of soil	Shear vane (kPa) measurement at surface, 10, 20, 30 & 40 cm	x	x	x	x
		Penetrologger until 40 cm depth	x	x	x	x
	Compaction of soil	Bulk density from 0-10, 10-20, 20-30 & 30-40 cm		x until 10cm		
	Soil properties	Grain size distribution		x until 10cm		x
		Water content		x until 10cm		

2.2.1 Vegetation measurements

Tussock elevation was measured using a DGPS at each location. Tussock diameter is defined by an average of two directions, and the diameters in Perkpolder were measured by walking around each Tussock with a DGPS and storing the points. When possible, the height of the shoots was determined by averaging the heights of ten random shoots. To determine aboveground biomass, I harvested shoots in the centre of tussocks inside a 25x25 cm square at Perkpolder. This was accomplished by counting the number of shoots and then drying them in the oven to determine dry weight at the NIOZ institute. However, I used 50x50 cm squares to determine visual cover estimates in percentages because the Marconi vegetation plots are new and should not be disturbed.

2.2.2 Soil measurements

I used various methods to directly measure soil strength, including a shear vane and a cone penetrometer. *In situ*, shear vane measurements were taken with a pocket vane tester to determine surface shear strength rapidly (Box & Giesbeek, 2012). A field vane tester (Eijkelkamp, NL) makes it possible to measure soil shear strength until 50 cm below the surface and ranges from 0 to 130 kPa. Furthermore, a penetrologger measured the resistance to soil penetration and digitally processed the data on a computer (Royal Eijkelkamp, 2017). Bulk density and penetration resistance are indicators of soil compaction. These parameters are used to investigate whether there is a clear relation between soil compaction and soil strength. Bulk density was measured by collecting sediment samples with a gouge auger at depth intervals from 0-10, 10-20, 20-30, and 30-40 cm. These bulk-density samples are used to analyse grain size distribution and water content. This analysis is done since the mentioned properties are expected to affect soil structure and erodibility.

2.3 Elaboration of data and statistical analysis

Data Preparation and visualisation
All the measurements taken in the field were elaborated into data format using Microsoft Excel and Python programming language (Python Software Foundation v 3.9). The data were prepared by cleaning, creating datasets, and removing missing values or outliers. Then, creating boxplots helped to explore the data using descriptive statistics, such as mean, standard deviation, and range, to understand the distribution of the variables. Plots and graphs were made to visualise the patterns and trends of the

data over time and across sites. Specifically, time series plots of vegetation coverage, elevation, and other variables were created, and the patterns between the two sites were compared.

Correlation analysis

Several correlation analyses were performed to determine which variables significantly predict vegetation development and soil stability at the study sites. The dependent variables for vegetation development were vegetation coverage/aboveground biomass estimation, shoot height or Tussock diameter. The independent ones were elevation, penetration resistance, surface shear strength, depth shear stress, and silt content of the soil matrix. The dependent variables for soil stability were penetration resistance and shear strength. The independent variables examined were elevation, vegetation coverage/aboveground biomass estimation, shoot height, tussock diameter, and grain size distribution of the soil matrix. The methodology used is similar for both sites, but the representation is slightly different.

Soil stability over time was assessed by creating and visualising the two time series of average shear stress in every tussock. Linear regressions were performed using vegetation data as the dependent variable to examine which abiotic and biotic factors influence vegetation development at Perkpolder and Marconi. Estimations of aboveground biomass, shoot height, and Tussock diameter have been tested for Perkpolder. We examined the correlation coefficients (r) as a measure of the strength and direction of the relationship between the variables and assessed the statistical significance. The predetermined value of $p < 0.05$ was set as the threshold to test the hypothesis that the observed relationship between the variables is statistically significant. Because it was determined that the aboveground biomass estimate was the most scientifically representative measure of vegetation compared to the other vegetation measurements, only results where this parameter was used as the dependent variable are reported in this study. Data for Tussock diameter and shoot height as dependent variables gave similar linear trends and correlation coefficients. However, the relations were not always statistically significant estimation. To simplify the analysis and compare the relations between variables in every Tussock in one plot, data are averaged for Perkpolder analysis.

Hypothesis testing

I examined if the hypotheses that the predictor variables are significantly related to vegetation development and soil stability at the study sites were true. Linear regressions, ANOVA and Tukey HSD tested the significance of the regression coefficients.

3 Results

The results of the statistical analyses and a general interpretation are presented in this section. Firstly, an overview of Marconi and Perkpolder's general vegetation and soil stability over time is given (section 3.1). This is followed by presenting the analyses' results to examine the factors affecting vegetation (section 3.2) and soil development (section 3.3) at Marconi and Perkpolder.

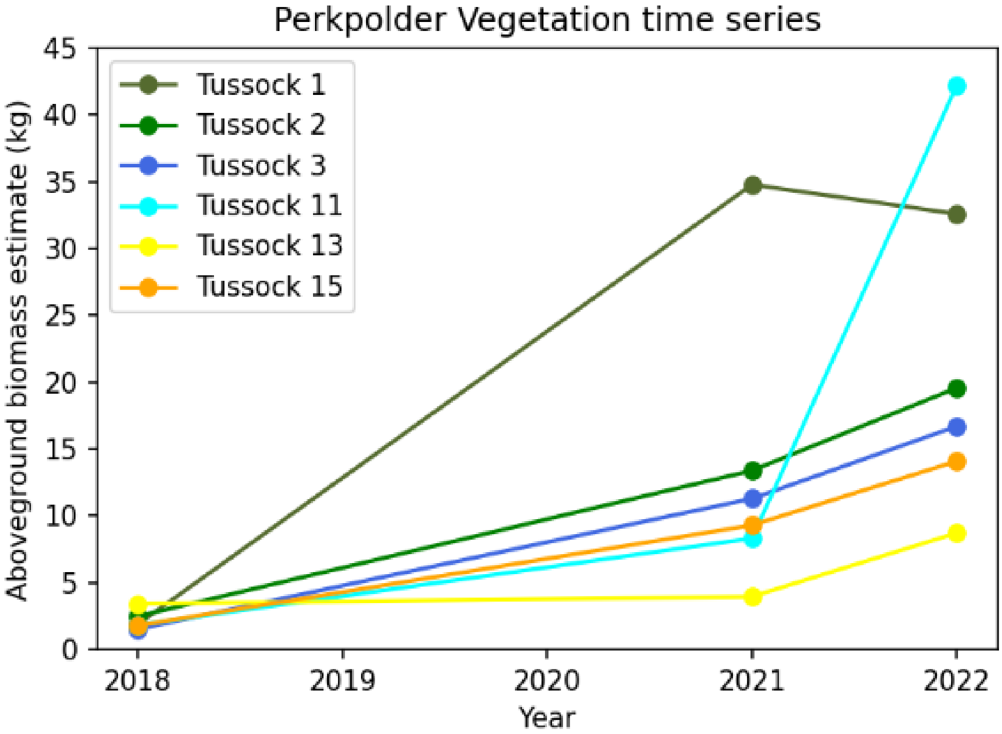
3.1 Vegetation and soil stability time series at the sites

Overall, vegetation at Perkpolder is steadily increasing in every Tussock. In particular, Figure 5a shows how Tussocks 2, 3, 13 and 15 have a consistently increasing aboveground biomass estimation. Tussocks 1 and 11 were the Tussocks with the highest mean biomass estimation over time, while the lowest mean vegetation estimate characterises Tussock 13. Furthermore, every tussock in Perkpolder is expanding (Figure 5b), although shoots are not necessarily higher (Figure 5c).

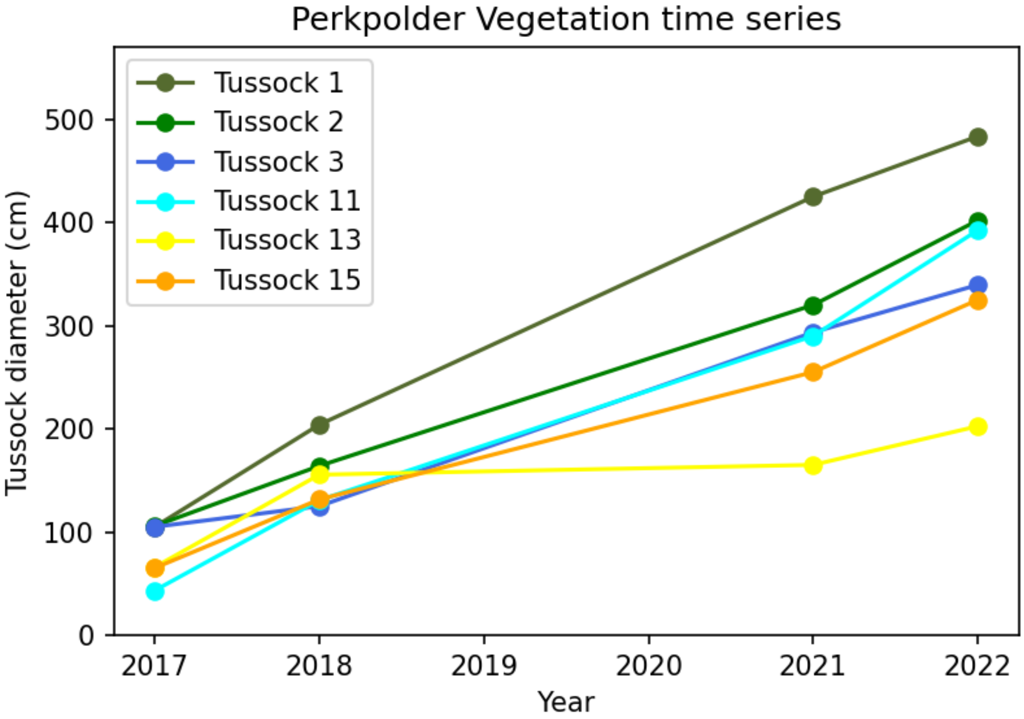
Elevation at Perkpolder is generally remaining very stable (Figure 5d). Tussock 11 is located at the highest elevation in the managed realignment site. On the other hand, Tussock 15 was found at the lowest.

Surface shear stress (Figure 5e) was found to be altogether steady across the years both inside and outside the Tussocks ("in" and "out", respectively), especially for Tussock 3, Tussock 13 and Tussock 15. Tussock 1 "out" and 11 "in" were found to be the locations where values for surface SS are highest. In location 1, surface SS outside the Tussock increased from 2.2 kPa in September 2021 to 2.8 kPa in September 2022. Whereas SSS inside Tussock 11, data for September 2021 are missing because measurements were impossible due to excessive vegetation. Nevertheless, an increase was found from May 2022 to September 2022 from 2.9 kPa to 3.1 kPa.

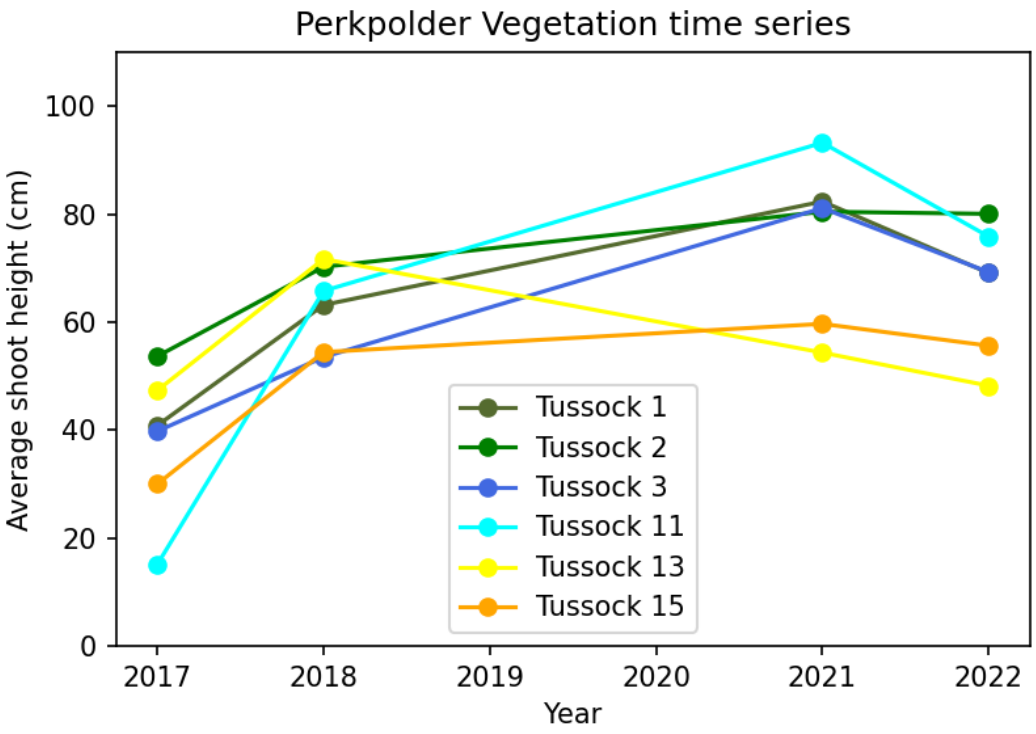
To understand how stability is developing in the subsoil, shear strength was measured at 10, 20, 30 and 40 cm below the surface (SSD). However, because the sub-soil was very hard, using the shear vane at depths larger than 20 cm at many locations was difficult. Hence the results for deep soil stability in this and the following sections present the SSD at a depth of 20 cm (Figure 5f). Nevertheless, Tussock 11 was found to have the most stable development of sub-soil stability over time and was also found to be the Tussock with the highest sub-soil shear strength.


Perkpolder Vegetation time series
Aboveground biomass estimate (kg)
0
5
10
15
20
25
30
35
40
45
2018
2019
2020
2021
2022
Year
Tussock 1
Tussock 2
Tussock 3
Tussock 11
Tussock 13
Tussock 15

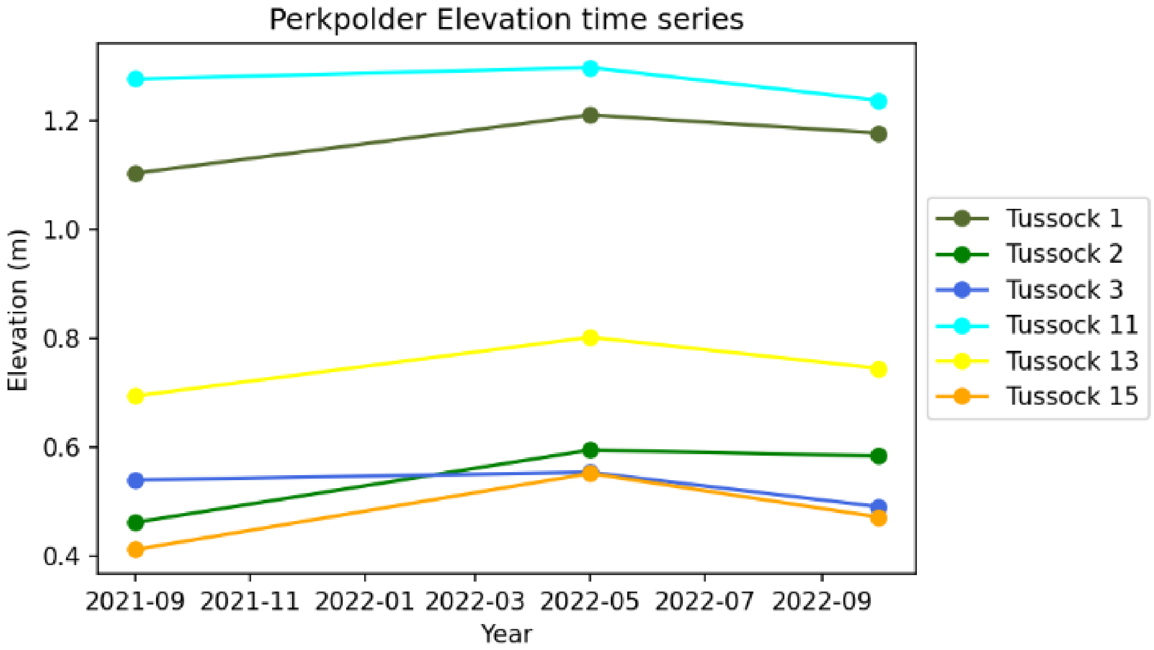
a)


Perkpolder Vegetation time series
Tussock diameter (cm)
0
100
200
300
400
500
2017
2018
2019
2020
2021
2022
Year
Tussock 1
Tussock 2
Tussock 3
Tussock 11
Tussock 13
Tussock 15

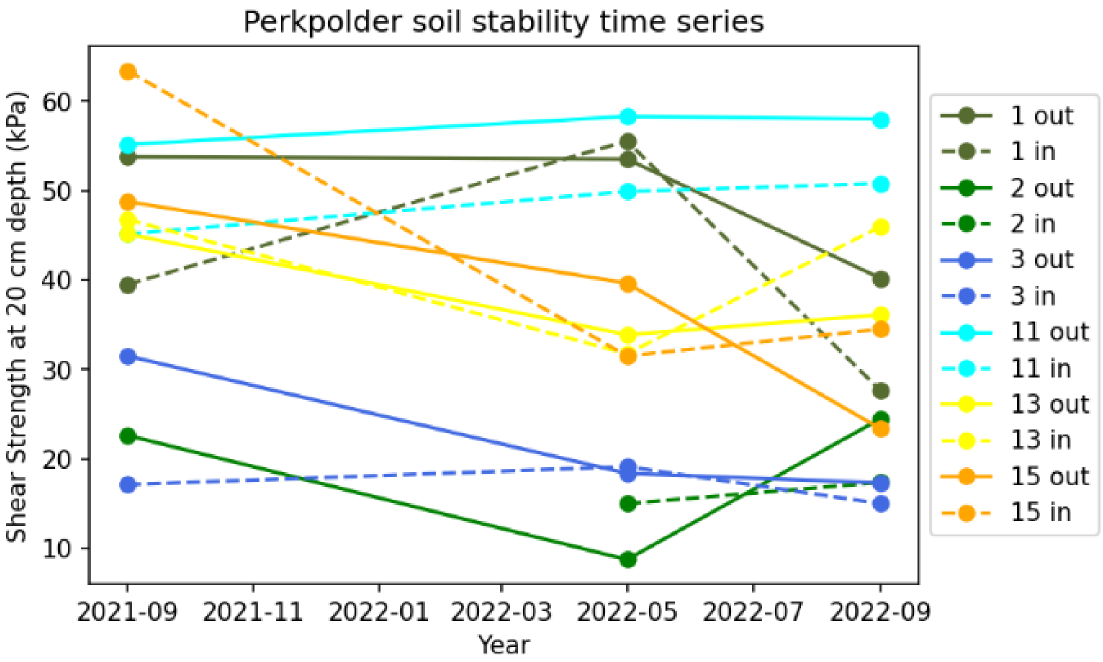
b)


Perkpolder Vegetation time series
Average shoot height (cm)
0
20
40
60
80
100
2017
2018
2019
2020
2021
2022
Year
Tussock 1
Tussock 2
Tussock 3
Tussock 11
Tussock 13
Tussock 15

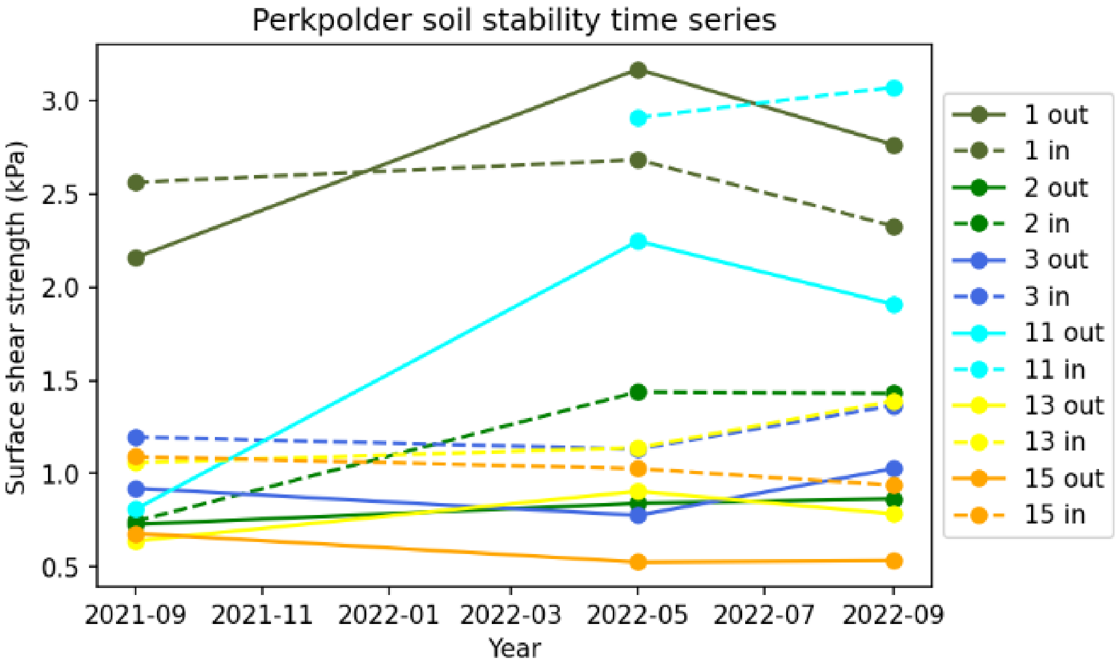
c)


Perkpolder Elevation time series
Elevation (m)
0.4
0.6
0.8
1.0
1.2
2021-09
2021-11
2022-01
2022-03
2022-05
2022-07
2022-09
Year
Tussock 1
Tussock 2
Tussock 3
Tussock 11
Tussock 13
Tussock 15

d)



e)

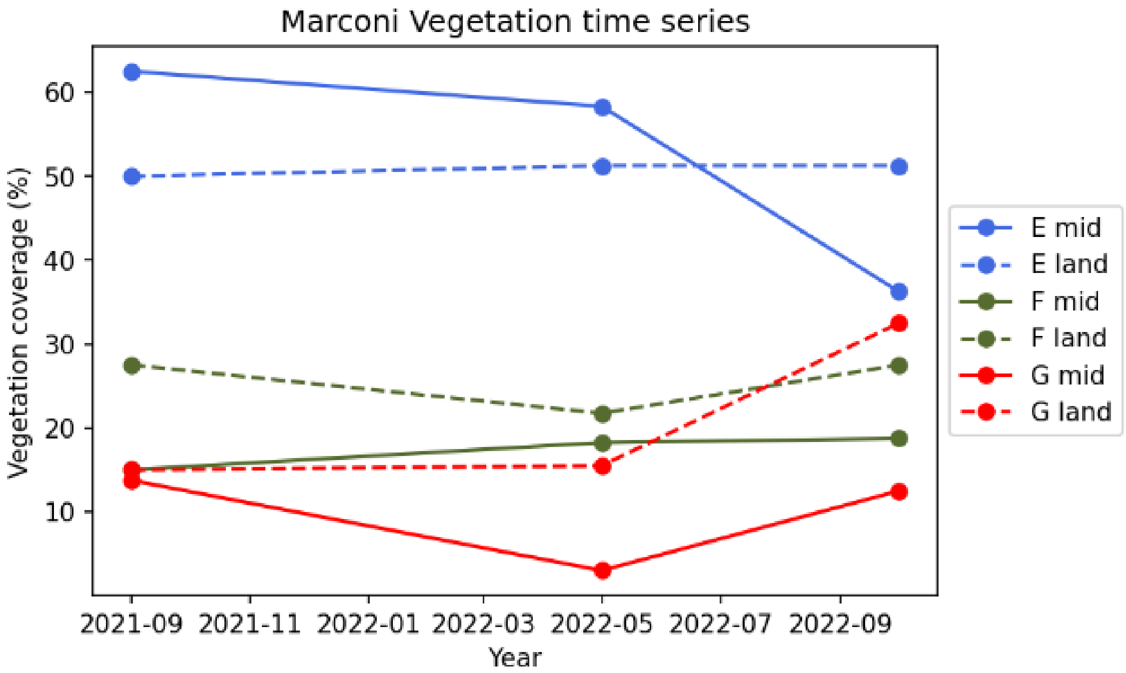


f)

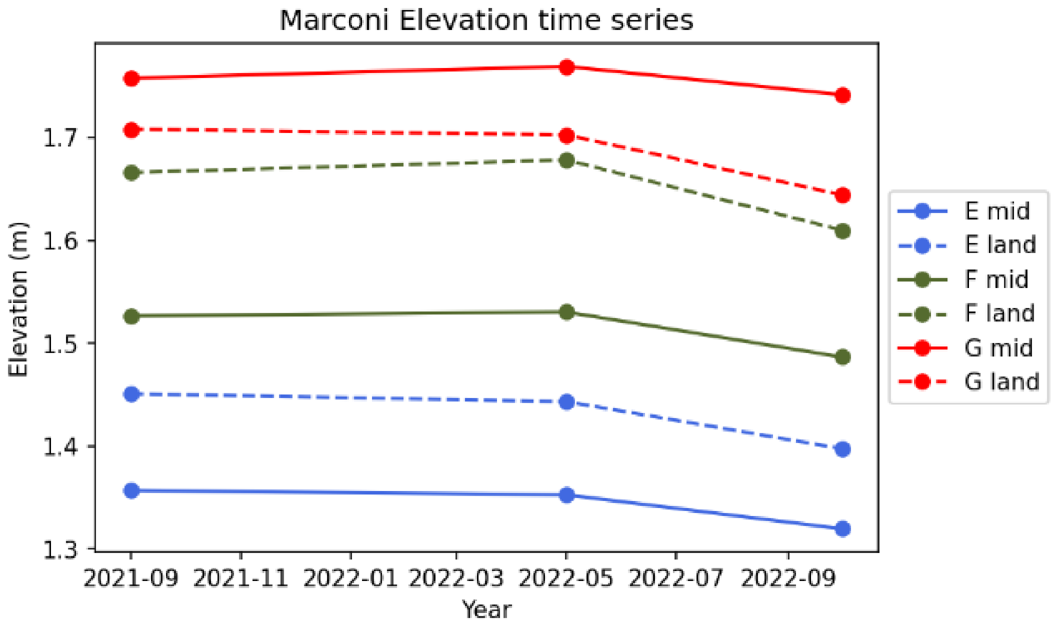
Figure 5 Time series of vegetation coverage (a), tussock diameter (b), shoot height (c), elevation (d), surface shear strength (e) and average shear strength at 20 cm deep (f). See Fig. 3 for the tussock number and location; out/in after the tussock number refers to outside/inside the tussock.

For Marconi results, in this study, all the variables analysed are from the Control plots because the vegetation in the Puccinellia plots died at many locations, and Spartina survived only in Block G. Within the three-time steps considered for this study, mean vegetation coverage % in the Control plots (Figure 6a) at the 20% silt block remained the most stable across the years. The siltiest area (block E landwards) has the highest vegetation coverage, with biomass remaining about 50%. In comparison, the mean vegetation at the seaward plots (E mid) halved from September 2021 to the end of 2022. In the sandy block seaward (G mid), vegetation increased, while in G land, the mean vegetation stayed stable over time.
Elevation at Marconi remained overall stable yet slightly decreased in every Block over the last period of this study (Figure 6b). The created salt marsh in Delfzijl is characterised by the G Block being the highest section in elevation (mean elevation over the period = 1.7 m) and the E Block the lowest (mean elevation over the period = 1.4 m).

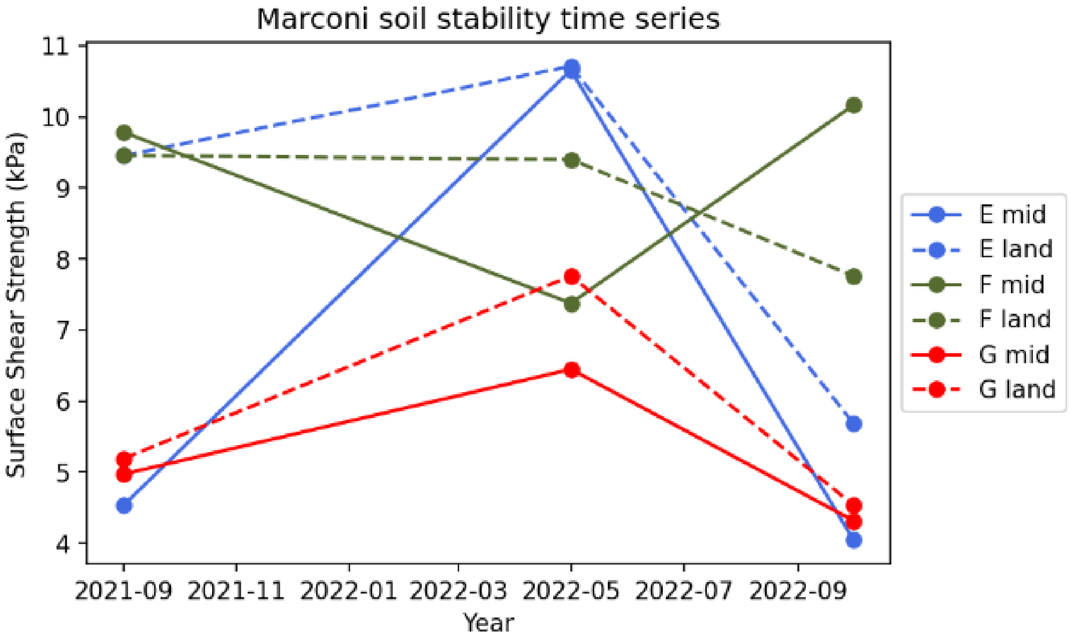
An average of surface shear strength (SSS) values was made to have an overview of soil strength over time (Figure 6c). However, values of SSS at Marconi show substantial variability. They were found to be higher in May 2022 than at the other moments in most Blocks, except for F mid, which on the contrary, decreased in May. The average shear strength for the first 40 cm at Marconi remained relatively stable by examining the subsoil. The 20% and 50% silt blocks, respectively, were shown to have a more consistent mean soil strength. From 45 kPa in September 2021 to 60.39 kPa in October 2022, soil shear strength in F mid grew steadily. Block G had the lowest average soil stability results over time.



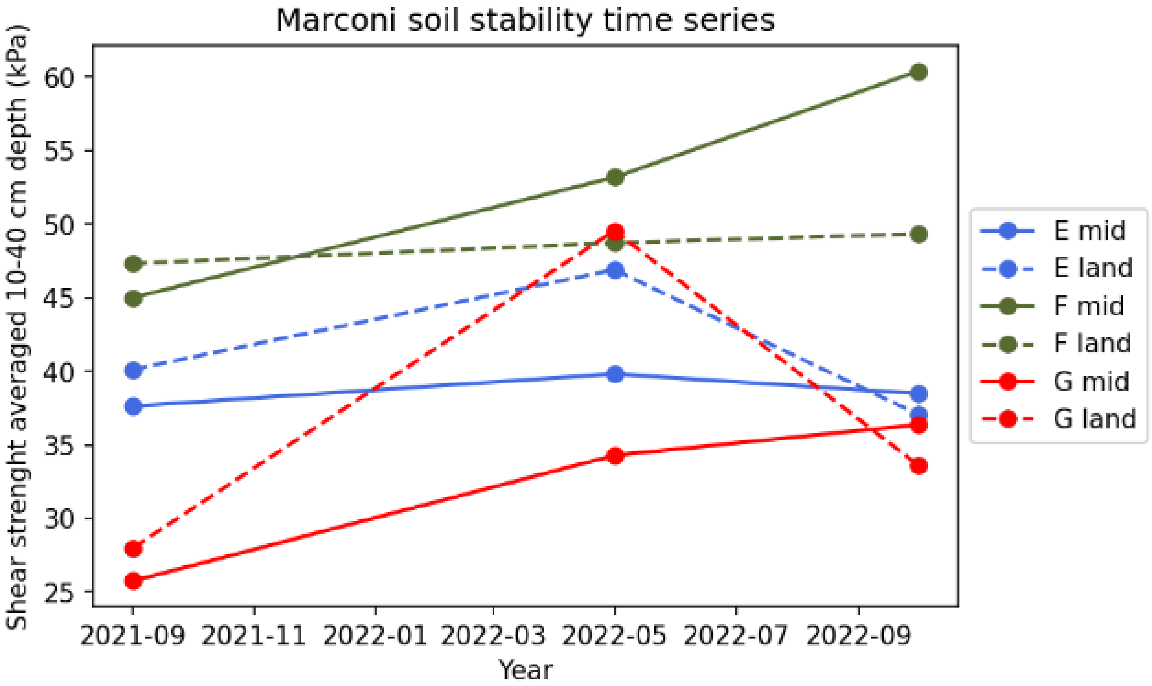
a)


Marconi Elevation time series
Elevation (m)
1.3
1.4
1.5
1.6
1.7
2021-09
2021-11
2022-01
2022-03
2022-05
2022-07
2022-09
Year
E mid
E land
F mid
F land
G mid
G land

b)


Marconi soil stability time series
Surface Shear Strength (kPa)
4
5
6
7
8
9
10
11
2021-09
2021-11
2022-01
2022-03
2022-05
2022-07
2022-09
Year
E mid
E land
F mid
F land
G mid
G land

c)



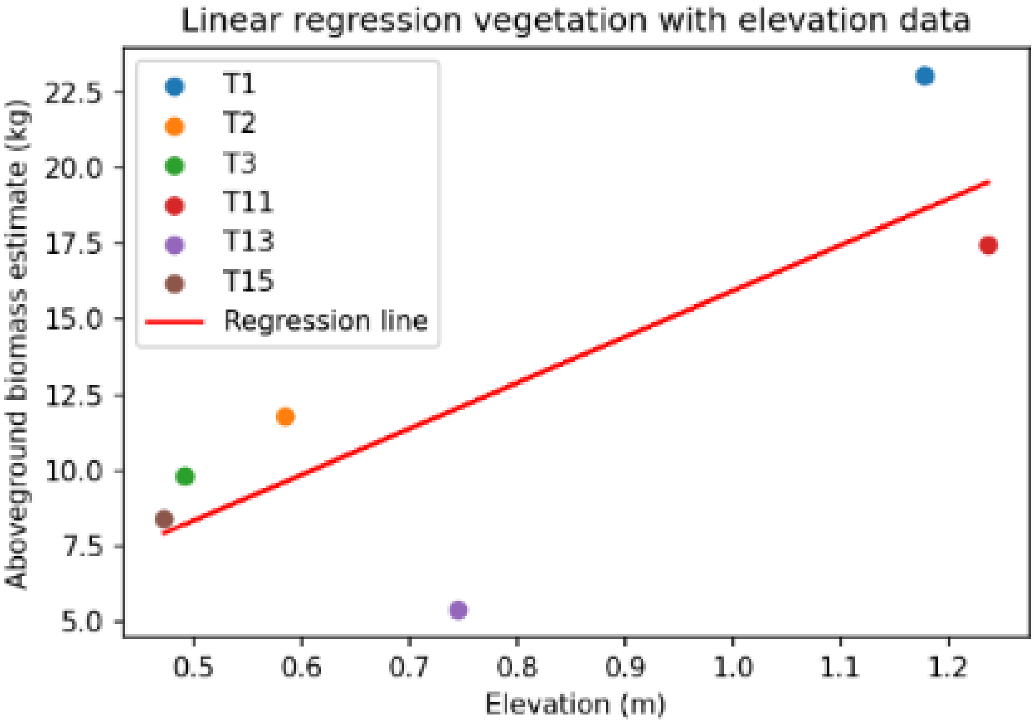
d)

Figure 6 Time series of vegetation coverage (a), elevation (b), surface shear strength (c) and average shear strength between 10 and 40 cm deep (d). Locations E-G are ordered from seaward to landward and from silty to sandy (see Fig. 4 for block name and plot location)

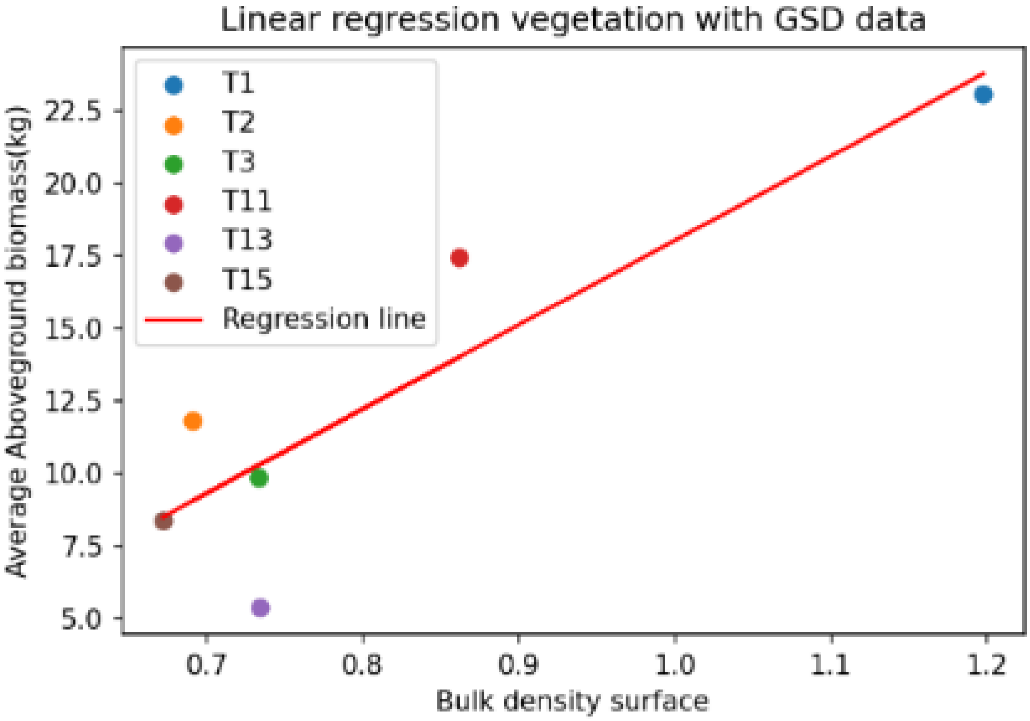
3.2 Vegetation development

3.2.1 Perkpolder

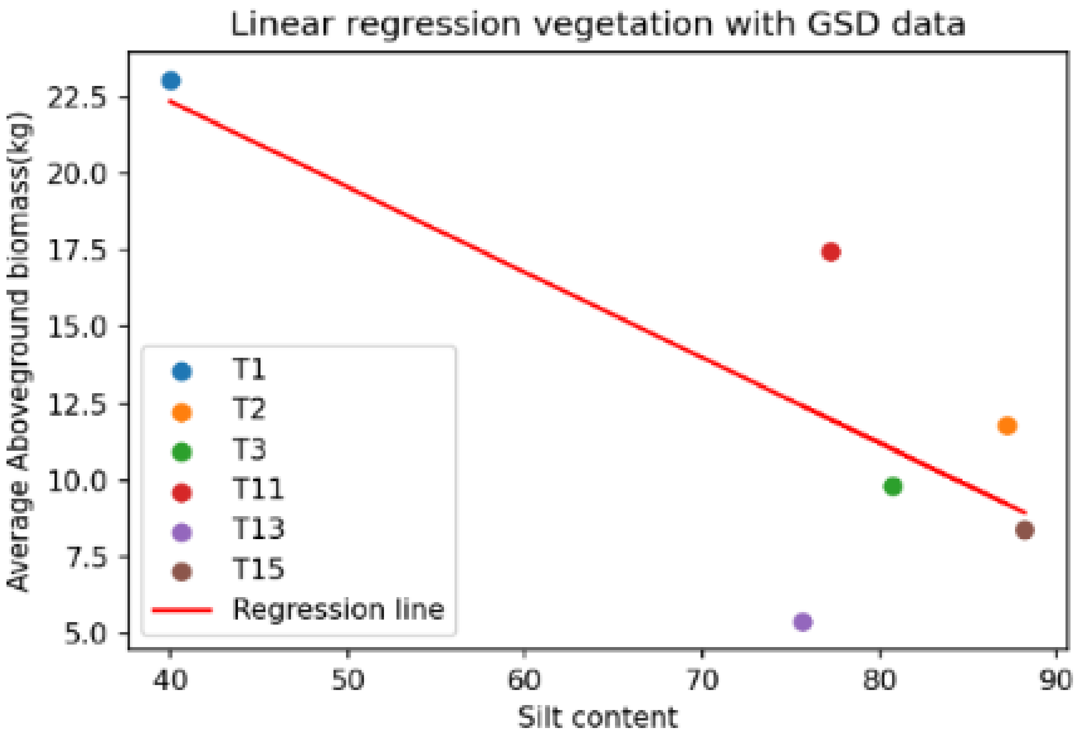
Figure 7 presents the relations between vegetation data and elevation, sediment properties and soil strength. A significant positive relation was found between biomass and elevation (*r* = 0.80, *p*-value = 0.05) (Figure 7a). The effect of bulk density on aboveground biomass at Perkpolder (Figure 7b) was quite strong and described by a positive relation (*r* = 0.89, *p*-value = 0.02). Accordingly, silt and water content are abiotic factors that detail a negative relation with vegetation at Perkpolder (Figures 7c and 7d). However, the relation with water content is stronger (*r* = -0.93, *p*-value = 0.01) than with silt content (*r* = -0.76, *p*-value = 0.08). Finally, Figures 7e and 7f show the results of the linear regressions between vegetation and soil strength data, composed of surface shear strength and shear strength at 20 cm. Surface shear strength has a stronger effect on vegetation development, as indicated by the positive relation (*r* = 0.77, *p*-value = 0.07). On the other hand, the impact of subsoil on vegetation development is straight, implying no significant relation (*r* = -0.01, *p*-value = 0.97). To summarise, higher aboveground biomass at Perkpolder is found at increasing elevations and is mainly affected by increasing bulk density and decreasing water content in the surface sediment.


Linear regression vegetation with elevation data
Aboveground biomass estimate (kg)
22.5
20.0
17.5
15.0
12.5
10.0
7.5
5.0
T1
T2
T3
T11
T13
T15
Regression line
0.5
0.6
0.7
0.8
0.9
1.0
1.1
1.2
Elevation (m)

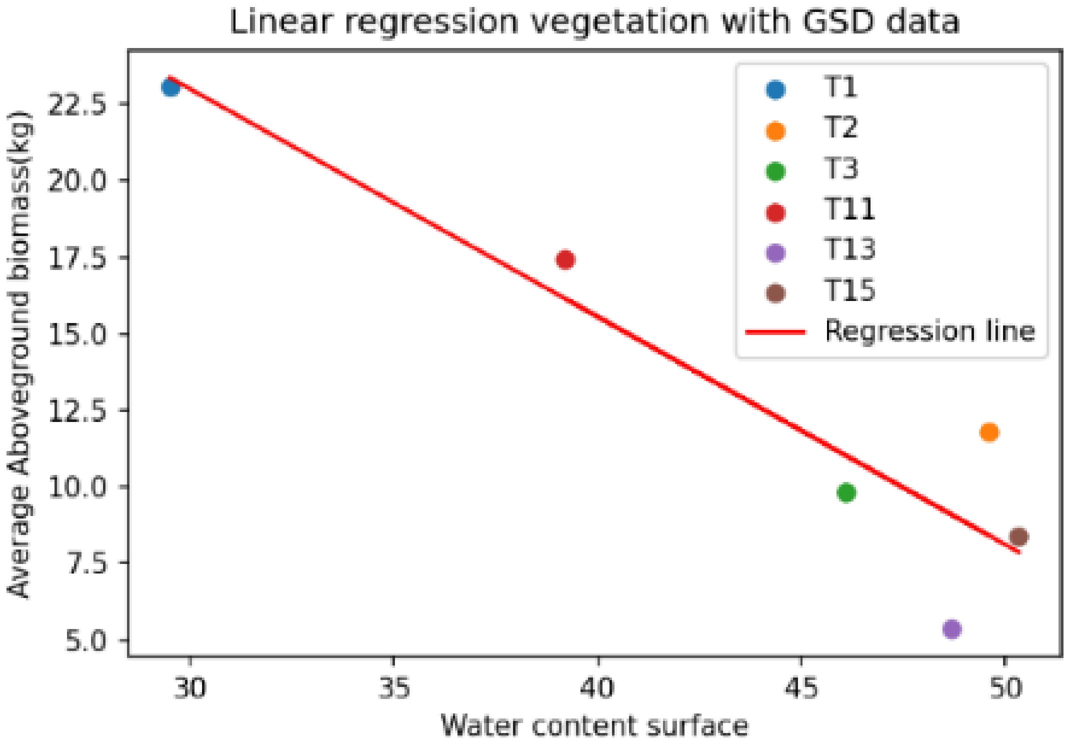
a)


Linear regression vegetation with GSD data
Average Aboveground biomass(kg)
22.5
20.0
17.5
15.0
12.5
10.0
7.5
5.0
T1
T2
T3
T11
T13
T15
Regression line
0.7
0.8
0.9
1.0
1.1
1.2
Bulk density surface

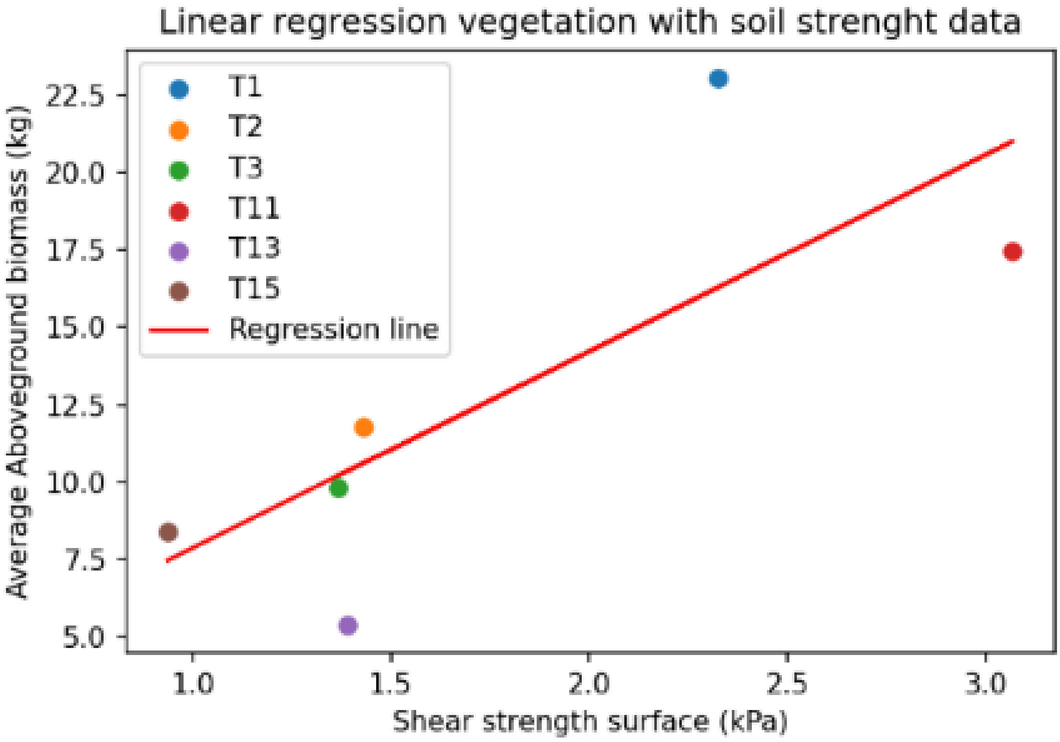
b)


Linear regression vegetation with GSD data
Average Aboveground biomass(kg)
22.5
20.0
17.5
15.0
12.5
10.0
7.5
5.0
40
50
60
70
80
90
Silt content
T1
T2
T3
T11
T13
T15
Regression line

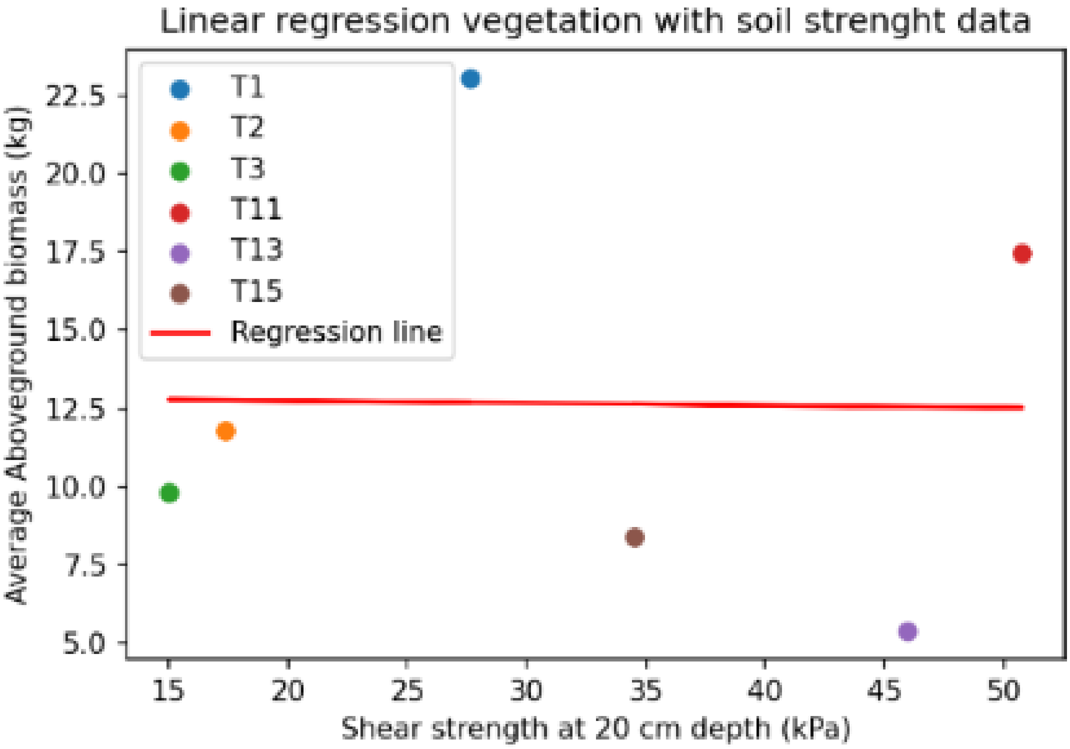
c)


Linear regression vegetation with GSD data
Average Aboveground biomass(kg)
22.5
20.0
17.5
15.0
12.5
10.0
7.5
5.0
30
35
40
45
50
Water content surface
T1
T2
T3
T11
T13
T15
Regression line

d)



e)

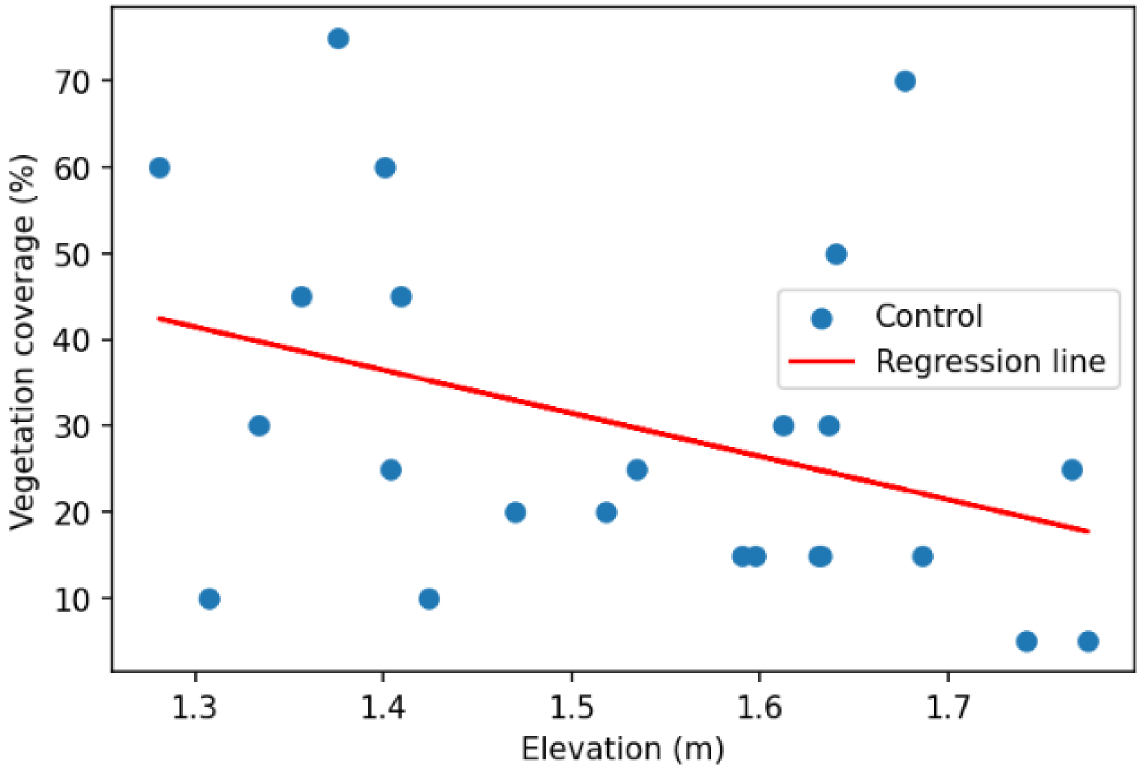


f)

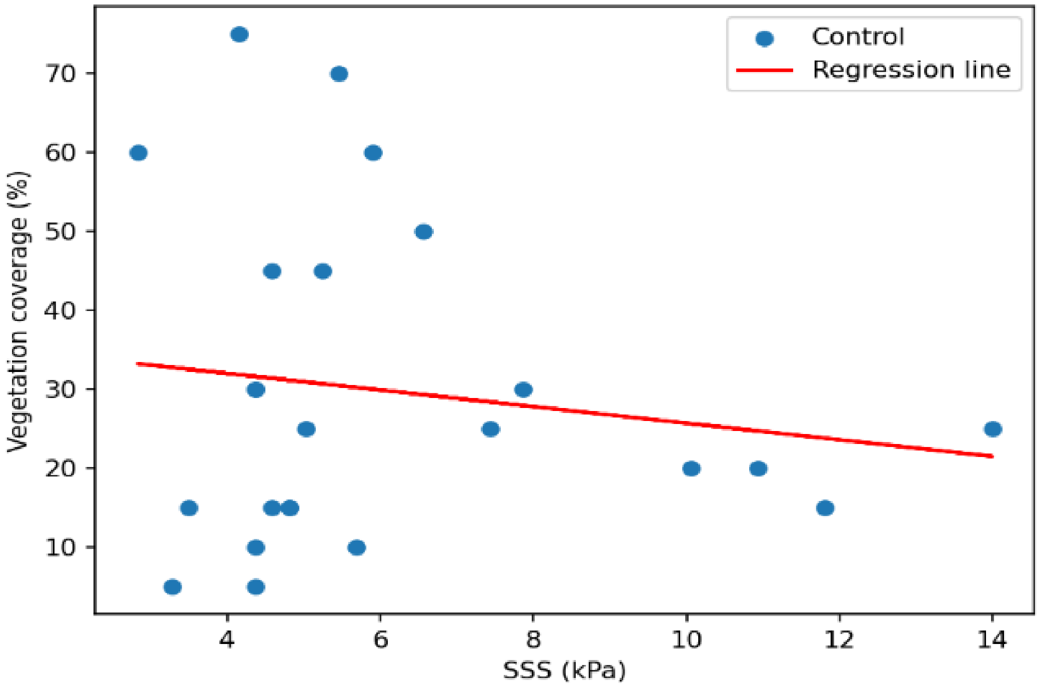
Figure 7 Multiple regressions for vegetation development in Perkpolder. T(number) refers to tussock (see Fig. 3 for tussock location and number)

3.2.2 Marconi

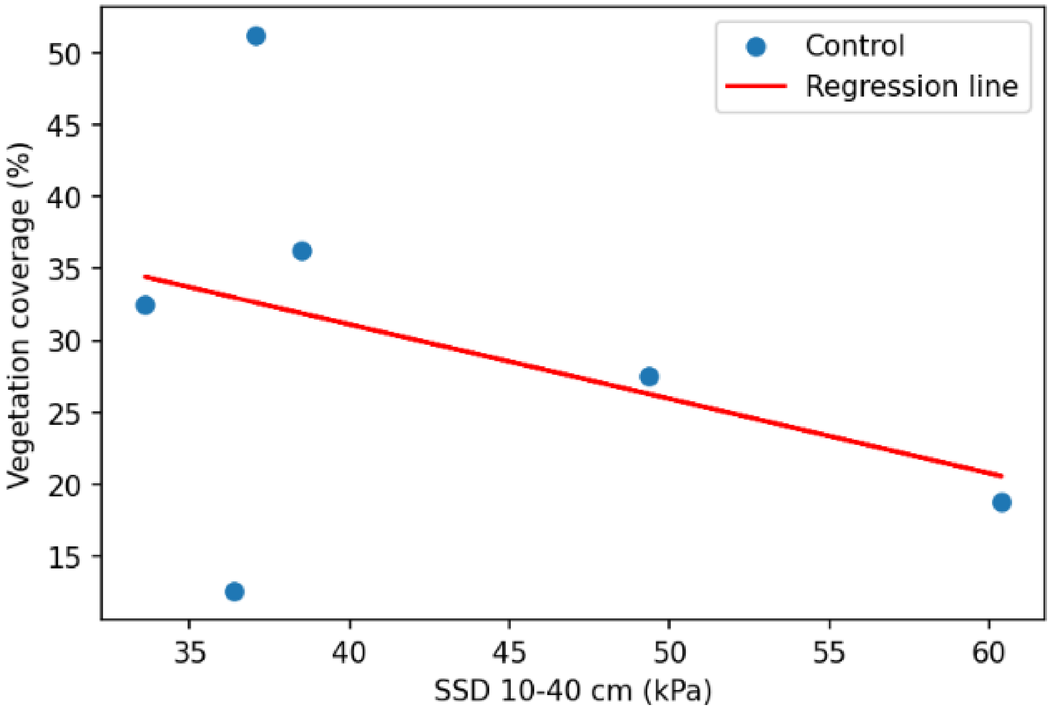
To investigate which abiotic factors control vegetation development at Marconi, vegetation coverage % of the Control plots was used as the only dependent variable for multiple regression analysis. Linear regressions between vegetation and elevation and vegetation and soil stability parameters were performed following a similar methodology used with Perkpolder data. Figure 8a shows how, at this site, the correlation between vegetation and elevation is negative, implying that higher vegetation coverages are found at lower elevations (r = -0.37, p-value = 0.07). Furthermore, the effect of soil stability on vegetation development is not strong at this site. This remains true for both the relation with surface shear strength (r = -0.20, p-value = 0.332) (Figure 8b) and for the one averaged SS of the first 40 cm of sub-soil (r = -0.39, p-value = 0.44) (Figure 8c). However, to further investigate which factors impact biomass presence at Marconi, a boxplot was made to analyse the variance of vegetation and grain size distribution (GSD) (Figure 8d). GSD is represented by the soil content of each Block (E = 50%, F = 20 %, G = 5%). ANOVA test demonstrates a significant difference in vegetation % depending on silt content at Marconi (p =0.002). This was further supported by the Tukey HSD test, showing a significant difference between vegetation growing in Blocks G and E and between vegetation growing in Blocks F and E. No significant difference occurs between Blocks F and G, suggesting that at Marconi, vegetation is developing more in Block E mainly as a consequence of higher silt content in the soil, also clearly shown in the boxplot.



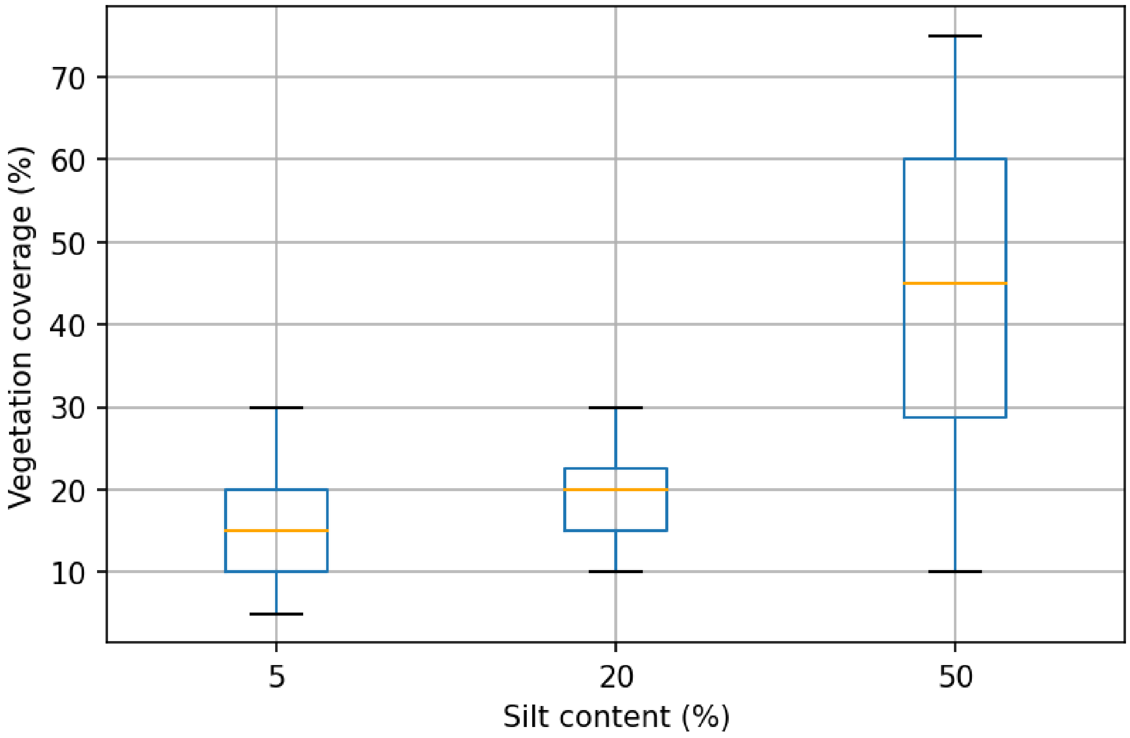
a)


Control
Regression line
Vegetation coverage (%)
10
20
30
40
50
60
70
4
6
8
10
12
14
SSS (kPa)

b)


Control
Regression line
Vegetation coverage (%)
15
20
25
30
35
40
45
50
35
40
45
50
55
60
SSD 10-40 cm (kPa)

c)



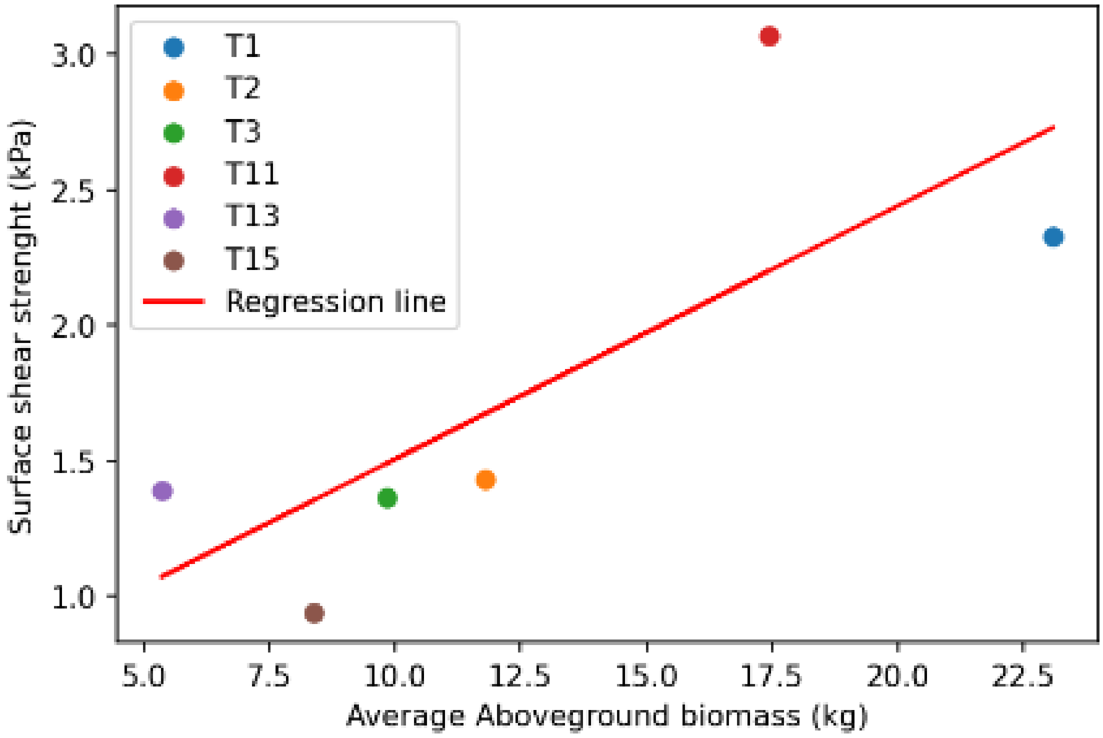
d)

Figure 8 Multiple regressions for vegetation development in Perkpolder (a,b,c) and boxplot of vegetation coverage grouped for silt content (d)

3.3 Soil development

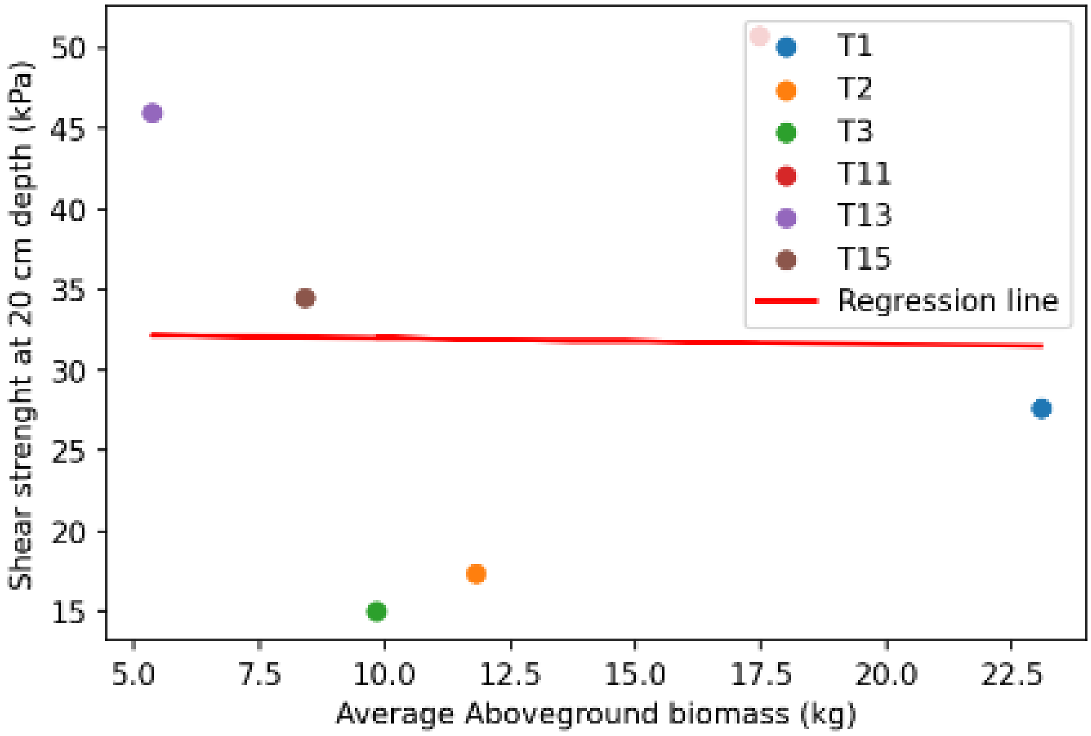
3.3.1 Perkpolder

To investigate which abiotic and biotic properties control the development of sediment stability at Perkpolder, multiple regressions were performed using surface shear strength, sub-soil shear strength and penetration resistance as dependent variables. The impacts of aboveground biomass, elevation and silt content were tested as independent variables. In addition, boxplots show the variance of soil stability factors inside and outside every Tussock. Figure 9 illustrates the effects of biomass on SSS (Fig.9a), SSD (Fig. 9b) and PR (Fig. 9c) inside the Tussocks. The positive relation is strongest yet non-significant when looking at the effect of vegetation on surface shear strength ($r = 0.77$, p-value = 0.07). The relation between aboveground biomass and penetration resistance at 10 cm of depth was weak, while non-existent with SSD.



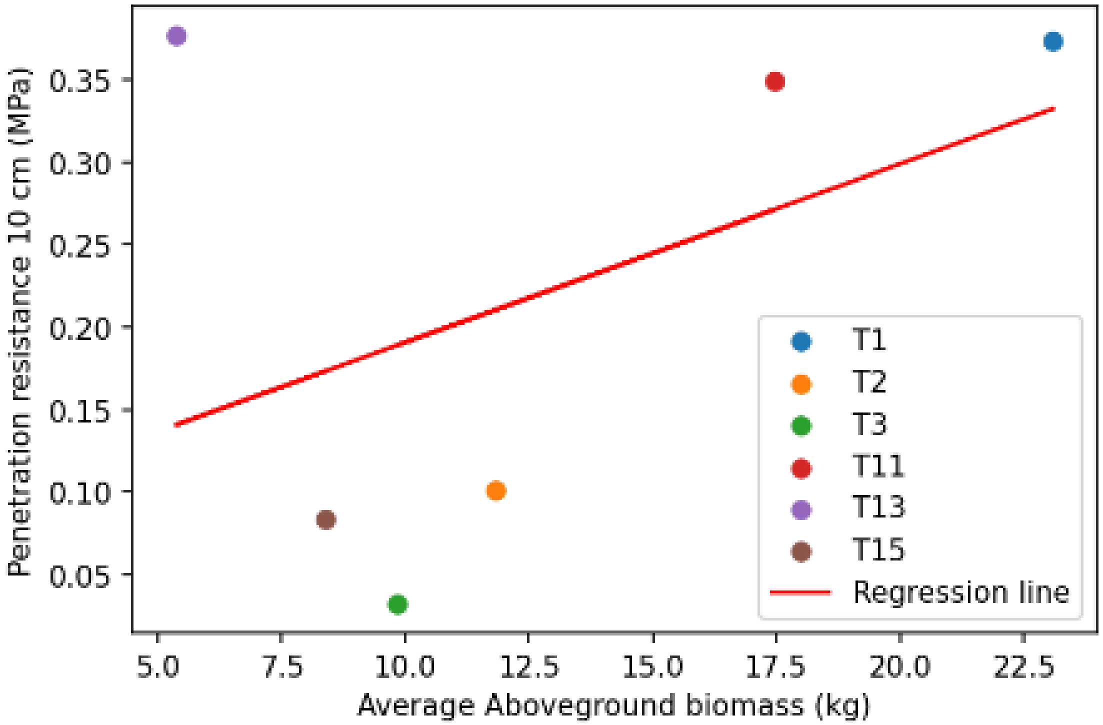
Surface shear strenght (kPa)
3.0
2.5
2.0
1.5
1.0
5.0
7.5
10.0
12.5
15.0
17.5
20.0
22.5
Average Aboveground biomass (kg)
T1
T2
T3
T11
T13
T15
Regression line

a)



Shear strenght at 20 cm depth (kPa)
50
45
40
35
30
25
20
15
5.0
7.5
10.0
12.5
15.0
17.5
20.0
22.5
Average Aboveground biomass (kg)
T1
T2
T3
T11
T13
T15
Regression line

b)

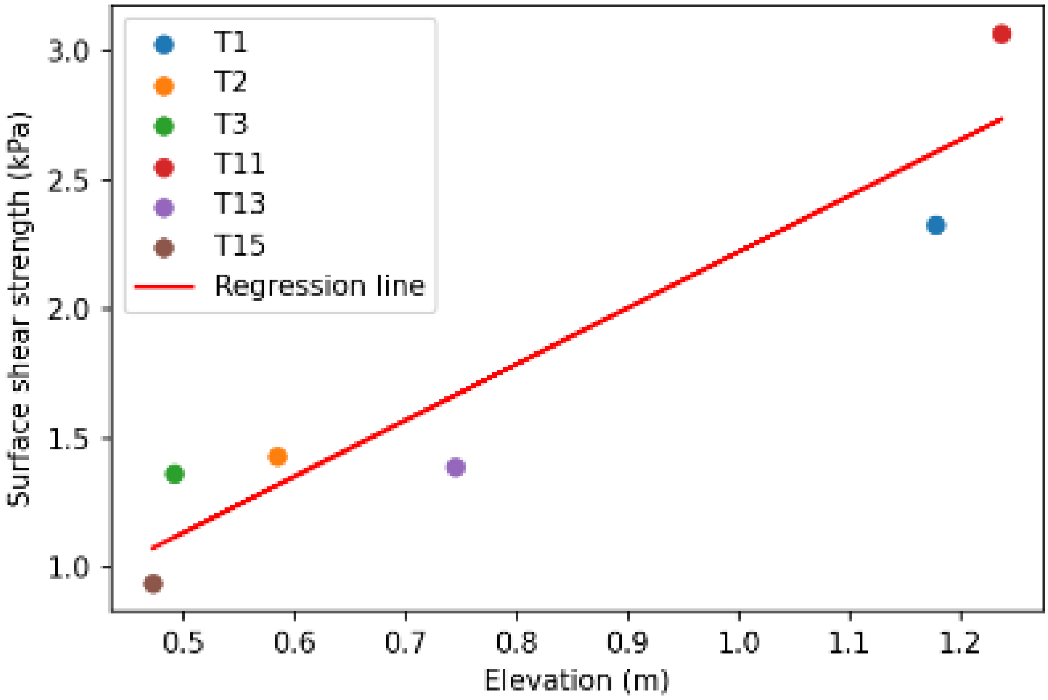


c)

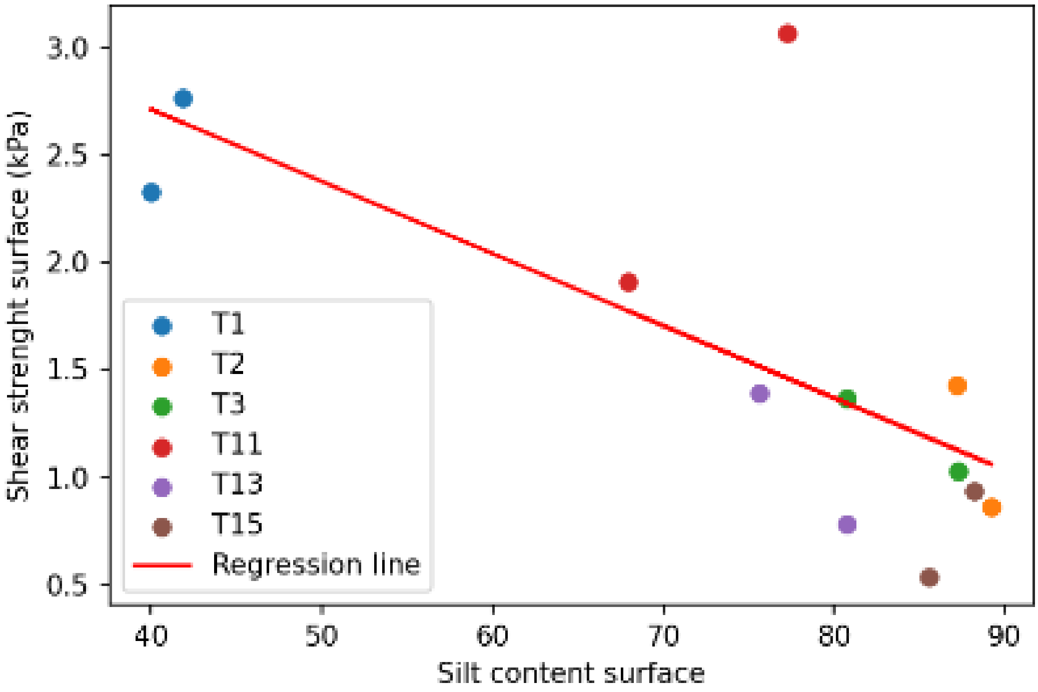
Figure 9 Multiple regressions for the effect of vegetation on soil stability in Perkpolder. Measurements were taken inside the tussocks.

Figure 10 shows the results of linear regressions of the main abiotic factors controlling soil stability. These are elevation and silt content. Boxplots are used to better visualise the dependent variable's variance inside and outside each Tussock. In Figures 10 a and 10b, surface shear strength is the dependent variable. A very strong positive relation was found between SSS and elevation (*r* = 0.94, *p*-value = 0.005). On the other hand, a significant relation was also found with the silt content, which appears to increase at lower soil strength (*r* = -0.70, *p*-value = 0.01). Figure 10c illustrates how surface shear strength is generally higher inside the Tussocks. This is especially true in Tussocks 11, 13 and 15, where the difference in the mean SSS inside and outside the Tussocks is more pronounced. Tussock 1 is the only location where the mean surface SS is higher outside the Tussock than inside. However, in Tussock 1, values of SSS inside the Tussock are largely variable.

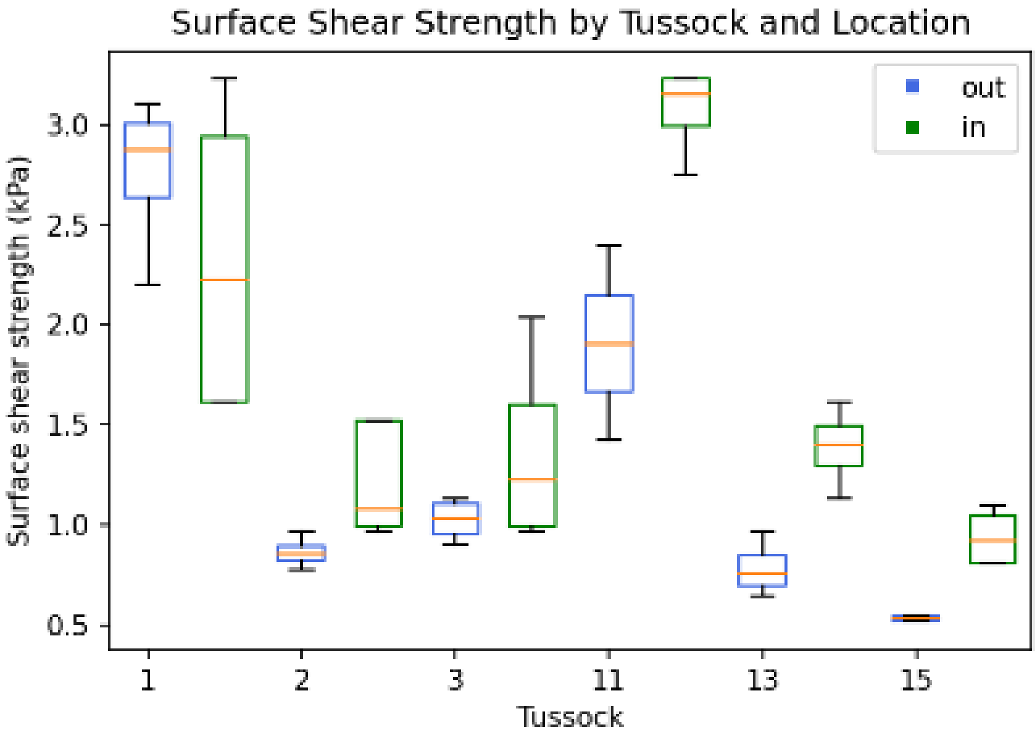
To examine the effect of abiotic factors on sub-soil, we show the results of penetration resistance at 10 cm depth used as the dependent variable for the linear regression analysis (Figure 10 d, e). Pearson's correlation coefficient between elevation and penetration resistance showed a significant positive relation between elevation and penetration resistance in the sub-soil (*r* = 0.84, *p*-value = 0.04). A stronger correlation was found between silt content and PR, implying that penetration resistance decreases with increasing silt content (*r* = -0.83, *p*-value = 0.001). The boxplots in Figure 10f show the difference in mean and variance of penetration resistance inside and outside the Tussocks at every location. Similarly as for the Tussock's 1 surface shear strength, results for Tussock 11 inside the Tussock were characterised by high variability, suggesting penetration resistance was highly affected by where the measurements were taken between the vegetation and roots inside the Tussock. Nevertheless, except for Tussock 1, penetration resistance shows less variability in the other Tussocks, and the mean PR is always higher inside the Tussock. To summarise, surface soil stability appears to be mainly impacted by elevation and silt content. Although, we can identify an apparent effect of increasing soil stability at locations where vegetation presence is higher, also supported by the mean difference of shear strength inside and outside the Tussocks. In addition, increasing silt content controls the penetration resistance in the first 10 cm when looking at the shallow subsoil. The vegetation seems to have an apparent effect on soil cohesiveness in the first 10 cm. At the same time, it is not certain to draw conclusions regarding soil stability development at greater depths based on the shear strength measurements collected at Perkpolder since the silt was so hard that the measurements were impossible to take with the instruments at many locations.



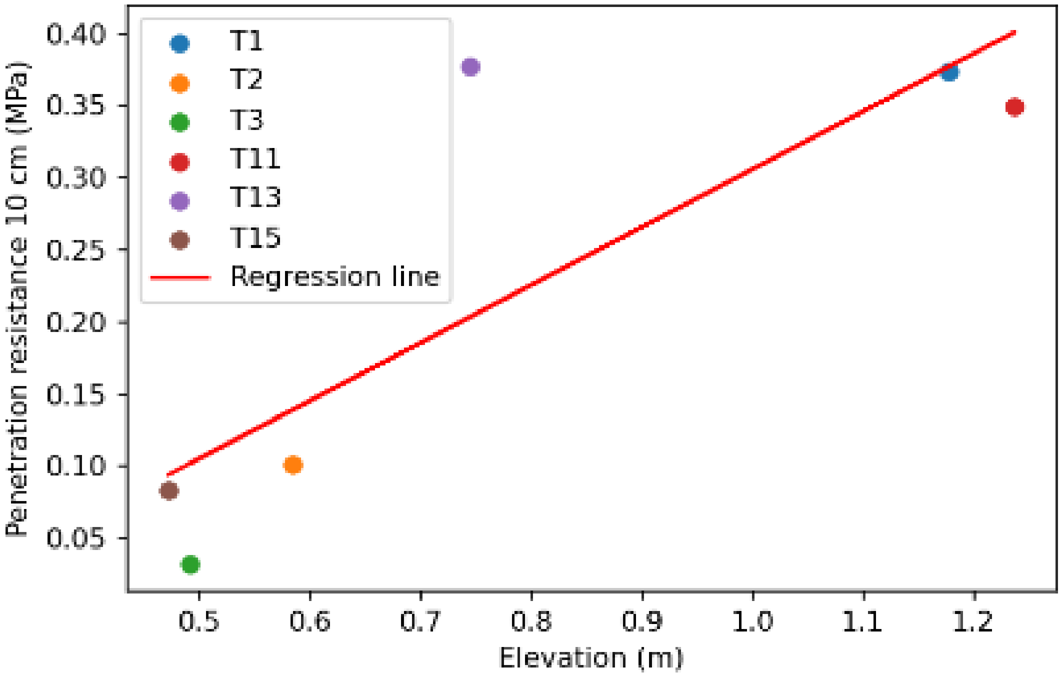
a)



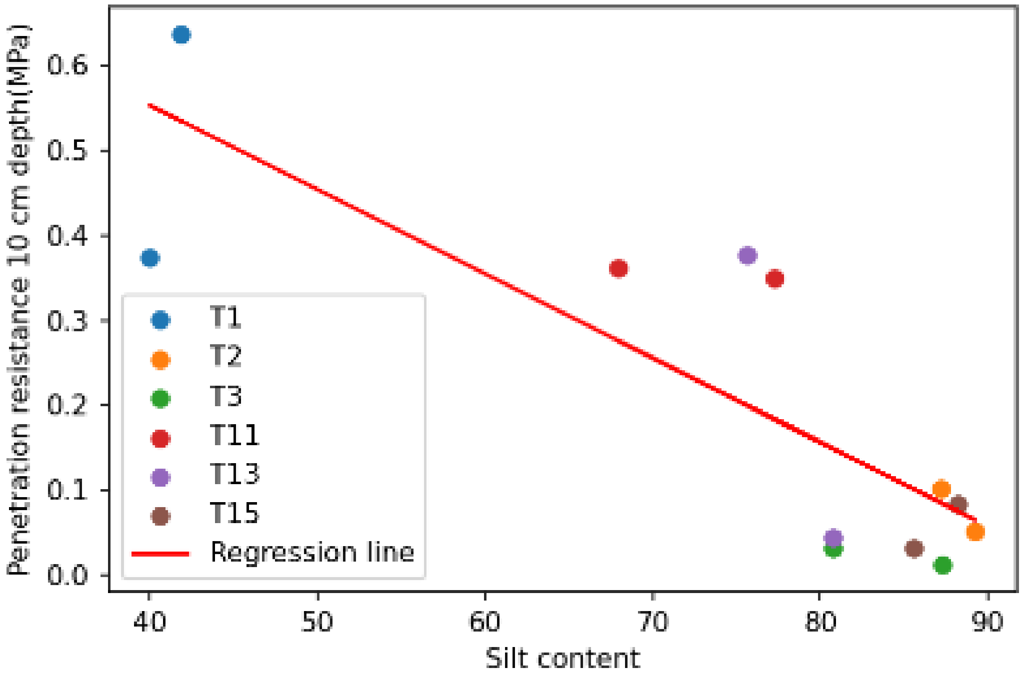
b)


Surface Shear Strength by Tussock and Location
Surface shear strength (kPa)
3.0
2.5
2.0
1.5
1.0
0.5
out
in
1
2
3
11
13
15
Tussock

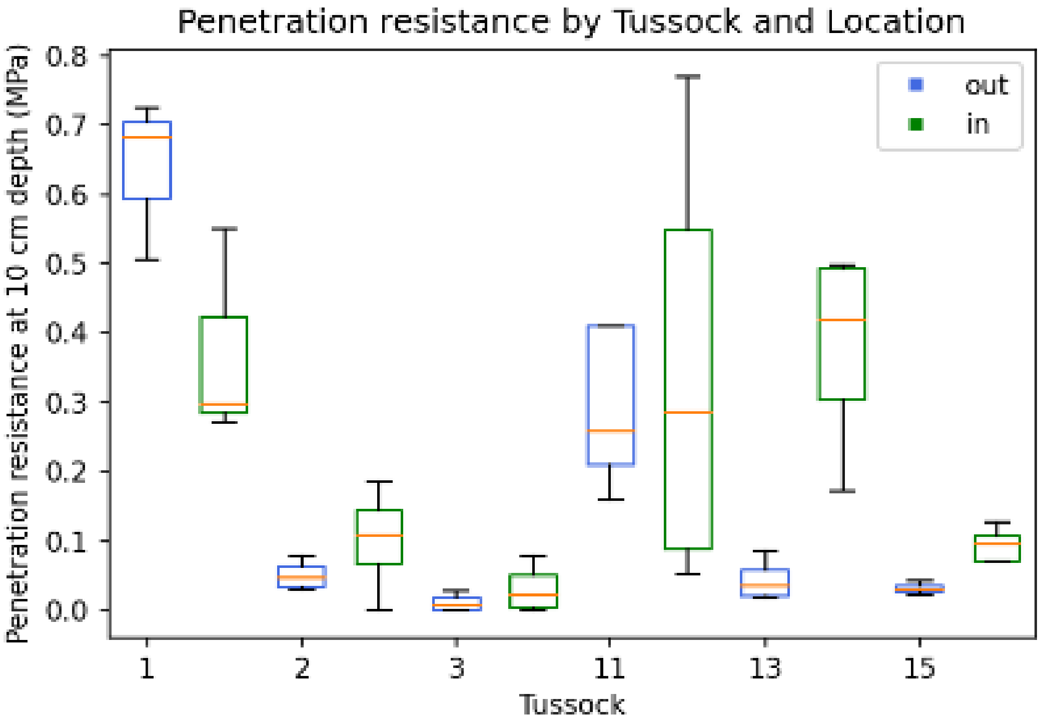
c)


Penetration resistance 10 cm (MPa)
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
T1
T2
T3
T11
T13
T15
Regression line
0.5
0.6
0.7
0.8
0.9
1.0
1.1
1.2
Elevation (m)

d)



e)



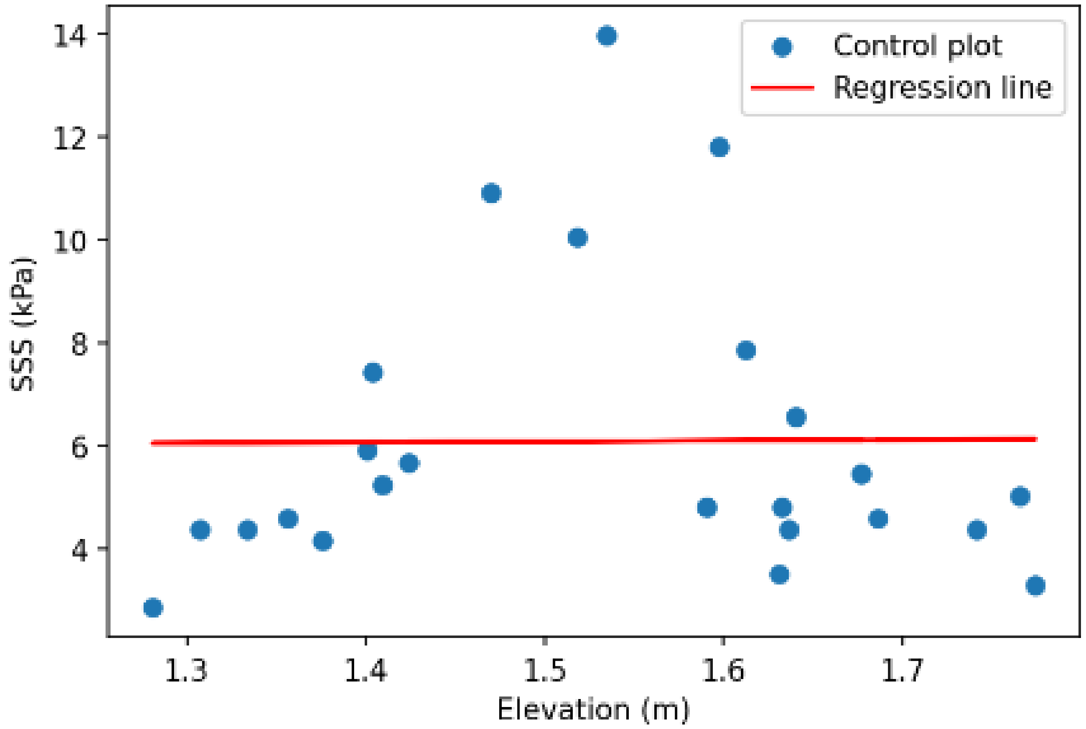
f)

Figure 10 Multiple regressions for Soil stability in Perkpolder(a,b,d,e) and boxplot of shear strength and penetration resistance outside and inside the tussocks (c,f). Elevation measurements show the average elevation at the tussock (a,e). Silt content measurements show two points per tussock (inside and outside)(b,d)

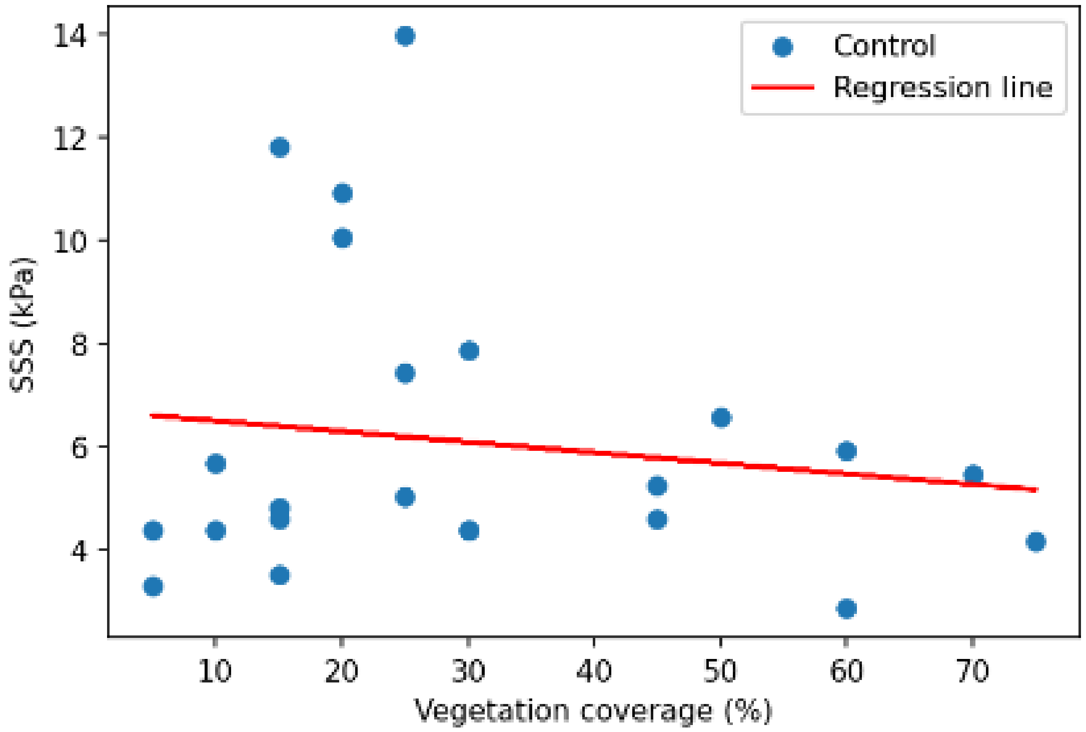
3.3.2 Marconi

In Figures 11a and 11b, the effects of elevation and vegetation on surface shear strength at Marconi are assessed. Linear regressions found that the relations were not strong or significant (*p*-value > 0.05). ANOVA was performed to test the effect of silt content on surface soil stability (Figure 11 c). The results demonstrated a significant difference in surface shear strength between the blocks at Marconi (*p* = 0.02). This was further supported by the Tukey HSD test, showing a significant difference between soil strength in the sandiest block (G) and F (20% silt) and between SSS in Blocks F and the siltiest block (E). No significant difference occurs between Blocks E and G, suggesting that at Marconi, sediment was more cohesive in Block F.

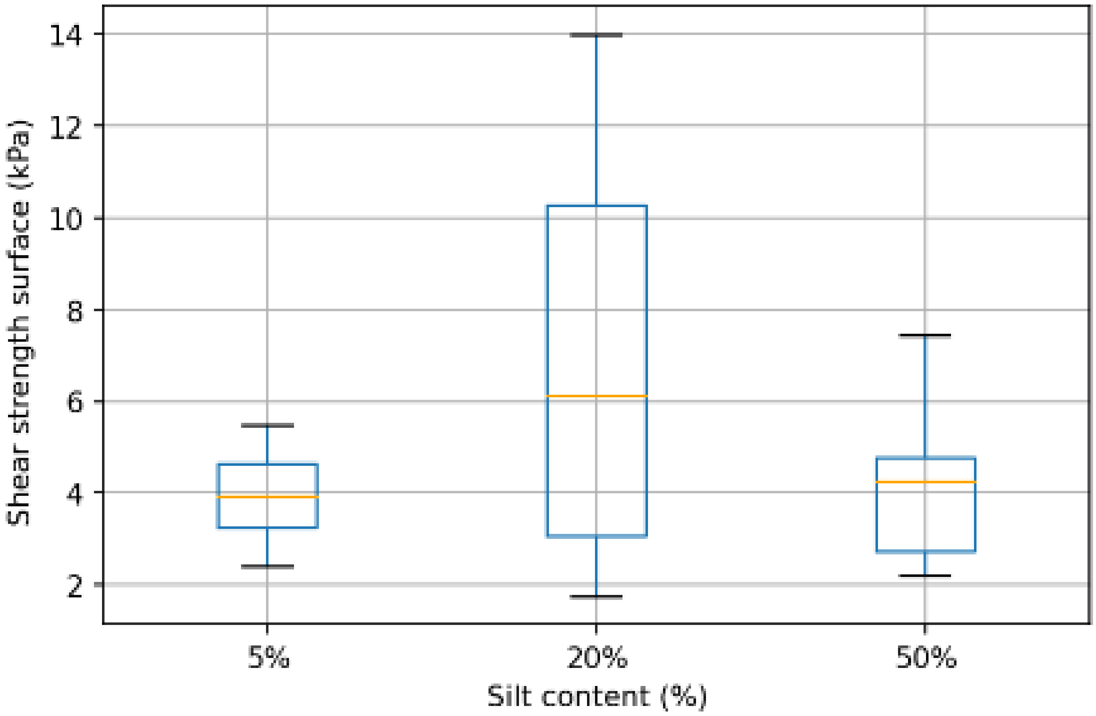
Finally, results of linear regressions with averaged SSD at 10-40 cm are presented in Figures 11 d, e and f. Similar to results for surface soil stability, elevation and vegetation coverage are not strongly related to the shear strength at depth (*p*-value > 0.05). Silt content was found to be the abiotic factor mainly controlling the development of sediment also for the sub-soil. ANOVA test confirmed the hypothesis that there is a difference in soil stability depending on silt percentage at Marconi (*p*-value = 0.03). This hypothesis was further confirmed using the Tukey HSD test to compare the means between groups. Differences were found to be significant only between Block G and F. Hence, deep soil stability seems significantly higher in locations with 20% silt content.



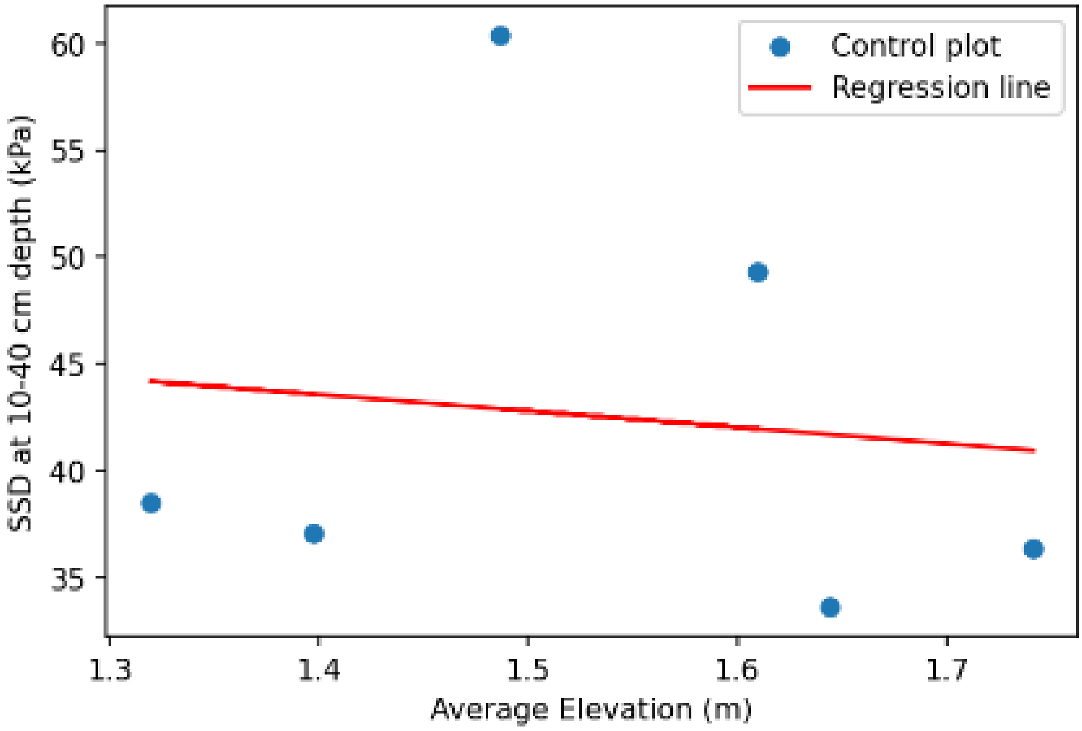
a)


14
12
10
8
6
4
SSS (kPa)
10
20
30
40
50
60
70
Vegetation coverage (%)
Control
Regression line

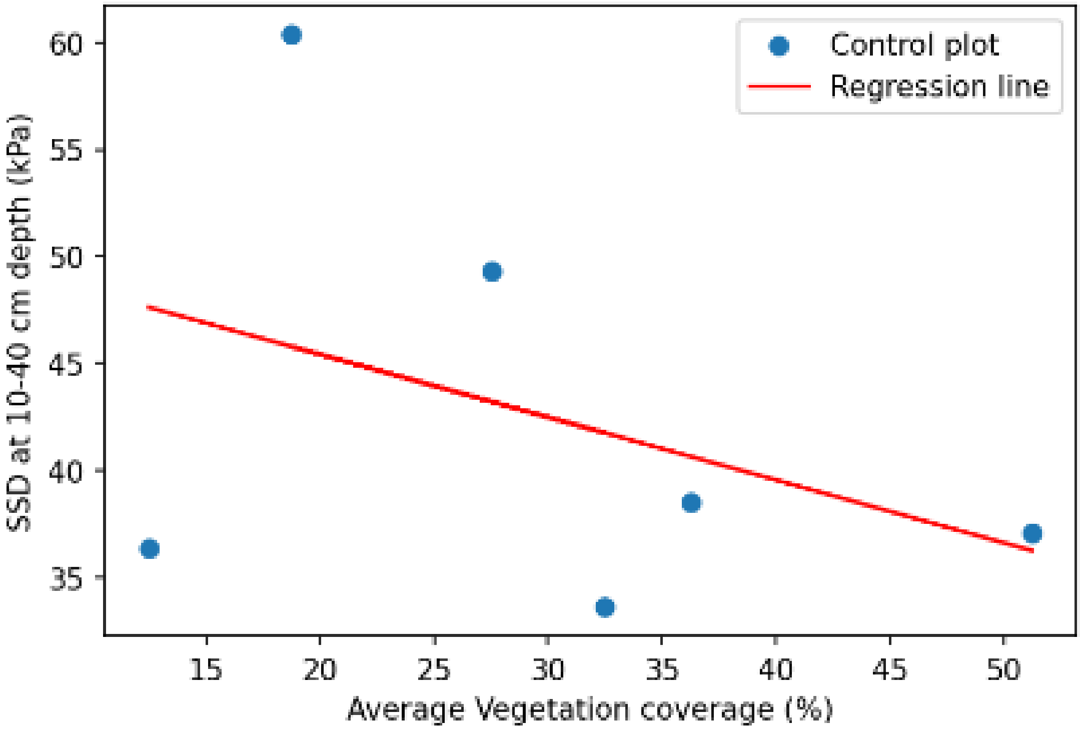
b)


14
12
10
8
6
4
2
Shear strength surface (kPa)
5%
20%
50%
Silt content (%)

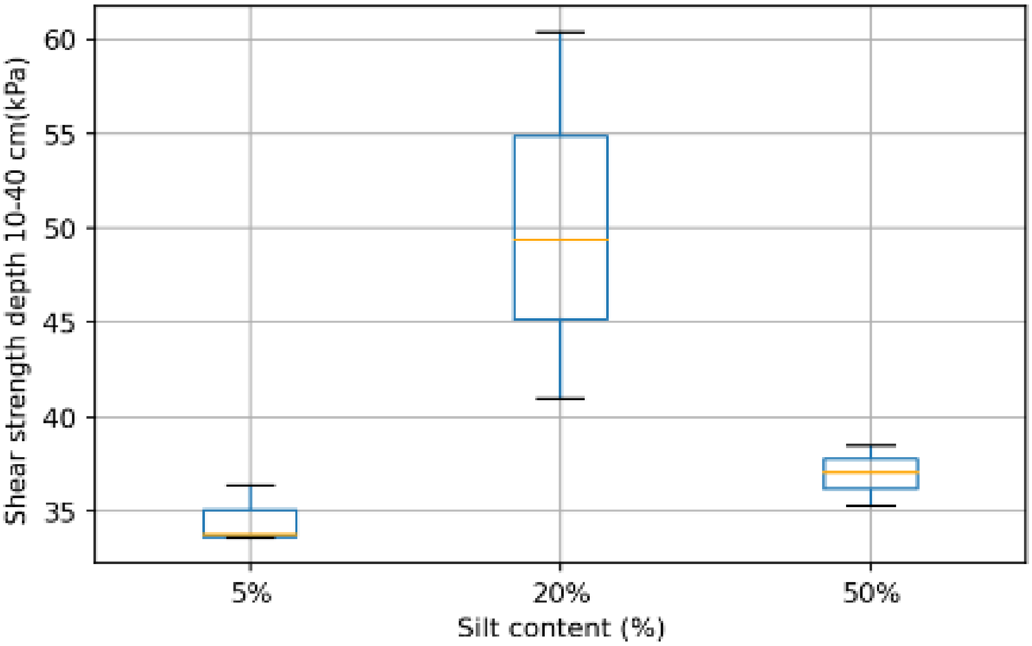
c)


60
55
50
45
40
35
SSD at 10-40 cm depth (kPa)
1.3
1.4
1.5
1.6
1.7
Average Elevation (m)
Control plot
Regression line

d)


60
55
50
45
40
35
SSD at 10-40 cm depth (kPa)
15
20
25
30
35
40
45
50
Average Vegetation coverage (%)
Control plot
Regression line

e)



f)

Figure 11 Multiple regressions for Soil stability in Marconi (a,b,d,e) and boxplots of shear strengths grouped by silt content (c,f)

3.4 Comparative analysis of Perkpolder and Marconi Restoration Projects: Elevation, Vegetation and Surface Shear Strength

To better understand how the elevation difference impacted the two sites, we compare our results with background information from previous studies and conclude the data elaboration. Perkpolder, located in the mid-part of the Scheldt Estuary, experiences the influence of marine and terrestrial sediments, predominantly mud type (Kuijper et al., 2004). Since the managed realignment was created, the whole tidal flat gets submerged by the salt water flow twice daily. According to Bakker (2014) and Brunetta et al. (2019), depending on the mean high water level, +2.53 m NAP was established as the conventional limit that defines the transition between tidal flats to salt marsh at Perkpolder. Based on previous literature, elevation measurements indicated that the highest elevations ranged from 0.8 to 1.10 m NAP in the northern areas of the inlet. Overall, the general bed level at Perkpolder showed a slight increase during the monitoring campaigns (Brunetta et al., 2019; De Paiva et al., 2019). The findings of this study until October 2022 indicated that elevation continued to stay stable at every location monitored (Figure 5d), with the most elevated sampling location (Tussock 11) slightly exceeding the elevation ranges calculated by Brunetta et al. (2019). Tussock 15 had the lowest elevation of 0.5 m, yet it remained consistent with the previous findings.

The second restoration project, the Marconi Project, was artificially created under different conditions than Perkpolder, with a less common method applied in Europe than managed realignment techniques. Marconi is located near the port of Delfzijl, in one of the major estuaries of the Wadden Sea. Initial conditions at Marconi were created by following previous findings of salt marsh construction projects (Bay Author et al., 2001; Haltiner et al., 1996; Shafer & Streever, 2000), as increasing the bed level and adding three different mixtures of mud and sand derived from the dredged material of the estuary. After defining 1.40 m +NAP as the optimal level of inundation for pioneer species, the bed level was set between 1.20 m and 1.70 m +NAP (Baptist et al., 2021). Based on our results, elevation at Marconi slightly decreased in every Block (Figure 6b). The bed level changes occurring uniformly in every compartment, especially towards the seaside (mid-blocks), might still result from sandbars migration starting in 2020 (EcoShape, 2021). Furthermore, measurements are in accord with the previous literature, hence Block G has the highest elevation of around 1,70 m +NAP, and Block E has the lowest, of 1.3 m +NAP. Because the local mean high water (MHW) level is at 1.4 m, only the seaward portions of the Blocks are flooded daily. Furthermore, during MHW, most water flows in and out from the seaward side of Block G, where its elevation is lower. In Block E, which has the lowest mean elevation, most water is stored during total submersion.

To conclude with the elaboration of data, Figure 12 shows the effect of silt content and the additional effect of vegetation on surface shear strength for both sites. The plotted points show the mean values of surface shear strength measured at every sampling location and the silt content percentage at the surface. The comparison illustrates that Marconi has generally lower silt content than Perkpolder. Consequently, we implemented the relation between the variables to show the different effects of vegetation presence and absence. Precisely, the degree of the effect of plants on soil stability is greater at Perkpolder, as illustrated by the yellow (no vegetation) and green (vegetation) lines. As both sites are plotted simultaneously, this result demonstrates a considerably larger variation between the sites than within each site. In contrast, the effect of vegetation is not strong. Moreover, a negative relation between shear strength and sediment composition is depicted at both sites, but this relation is significant only in the Perkpolder mudflat ($p < 0.05$). Overall, shear strength significantly decreases at higher silt contents and in sediments with vegetation ($p > 0.05$).

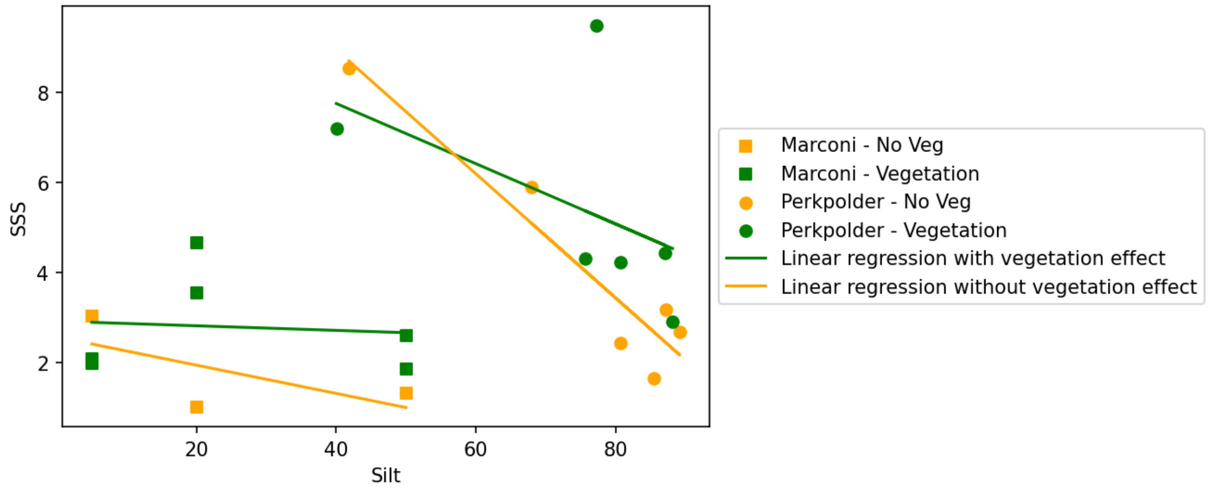


Figure 12 Linear regression between surface shear strength (SSS) and Silt content (significant at Perkpolder) and added effect of vegetation presence (green) or absence (yellow) (non-significant relation)

Discussion

To address the research questions posed in the study, I compared two different adaptive management methods. I examined the development of vegetation and soil stability at two different salt marshes in the Netherlands: Perkpolder (Zeeland) and the Marconi Project (Wadden Sea). Our results indicate that: (1) Whether Perkpolder and Marconi can be categorised as fully established salt marshes is uncertain based on the time series analyses conducted for this study. While both locations have shown considerable elevational stability through time, estimating the precise time needed for the marshes to develop and be classified as efficient is challenging. However, the vegetation has been growing, and we anticipate that this trend will continue in the future (2) higher elevation and presence of cohesive sediment, as hypothesised- increases vegetation development, both at Perkpolder and in Marconi; (3) shear strength and penetration resistance were higher in Perkpolder sediments with silt content ranging between 40% and 75% rather than higher percentages. Moreover, soil stability was higher in vegetated locations than in bare flats. Similarly, higher erosion resistance values were found at the Marconi site in sediments with intermediate silt percentages (20%) instead of higher percentages. (4) These results deepen our understanding of using such environments as potential Nature-based coastal defence by investigating the feedback effects between biotic and abiotic factors. By monitoring the progress and differences of newly built restoration projects, we can make more informed decisions regarding their implementation and maximise their effectiveness as coastal protection.

4.1 Vegetation Expansion and Marsh Stabilisation at the study sites

Building upon previous research, I focused on identifying the common key factors that define the transformation of a tidal flat into a (pioneer) salt marsh over time. Monitoring campaigns were designed for both sites, and updated literature describes the evolution of the inlet in detail for Perkpolder until 2017 (Brunetta et al., 2019; De Paiva et al., 2019) and for Marconi experiment until 2020 (Baptist et al., 2021; EcoShape, 2021). In Perkpolder, it was quantified that because of the overall low elevation characterising the inlet, it would take about eight years for conditions to be favourable to establish a salt marsh (Brunetta et al., 2019), which may explain why the majority of the tidal flat is still unvegetated. However, there is uncertainty about the precise number of years it will take to become fully established because of the asymptotic patterns typical of salt marshes' growth (D'Alpaos et al., 2011; Marani et al., 2010). In fact, accretion rates are expected to slow down and eventually reach the lower values of natural marshes (Brunetta et al., 2019). Although we cannot estimate the exact number of years the marsh will take to stabilise based on the time series analyses conducted for this study, we can say that vegetation has been expanding at every location monitored between 2018 and 2022, and we anticipate this trend to continue. This is supported by increasing aboveground biomass, average shoot height and diameter of every tussock. The initial conditions at Marconi, including sufficient bed elevation, specific mud-sand mixtures in the Blocks, and low hydrodynamics, provided favourable conditions for vegetation to establish and grow quickly compared to the initial conditions at Perkpolder, which relies on natural sedimentation. However, our time series analyses reveal that vegetation density at Marconi has not increased as fast as Perkpolder from 2021 to 2022, yet remained relatively stable in Blocks E and F and increased in Block G. The vegetation time series implemented in this study aligns consistently with the vegetation growth trends measured before 2021, as we found that the higher vegetation density was at the E Block (50% silt). Overall, the approach used at Marconi markedly reduces the time necessary to achieve the proper elevation for vegetation growth and can be considered one of the fastest ways to create salt marshes, as pioneer species developed in every compartment a year after construction (EcoShape, 2021).

4.2 Effect of elevation and mud-sand mixture on vegetation development

The vegetation density in October 2022 at both sites was primarily influenced by bed elevation and sediment characteristics, including grain size distribution and water content. In Perkpolder, the tussocks at higher bed levels (thus, with lower inundation time) showed a significant positive relationship between vegetation density and bulk density. Conversely, a negative relationship was observed between vegetation density and silt content. The hydrodynamics at Perkpolder follow natural processes, characterising the inlet by coarser sediment in the creeks and at finer particles on top flats (Friedrichs, 2011; Mai & Bartholomä, 2000). While the northernmost part of the streams experiences stronger flow and transports coarser (sand) sediment, the southern areas have fine suspended sediment due to a lower hydrodynamic regime. Our findings align with Cao et al. (2018), indicating that *Spartina* survives best in well-drained soil, specifically after a free-disturbance period from long inundations and high erosion rates. Tussock 1, situated at a high elevation and away from the creek, exhibited the highest mean vegetation density. These observations suggest that lower disturbance combined with higher elevations create favourable conditions for developing larger and denser tussocks, such as Tussocks 1 and 11. This is because usually higher locations have better-drained surfaces. The southwards areas are characterised by fine suspended sediment because of a lower hydrodynamic regime. Managed realignments are also characterised by generally low rates of soil compaction in the first years of development (de Paiva et al., 2019). This was observed in Perkpolder, where the bulk density at the surface is generally low, allowing roots to penetrate the sediment more easily. However, our results are supported by previous studies (Evans et al., 2022), demonstrating a strong association between aboveground biomass and bulk density. The higher bulk densities at higher vegetation densities might indicate the sediment compaction effect exercised by the roots.

At Marconi, the relation between vegetation cover and elevation was not found to be significant. However, different mud contents mixed within the bed significantly affected vegetation coverage. Unlike previous findings highlighting the relative elevation in the tidal frame and sufficient drainage as primary factors determining vegetation colonisation (Crooks et al., 2002), our results show that Block E has the highest vegetation cover at Marconi, although it lays at the lowest elevation. Nevertheless, the compartment has the highest mud content in its sediment composition. At the same time, Block G is the most seaward location and is characterised by 5% silt content, yet it has the highest elevation in the tidal flat and the lowest vegetation coverage. Hence, ANOVA and Tukey HSD revealed a significant difference in vegetation percentages based on silt content, and results showed that the highest vegetation coverage was found at 50% silt content. In contrast, the weak relation between surface elevation and vegetation density indicates that the site already had a sufficient elevation for salt marsh vegetation to develop (Baptiste et al., 2021). However, while vegetation remained relatively stable in Blocks E and F, the increment of vegetation in Block G from 2021 to 2021 could be attributed to a direct effect of its high elevation.

4.2 Effect of elevation, mud-sand mixtures and vegetation presence on soil stability

In this study, we integrated the results from shear strength, penetration resistance and mud-sand content measurements to understand which factors mainly influence the cohesion of sediments at Perkpolder and Marconi and the relation with resistance to erosion. In previous literature, soils rich in silts and clay have been correlated with higher erosion resistance because soils with low mud content, like sand, are considered non-cohesive, hence have a low resistance to wave erosion (Feagin et al., 2009; Ford et al., 2016; Wang et al., 2017). Contrary to previous findings, in this study, the relation between soil stability and silt content was significantly negative in Perkpolder. Moreover, we found a negative relation between aboveground biomass and water content in the sediment. Our findings are explained by surface shear strength and penetration resistance used as indirect measurements that assess soil stability and erodibility. The negative correlation can be attributed to the weakening effect of high water content on sediment cohesiveness when silt concentrations are particularly high in Perkpolder, being a weakly consolidated silt-dominated tidal flat. The high silt content in the muddy salt marsh causes vertical drainage to be strongly restricted because capillary forces increase with decreasing pore sizes, leading to more inter-particle attraction (Cao et al., 2021; Winterwerp et al., 2012). However, these forces are insufficient to overcome the silt particles' tendency to slide past one another when subjected to a strong force, leading to weaker bonding and resulting in lower shear strength and penetration resistance values (Grabowski et al., 2011; Van Ledden et al., 2004). In addition, results at the managed realignment also showed a positive relation between elevation and erosion to resistance. In the tussocks, higher elevations lead to less inundation, which may indicate better-drained and consolidated soils and, thus, higher shear strengths.

Furthermore, based on the findings at Marconi, the results of pairwise comparisons for silt content showed significant differences in shear strength between 20%-50% silt blocks and between 20%-5% silt block, highlighting how shear strength was highest in intermediate block. Similarly to what happened in Perkpolder, at Marconi, the sediment was not found to be more cohesive at the high silt percentages. In this case, these results are a consequence of the fact that the most silty and most sandy blocks are the most frequently inundated. Thus, the high water content in the sediment affected the measurements at Block E (50% silt), as soils with higher mud contents also absorb more water and have higher moister contents, resulting in less cohesive sediment (Flemming et al., 2000; Grabowski et al., 2011). Moreover, we already expected to find lower shear strength measurements typical of non-cohesive sediment in the sandy location (block G). Although we did not measure sedimentation and erosion rates, the results of shear strength measurements taken for this study remain coherent with previous findings (Baptist et al., 2019), showing that a mud content of over 20% results in cohesive sediment and is expected to reduce erosion 6 to 8 times more than sandy sediment (Houwing, 2000). By comparing the sites, a clear distinction can be made based on the composition and, therefore, on the different erodibility of the sediments. The sediment's shear strength and penetration resistance varied between and, with a weaker effect, within the sites based on the mud-sand content. At both sites, however, the negative relation between soil stability and silt content can be associated with the high soil moisture levels in the sediment, which was mainly retained at locations with higher silt percentages due to its highly absorbent characteristics. Additionally, combining methods to quantify the sediment's stability, including the cohesiveness (compaction) and penetration resistance, is a better indicator of sediment erodibility than shear strength alone (Evans et al., 2022).

Furthermore, based on our findings, vegetation's effect on soil stability and erosion resistance was weak. The linear effect of vegetation density on shear strength and penetration resistance was insignificant at the sites. However, erosion resistance in Perkpolder was found to be higher inside the tussocks than outside at every location except Tussock 1 (silt content < 45%), as shown in the boxplots. These findings align with previous studies, as sediments with *Spartina* showed higher shear strength and penetration resistance, while bare sediments exhibited lower values (De Battisti et al., 2019; Evans et al., 2022; Lo et al., 2017; Marin-Diaz et al., 2022; Wang et al., 2017). Although the common findings are that the combination of vegetation and sediment characteristics control and positively affect factors that are related to increasing stability and decreasing erodibility (like SS and PR) (Bernik et al., 2018; Chen et al., 2019; Watts et al., 2003), there is still no generic way to relate specific geotechnical properties and erodibility easily (Evans et al., 2022). For example, sandier sediments at Marconi (20% silt), so usually poorly cohesive sediments, produced similar or higher shear strengths than locations with higher silt content at Perkpolder. On the other hand, higher vegetation densities were only sometimes found in sediments with lower erosion resistance. This is again true for Tussock 1, which has the highest aboveground biomass in Perkpolder and is established at the sandier location. Furthermore, at Marconi, *Spartina* only survived in block G, the compartment with the higher sand component. Although the presence of *Spartina* in the sandier location would align with previous research (Lo et al., 2017; Feagin et al., 2009; De Battisti et al., 2019), indicating that the roots of the pioneer vegetation penetrated better into less cohesive sediment, our findings are not sufficient to assess whether the vegetation might have had a stronger effect on erosion resistance than in siltier locations.

4.3 Limitations of the study & Relevance to practice

Limitations of this study should be considered to gain a comprehensive understanding of the findings and pave the way for further investigations. We addressed the objective of studying two adaptive management strategies to compare the marsh developments using the same methodology. This study compared a managed realignment site and a created salt marsh. However, one significant limitation is that only one marsh per method was studied. Including additional study sites would improve the generalizability of the findings and facilitate more accurate conclusions that could be applied to these two restoration techniques. For instance, van den Hoven et al. (2020) categorised 90 European realigned dikes projects to determine which opportunities for coastal protection they can offer, showing that MR can generally provide effective flood protection when accidental breaches occur in multiple dike systems.

On the other hand, the methodology used in Marconi Project is less widely spread in Europe. However, studies like the one by Baptiste et al. (2018) showed how creating a Mud Motor could be an innovative and beneficial way to enhance salt marsh development by re-using dredged material. Hence, future studies comparing similar techniques could also help promote their use in Europe after assessing their success. Another area for improvement lies in the measurement methods employed in the study. Field measurements can vary from person to person, leading to potential inconsistencies in data collection. This variability could introduce bias and affect the reliability and comparability of the results. However, this research set-up included repeating four replicas at every sampling location to minimise the high variability risk. Therefore, future monitoring studies at these sites should standardise measurement protocols and ensure consistent data collection across different observers to enhance the reliability and validity of the findings. Finally, the results obtained for this research are based on a relatively short time series. Despite this limitation, examining time series data has provided valuable insights into the changing vegetation dynamics within the study sites. However, it would be highly beneficial to have a longer time series to obtain a more in-depth understanding of the long-term dynamics of the salt marshes. An extended time series would provide valuable information on the stability and resilience of these ecosystems over time and improve our ability to make informed decisions regarding their creation and management.

The results of this study support the idea of creating managed realignments projects and salt marshes using dredged material in combination with hard engineering structures. This study contributes to our understanding of how pioneer species spread, based on the rapidity at which they are expanding, and suggests using such environments for coastal protection. Our results demonstrate that raising the elevation in created marshes above the local Mean High Water level can lead to rapid growth and expansion of pioneer species. On the other hand, in managed realignments projects, it might take more time for elevation to increase due to the natural processes that influence sedimentation. Similarly, based on previous findings, mixing specific quantities of sand and mud can help stabilise sediments and promote vegetation development in these areas.

Conclusions

This study examines the factors impacting vegetation growth and soil stability at two different sites using adaptive management strategies. One is a managed realignment, while the other is a created salt marsh. Through field measurements and data analysis, it was observed that both salt marshes are developing over time, and significant observations were made.

Elevation and sediment characteristics determined the vegetation settling and expansion. In Perkpolder, since the dike was breached, sedimentation is occurring naturally, and overall elevation has only slightly increased, while aboveground biomass showed steady growth throughout the years. On the other hand, the salt marsh at the Marconi project in Delfzijl was created by immediately increasing elevation above the local mean high water level. Vegetation at this location is expanding faster, mainly due to specific mud-sand mixtures.

While time series analysis cannot determine how long is needed for both salt marshes to transition entirely from a tidal flat into a stable salt marsh, the main factors affecting vegetation and soil stability emerged. (1) Sufficient elevation, which shortens flooding times, and sediments rich in silts and poor in moister concentrations, which affect the cohesiveness, allowed the vegetation expansion. (2) Higher elevations mostly have better surface drainage, which helps the soil become more solid and stable. Additionally, siltier sediments also generally raise soil stability and strength. However, this differs for locations with extremely high mud concentrations because silt characteristics hamper surface drainage and keep the sediment too wet.

Finally, it was shown that there was a greater difference between the sites, rather than within, regarding the impact of mud-sand mixtures and vegetation on soil stability. In general, this difference in soil stability may be due to the geological difference between sediments from the hinterland of the Scheldt and the Ems estuaries and the fact that one site was artificially deposited. Also elevations, hence inundation times, are different. Implementing a longer time series in future research would be of great value for a clearer understanding of the long-term dynamics of these salt marshes.

The results of this study strongly suggest that when implementing restoration projects, increasing elevation using dredged material, especially above the local mean high water level, may accelerate the development of salt marshes by years. This can be beneficial to know if we want to implement the creation of such ecosystems for coastal protection.

Reference

Adam, Paul. (2002). “Saltmarshes in a Time of Change.” *Environmental Conservation* 29(1): 39–61.

Bakker, J. P. (2014). *Ecology of salt marshes: 40 years of research in the Wadden Sea*. Waddenacademie.

Baptist, M J et al. (2019). *A Large-Scale Field Experiment on Salt Marsh Construction in the Ems Estuary, the Netherlands*.

Baptist, M. J., Gerkema, T., Van Prooijen, B. C., Van Maren, D. S., Van Regteren, M., Schulz, K., ... & van Puijenbroek, M. E. B. (2019). Beneficial use of dredged sediment to enhance salt marsh development by applying a ‘Mud Motor’. *Ecological Engineering*, *127*, 312-323.

Baptist, Martin J. et al. (2021). “Salt Marsh Construction as a Nature-Based Solution in an Estuarine Social-Ecological System.” *Nature-Based Solutions* 1: 100005.

Barbier, Edward B et al. (2011). “The Value of Estuarine and Coastal Ecosystem Services.” *Ecological Monographs* 81(2): 169–93. https://esajournals.onlinelibrary.wiley.com/doi/10.1890/10-1510.1 (February 27, 2023).

De Battisti, Davide et al.(2019). “Intraspecific Root Trait Variability Along Environmental Gradients Affects Salt Marsh Resistance to Lateral Erosion.” *Frontiers in Ecology and Evolution* 7.

Bay Author, Chesapeake et al. (2001). Source: Journal of Coastal Research *Tidal Wetland Restoration: Physical and Ecological Processes*. https://about.jstor.org/terms.

Bernik, Brittany M., John H. Pardue, and Michael J. Blum. (2018). “Soil Erodibility Differs According to Heritable Trait Variation and Nutrient-Induced Plasticity in the Salt Marsh Engineer Spartina alterniflora.” *Marine Ecology Progress Series* 601: 1–14.

Billah, Masum et al. (2022). “Salt Marsh Restoration: An Overview of Techniques and Success Indicators.” *Environmental Science and Pollution Research* 1: 3. https://doi.org/10.1007/s11356-021-18305-5 (April 3, 2023).

Bouma, T. J. et al. (2016). “Short-Term Mudflat Dynamics Drive Long-Term Cyclic Salt Marsh Dynamics.” *Limnology and Oceanography* 61(6): 2261–75.

Bouma, Tjeerd J. et al. (2014). “Identifying Knowledge Gaps Hampering Application of Intertidal Habitats in Coastal Protection: Opportunities & Steps to Take.” *Coastal Engineering* 87: 147–57.

Box, P O, and Z G Giesbeek. (2012). *4.10 Pocket Vane Tester Operating Instructions Description*. www.eijkelkamp.com.

Box, P O, and Z G Giesbeek (2009). *Field inspection vane tester all it takes for environmental research* www.eijkelkamp.com.

Brooks, Helen et al. (2020). “Resistance of Salt Marsh Substrates to Near-Instantaneous Hydrodynamic Forcing.” *Earth Surface Processes and Landforms* 46(1): 67–88.

Brückner, Muriel Z.M. et al. (2019). “Salt Marsh Establishment and Eco-Engineering Effects in Dynamic Estuaries Determined by Species Growth and Mortality.” *Journal of Geophysical Research: Earth Surface* 124(12): 2962–86.

Brunetta, Riccardo, João Salvador de Paiva, and Paolo Ciavola. (2019). “Morphological Evolution of an Intertidal Area Following a Set-Back Scheme: A Case Study From the Perkpolder Basin (Netherlands).” *Frontiers in Earth Science* 7.

Cao, Haobing et al. (2018). “Effects of Sediment Disturbance Regimes on Spartina Seedling Establishment: Implications for Salt Marsh Creation and Restoration.” *Limnology and Oceanography* 63(2): 647–59.

Cao, H., Zhu, Z., van Belzen, J., Gourgue, O., van de Koppel, J., Temmerman, O. S., & Bouma, T. J. (2021). Salt marsh
Establishment in poorly consolidated muddy systems: effects of surface drainage, elevation, and plant
age. *Ecosphere, 12*(9), e03755.

Chen, Y., Charlotte Thompson, & Michael Collins. (2019). “Controls on Creek Margin Stability by the Root Systems of Saltmarsh Vegetation, Beaulieu Estuary, Southern England.” *Anthropocene Coasts* 2(1): 21–38.

Coleman, Daniel J. et al. (2022). “Reconciling Models and Measurements of Marsh Vulnerability to Sea Level Rise.” *Limnology And Oceanography Letters* 7(2): 140–49.

Crooks, Stephen et al. (2002). “Drainage and Elevation as Factors in the Restoration of Salt Marsh in Britain.” *Restoration Ecology* 10(3): 591–602. https://onlinelibrary.wiley.com/doi/10.1046/j.1526-100X.2002.t01-1-02036.x (January 29, 2023).

D’Alpaos, A., S. M. Mudd, and L. Carniello. (2011). “Dynamic Response of Marshes to Perturbations in Suspended Sediment Concentrations and Rates of Relative Sea Level Rise.” *Journal of Geophysical Research: Earth Surface* 116(4).

EcoShape (2021) *Salt Marsh Pilot Marconi Monitoring Results*. www.ecoshape.nl.

Evans, B. R. et al. (2022). “Vegetation Interactions with Geotechnical Properties and Erodibility of Salt Marsh Sediments.” *Estuarine, Coastal and Shelf Science* 265.

Fagherazzi, S., Kirwan, M. L., Mudd, S. M., Guntenspergen, G. R., Temmerman, S., D'Alpaos, A., ... & Clough, J. (2012). Numerical models of salt marsh evolution: Ecological, geomorphic, and climatic factors. *Reviews of Geophysics, 50*(1).

Feagin R. A. et al. (2009). 106 *Does Vegetation Prevent Wave Erosion of Salt Marsh Edges?*

Feagin, Rusty A. et al. (2015). “Going with the Flow or against the Grain? The Promise of Vegetation for Protecting Beaches, Dunes, and Barrier Islands from Erosion.” *Frontiers in Ecology and the Environment* 13(4): 203–10.

Flemming, B W, and M T Delafontaine. (2000). 20 Continental Shelf Research *Mass Physical Properties of Muddy Intertidal Sediments: Some Applications, Misapplications and Non-Applications*.

Friedrichs, C. T. (2011). “Tidal flat morphodynamics,” in Treatise on Estuarine and Coastal Science, eds E. Wolanski and D. McLusky (Waltham: Academic Press),137–170. doi: 10.1016/b978-0-12-374711-2.00307-7

Ford, Hilary et al. (2016). “Soil Stabilization Linked to Plant Diversity and Environmental Context in Coastal Wetlands.” *Journal of Vegetation Science* 27(2): 259–68.

Grabowski, Robert C., Ian G. Droppo, and Geraldene Wharton. (2011). “Erodibility of Cohesive Sediment: The Importance of Sediment Properties.” *Earth-Science Reviews* 105(3–4): 101–20.

Groot, A. V, and W. E. Duin. (2013). *Best Practices for Creating New Salt Marshes in an Estuarine Setting, a Literature Study*. www.imares.wur.nl.

Haltiner, J., Zedler, J. B., Boyer, K. E., Williams, G. D., & Callaway, J. C. (1996). Influence of physical processes on the design, functioning and evolution of restored tidal wetlands in California (USA). *Wetlands ecology and management*, *4*, 73-91.

Hu, K., Chen, Q., & Wang, H. (2015). A numerical study of vegetation impact on reducing storm surge by wetlands in a semi-enclosed estuary. *Coastal Engineering*, *95*, 66-76.

van den Hoven, K., Kroeze, C., & van Loon-Steensma, J. M. (2022). Characteristics of realigned dikes in coastal Europe: Overview and opportunities for nature-based flood protection. *Ocean & Coastal Management*, *222*, 106116.

Kuijper, C et al. 2004. *Morphological Modelling of the Western Scheldt. Morphological Modelling of the Western Scheldt*.

Van Ledden, M., W. G.M. Van Kesteren, and J. C. Winterwerp. 2004. “A Conceptual Framework for the Erosion Behaviour of Sand-Mud Mixtures.” *Continental Shelf Research* 24(1): 1–11.

Leonardi, Nicoletta, Neil K. Ganju, and Sergio Fagherazzi. 2016. “A Linear Relationship between Wave Power and Erosion Determines Salt-Marsh Resilience to Violent Storms and Hurricanes.” *Proceedings of the National Academy of Sciences of the United States of America* 113(1): 64–68.

Lo, V. B. et al. (2017). “Interactive Effects of Vegetation and Sediment Properties on Erosion of Salt Marshes in the Northern Adriatic Sea.” *Marine Environmental Research* 131: pp. 32–42.

M van Zelst, Vincent T et al. “Cutting the Costs of Coastal Protection by Integrating Vegetation in Flood Defences.” https://doi.org/10.1038/s41467-021-26887-4 (February 20, 2023).

Mai, S., and Bartholomä, A. (2000). “The missing mud flats of the Wadden Sea: are the construction of sediments and accommodation space lost in the wake of land reclamation,” in Muddy Coast Dynamics and Resource Management, Vol. 2, eds B. W. Flemming, M. T. Delafontaine, and G. Liebezeit (Amsterdam: Elsevier),257–272. doi: 10.1016/s1568-2692(00)80021-2

Marani, Marco et al. 2010. “The Importance of Being Coupled: Stable States and Catastrophic Shifts in Tidal Biomorphodynamics.” *Journal of Geophysical Research: Earth Surface* 115(4).

Marin-Diaz, Beatriz et al. 2022. “The Importance of Marshes Providing Soil Stabilization to Resist Fast-Flow Erosion in Case of a Dike Breach.” *Ecological Applications* 32(6).

Royal Eijkelkamp. (2017). *Meet the Difference User Manual Brand Data*.

Salvador De Paiva, Joao N et al. 2019. “PERKPOLDER TIDAL RESTORATION FINAL REPORT CENTRE OF EXPERTISE DELTA TECHNOLOGY.”

Schoutens, Ken et al. 2019. “How Effective Are Tidal Marshes as Nature-Based Shoreline Protection Throughout Seasons?” *Limnology and Oceanography* 64(4): 1750–62.

Shafer, D J, and W J Streever. 2000. 8 Wetlands Ecology and Management *A Comparison of 28 Natural and Dredged Material Salt Marshes in Texas with an Emphasis on Geomorphological Variables*. www.swg.usace.army.mil/hgnc/.

Temmerman, Stijn et al. 2013. "Ecosystem-Based Coastal Defence in the Face of Global Change." *Nature* 504(7478): 79–83.

Temmerman, S., Horstman, E. M., Krauss, K. W., Mullarney, J. C., Pelckmans, I., & Schoutens, K. (2023). Marshes and mangroves as nature-based coastal storm buffers. *Annual Review of Marine Science*, *15*, 95-118.

Temmerman, Stijn, Mindert B. De Vries, and Tjeerd J. Bouma. 2012. "Coastal Marsh Die-off and Reduced Attenuation of Coastal Floods: A Model Analysis." *Global and Planetary Change* 92–93: 267–74

Wang, Heng et al. 2017a. "Zooming in and out: Scale Dependence of Extrinsic and Intrinsic Factors Affecting Salt Marsh Erosion." *Journal of Geophysical Research: Earth Surface* 122(7): 1455–70.

Watts, C. W., T. J., T., K. S. Black, & A. P. Whitmore. (2003). "In Situ Measurements of Erosion Shear Stress and Geotechnical Shear Strength of the Intertidal Sediments of the Experimental Managed Realignment Scheme at Tollesbury, Essex, UK." *Estuarine, Coastal and Shelf Science* 58(3): 611–20.

Willemsen, Pim W.J.M. et al. 2022. "Facilitating Salt Marsh Restoration: The Importance of Event-Based Bed Level Dynamics and Seasonal Trends in Bed Level Change." *Frontiers in Marine Science* 8.

Winterwerp, J. C., W. G.M. van Kesteren, B. van Prooijen, and W. Jacobs. 2012. "A Conceptual Framework for Shear Flow–Induced Erosion of Soft Cohesive Sediment Beds." *Journal of Geophysical Research: Oceans* 117: 1–17.

Winterwerp, J. C., Zhou, Z., Battista, G., Van Kessel, T., Jagers, H. R. A., Van Maren, D. S., & Van Der Wegen, M. (2018). Efficient consolidation model for morphodynamic simulations in low-SPM environments. *Journal of Hydraulic Engineering, 144*(8), 04018055.

Wolters, Mineke, Angus Garbutt, and Jan P. Bakker. 2005. "Salt-Marsh Restoration: Evaluating the Success of de-Embankments in North-West Europe." *Biological Conservation* 123(2): 249–68.

Zhu, Zhenchang et al. (2020). "Historic Storms and the Hidden Value of Coastal Wetlands for Nature-Based Flood Defence." *Nature Sustainability* 3(10): 853–62.