The effects of increased coastal dynamics on the vegetation distribution and diversity of the Boschplaat, Terschelling

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Abstract

Salt marshes are vital ecosystems that provide numerous essential services and harbour biodiversity from many taxa. Yet, they are rapidly disappearing worldwide and experiencing significant declines in quality. This decline in quality stems from reduced natural dynamics, often resulting from human activities such as dike construction, which leads to succession towards older stages. A possible solution could be to reintroduce coastal dynamics, which will be implemented at the Boschplaat on Terschelling.

Research aim: Explore past changes in vegetation community distribution and diversity on the Boschplaat, along with their underlying drivers, to gain insights into the potential future effects of increased coastal dynamics on the Boschplaat.

Location: Salt marsh the Boschplaat, located on the island tail of Terschelling situated in the Dutch Wadden Sea.

Methods: Two main analyses were conducted: 1) spatial GIS analyses of vegetation changes over the past two decades (1999–2018), and 2) field assessment of associations between community distribution and environmental drivers (salinity, silt depth, elevation, organic matter).

Results: Many of the vegetation types harbouring late successional communities, such as high and low marsh, remained stable. Other late successional types, such as brackish marsh, showed an increase. Within the high marsh, most communities rapidly changed into the climax community *Elymus athericus*. Especially around the creeks, dunes, and behind the dike, an increase in late successional vegetation took place. Furthermore, all environmental variables were strongly associated with community composition, with salinity being the most pronounced driver. Lastly, higher salinity and lower organic matter were associated with early successional vegetation.

Conclusions: These results indicate ongoing succession, progressing toward late successional stages without yet reaching complete climax. Decreased salinity and increased organic matter drive late successional growth, suggesting a lack of inundation and sand drift in many areas. Salinity, and thus inundation, in particular, turns out to be essential in returning early successional vegetation. These patterns suggest that increased coastal dynamics could likely promote rejuvenation by restoring the key variables necessary for early successional communities. Restoration will create a mosaic of young and old vegetation and enhance overall vegetation distribution and diversity. Therefore, bringing back coastal dynamics is expected to be necessary for the recovery of salt marshes.

Keywords: Salt marsh, Vegetation succession, Increased coastal dynamics, Spatial analysis, Boschplaat Terschelling.

Contents

Introduction

1.1 Loss of salt marsh quality

Salt marshes are vital coastal ecosystems that provide critical environmental services, yet they are facing multiple threats and are therefore rapidly disappearing. Approximately 71,900 hectares of marshland have disappeared globally between 2000 and 2019, with an average annual decline of 0.28% (Campbell et al., 2022). In mainland Europe, about 35,700 hectares of salt marsh remain (Mcowen et al., 2017), with a significant portion of 9,852 hectares located adjacent to the Dutch Wadden Sea (Jentink, 2018). Protecting these areas is crucial for maintaining ecosystem services and safeguarding biodiversity across various taxa (Teixeira et al., 2014). The importance of salt marsh preservation is further underscored by the inclusion of multiple salt marsh plant communities in the European Habitats Directive, which obliges Europe to protect these ecosystems (European Union, 1997). Due to this decline, efforts have been made to gain a deeper understanding of the salt marsh ecosystem, with a specific focus on the conservation of beneficial ecosystem services, such as carbon sequestration (Campbell et al., 2022), habitat provision (Carrasco, 2019), and flood protection (Temmerman et al., 2013). Additionally, attention has been given to current threats like coastal squeeze, driven by increasing human settlement and rising sea levels (Torio & Chmura, 2013). While these major threats are expected to further reduce the extent of salt marshes (Valiela et al., 2018), an additional, less studied, and less visible problem is also emerging: the decline in salt marsh quality.

Within this study, a high-quality salt marsh is defined as having high vegetation diversity and an even distribution of vegetation communities, resulting from a mosaic of different successional stages. The loss of quality has been attributed to reduced coastal dynamics, often caused by human activities such as dike construction (Esselink et al., 2009; de Groot et al., 2017). Naturally, wind and inundation periodically erode older vegetation forms, creating opportunities for pioneer stages to develop, causing differences in age and succession stages across the marsh (Esselink et al., 2009; de Groot et al., 2017). Without these dynamics, salt marshes progress toward their final succession stages (Esselink et al., 2009). Additionally, when dikes or dune ridges are introduced, environmental conditions alter at once. This allows salt marshes to grow simultaneously, resulting in even less variation in vegetation age (Esselink et al., 2009). These trends towards late successional stages are observed on the tails of the Dutch Wadden Sea islands, including Terschelling (de Groot et al., 2017). A solution could be to allow the partial reintroduction of coastal dynamics (Gonçalves, 2024). Staatsbosbeheer, the Dutch state forestry service, plans to implement this at the Boschplaat nature reserve on Terschelling by opening up sections of the dike along the northern side of the tail.

1.2 Lack of coastal dynamics

By partially opening the dike, coastal dynamics can be reintroduced, allowing for local erosion and sedimentation of the salt marshes. Erosion primarily occurs along the coastline, where dynamics are most pronounced (Bouma et al., 2016). In these areas, existing vegetation is disturbed, creating an opportunity for pioneer zone to establish (Esselink et al., 2009). Sedimentation mainly depends on hydrodynamic conditions, vegetation, and elevation. Rates of sedimentation are higher closer to creeks and the sea (Esselink et al., 2009). In areas where vegetation is present, more sedimentation occurs, while its absence leads to greater erosion (Mariotti & Fagherazzi, 2010). At lower elevations, there is generally more sedimentation, especially in the form of silt. When salt marshes experience increases in silt (Leendertse et al., 1997; Roozen, 1985), this further reduces coastal dynamics

(Esselink et al., 2009), as sandy marshes typically experience more erosion than muddy ones (Mariotti & Fagherazzi, 2010).

Among all these factors, two are the most prominent drivers of salt marsh degradation. The first is an increase in marsh elevation due to sedimentation (Esselink et al., 2009; Castillo et al., 2021). Such an increase has also been observed at the Boschplaat (Leendertse et al., 1997). As elevation rises, wave attenuation decreases (Mariotti & Fagherazzi, 2010), resulting in shorter inundation frequencies and periods (Castillo et al., 2021). The second cause is increased nutrient levels, particularly nitrogen. In back-barrier marshes like the Boschplaat, nutrient availability appears to be the key driver (Olff et al., 1997; Esselink, 2009). The previously mentioned increase in silt also contributes to nutrient availability, as nutrients accumulate in this top layer (Olff et al., 1997).

It is difficult to predict and understand how marshes specifically react to an increase in coastal dynamics. To grasp the idea behind increasing coastal dynamics to enhance vegetation distribution and diversity, the following concept is important: Coastal dynamics create various macro-gradients, such as in salinity, silt depth (Roozen, 1985; Leendertse et al., 1997), elevation (Roozen & Westhoff, 1985), and organic matter content (van Wijnen & Bakker, 1999). These gradients interact with one another, resulting in unique micro-gradients at each location. The variations in micro-gradients contribute to greater plant diversity (Oost et al., 2018). When less coastal dynamics are present, these macro-gradients converge toward similar conditions, leading to reduced variation in micro-gradients, which causes decreased plant diversity (de Groot et al., 2017).

1.3 Knowledge gap and research aim

The vegetation on the Boschplaat has been studied to some extent, but a recent evaluation is lacking, as the latest vegetation data used in research is from 2012 (Jentink et al., 2018; Oost et al., 2018). Before implementing coastal dynamics, it is essential to have a clear understanding of the initial conditions, as these will serve as a baseline for comparing developments after restoration. Additionally, the areas where dynamic processes are most needed, in relation to current vegetation, have not yet been identified. There has also been no research linking specific environmental variables to the desired vegetation communities in salt marshes. These are all important aspects that must be studied before an effective restoration plan can be created. Finally, limited information exists on the degradation of salt marsh quality, highlighting the importance of case studies like this in addressing that knowledge gap.

This research aims to explore past changes in vegetation community distribution and diversity on the Boschplaat, along with their underlying drivers, to gain insights into the potential future effects of increased coastal dynamics on the Boschplaat. In this study, I will evaluate the changes in vegetation over the past two decades (1999 to 2018) and identify the key environmental variables driving these changes. The following questions will be addressed: ‘How did the spatial distribution and composition of (desired) vegetation change over the period 1999-2018?’ and ‘Which environmental drivers explain the spatio-temporal variation in (desired) vegetation best?’

By analysing changes in vegetation over the past two decades and the environmental factors driving them, I can investigate whether decreased vegetation diversity and distribution are actually due to the lack of coastal dynamics. Based on this information, I can speculate on whether increased coastal dynamics could help restore the diversity and distribution of vegetation on the Boschplaat. Ultimately, this will contribute to an improved understanding of current processes and future processes after the restoration of coastal dynamics. This research will ensure that society can be

adequately informed about the initial situation and the expected outcomes of the proposed restoration plans. This knowledge can also be extrapolated and applied to other salt marshes.

Two main analyses are done fulfil the research aim. Part one is a spatial GIS analysis of vegetation changes over the past two decades (1999-2018) and the second analysis is a field-assessment of associations between vegetation distribution and environmental drivers (salinity, silt depth, elevation, and organic material).

1.4 Expectations

This research is expected to reveal that the communities present on the Boschplaat are predominantly transitioning toward older successional stages, resulting in increased homogeneity of communities (Oost et al., 2018). A further increase in climax species, such as *Elymus athericus* and *Phragmites australis*, is anticipated (Esselink et al., 2009). Additionally, lower salinity, thicker silt layers, higher elevation, and increased organic matter are expected to be associated with decreased dynamics and will be found in the late successional communities. All of these environmental variables are expected to play a significant role in explaining which communities are present, based on the micro-gradients they create (Oost et al., 2018). However, as elevation and nutrient availability seem to be prominent in driving succession (Esselink et al., 2009), silt depth, organic matter, and elevation are expected to have the greatest influence.

Methods

2.1 Site description

2.1.1 Formation and development of the Boschplaat

The barrier island Terschelling lies in the northern part of the Netherlands. The Boschplaat is situated on its island tail, and is a designated Natura 2000 reserve of over 4,000 hectares (Roozen & Westhoff, 1985; Ministerie van Landbouw, Natuur en Voedselkwaliteit, 2008). Before the 17th century, the Boschplaat was a bare sand plain. Over time, dune formation occurred, leading to the establishment of five dunes. Water from the North sea would flood the plain during high tide and deepen the creeks between these dunes. Concerned about potential land loss due to the island breaking apart, inhabitants of Terschelling built a 9-kilometer-long dike. The 'Stuifdijk' was completed in 1937 and shields the Boschplaat from North Sea inundation (Elias, 2021). From then on, flooding was limited to water from the Wadden Sea. This water flowed slowly and resulted in high levels of silt deposition (Leendertse et al., 1997), especially along the creek banks (Roozen, 1985; Reed et al., 1999). These developments allowed rich salt marsh vegetation to grow on the plain alongside the already existing dunes (Oost et al., 2018; Reitsma et al., 2020).

Sometime after the placement of the dike, there appears to have been a shift in the quality of the salt marsh. Between 1954 and 1990, a general decline in species richness was observed (Leendertse et al., 1997). Additionally, areas across the salt marshes began exhibiting a more homogeneous species composition, progressing toward final successional stages (Roozen, 1985). *Lastly*, there has been an increase in characteristic final succession species. Between 1991 and 2006, the presence of Elymus athericus communities doubled to around 30%, accompanied by an increase in Phragmites australis communities from 1% to 8% (Esselink et al., 2009).

2.1.2 Restoration plans

The state forestry's final plan is still under development, but the proposal includes creating two clusters of openings and one large wash over (Fig. 1). Each cluster will consist of two small openings. The first cluster will be located between poles 20,300 and 20,850, and the second between poles 22,800 and 23,600. The openings are planned to be about 100 to 125 meters wide and allow fresh sand to spread behind the dike up to 1.5 km. The wash over will be located between poles 24,500 and 25,500 and will be up to 600 meters wide. It allows water to inundate the area during storms and lets fresh sand drift in. Additionally, a strip of grazing area will be created along the current path at the foot of the dike. It will be around 65 hectares and will lie in between poles 20 and 22. Grazing in this area will be limited to late summer. The interventions are planned to take place within the next three years (Jan Meijer, Personal communication, 2024).

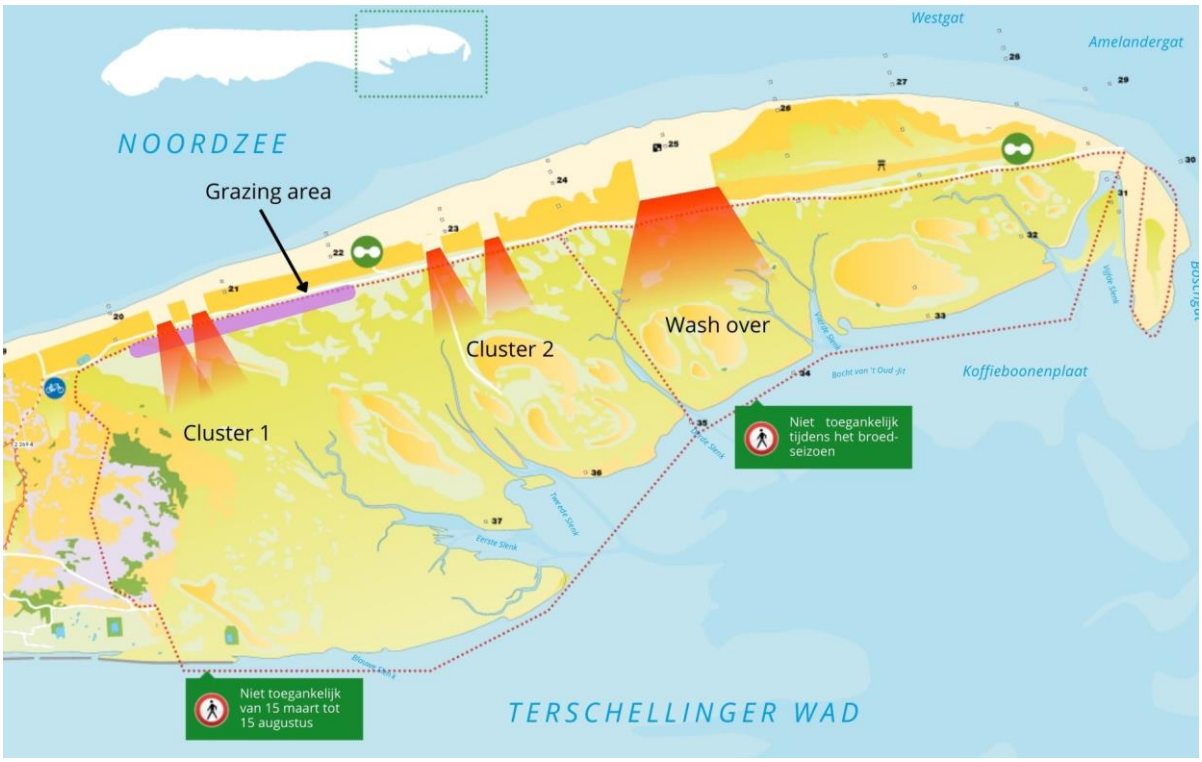


Fig. 1. Restoration plans created by the state forestry service to increase coastal dynamics at the Boschplaat. Grazing area is displayed in purple. From left to right, cluster 1, cluster 2 and the wash over are displayed [original picture without interventions retrieved from Staatsbosbeheer Terschelling (2024)].

2.2 Research design

Two main analyses are done: A spatial GIS analysis of vegetation changes over the past two decades (1999-2018) and a field-assessment of associations between vegetation distribution and environmental drivers (salinity, silt depth, elevation, and organic material).

2.2.1 Vegetation change analyses

Within the change analyses, two separate analyses were conducted. First, a change analysis was performed, consisting of three sub-components. The first component shows how vegetation type coverage changed over the last two decades (1999–2018), the second displays where these changes occurred on the tail and the third highlights how transitions between all these vegetation types are distributed. The second analysis is a desirability analysis, conducted to help identify how desired and undesired communities are distributed and how this changed over the last two decades (1999–2018). Desired communities consist of pioneer species, while undesired communities included late successional species. All analyses were conducted using ArcGIS Pro and R Studio.

2.2.2 Environmental drivers analysis

For the environmental drivers field analysis, plots were selected based on the presence of either desired early or undesired late successional vegetation communities. Within these plots, environmental conditions were measured to examine the association between specific environmental variables and whether vegetation is early or late successional. This analysis was conducted using R Studio.

2.2.3 Used data

To analyse changes in vegetation distribution and composition, I used vegetation community maps from 1999 (Gennip & Severijn, 2002) and 2018 (Reitsma et al., 2020) created for the VEGWAD program from Rijkswaterstaat. These maps are derived from false-colour aerial images, have a resolution of 0.25 meters and are verified through fieldwork. From the images, homogeneous vegetation areas are delineated and represented as polygons. Within these polygons, multiple plant communities can occur, with their coverages indicated as percentages. The classification originally employed the salt08 method, which offers a high level of detail (Janssen & Hennekens, 2018). To make the data more manageable, the salt08 classification was converted to the TMAP typology (Rijkswaterstaat, 2024), which is less specific and more frequently used on an international scale (Petersen et al., 2014). Within the TMAP typology, there are TMAP types which indicate land coverage and TMAP communities which fall within these types (Table 1). Dune vegetation is classified differently (using the GST method) (Gennip & Severijn, 2002; Reitsma et al., 2020). Due to these methodological differences and the focus of the thesis on salt marshes, dune vegetation is mostly excluded.

2.3 Vegetation change analyses

The analyses were conducted in ArcGIS Pro 3.3.0 and R 4.3.1. Within R, the meta-package tidyverse was used in all scripts (Wickham et al., 2019). When needed, other packages were used, which are mentioned below in the analysis descriptions.

2.3.1 Change analysis

The first component of the change analysis is the change in coverage. To analyse the main vegetation development on the Boschplaat between 1999 and 2018, I created an overview of the overall coverage and its changes in hectares (Appendix A). To obtain the coverage per community, polygon areas were multiplied by the percentages of the communities present within these polygons. By summing the areas per communities, I calculated the total area covered by each community. Additionally, communities were assigned to their respective TMAP types, allowing for the calculation of the total area per TMAP type. The changes in TMAP type or community coverage were determined by subtracting the 1999 area from the 2018 area.

The second component visualises where spatial changes took place within the TMAP type land coverage. I created maps displaying the predominant TMAP types for 1999 and 2018. I established this by adding a new field to the dataset, where I created a function that selected the TMAP type with the highest coverage percentage for each polygon.

Lastly, the final component determines how the TMAP types transitioned between 1999 and 2018. I created a Markov chain to compare the TMAP land coverage maps pixel by pixel. This made it possible to determine, for each TMAP type, the proportions changing to other TMAP types or remaining within their own type. Since the Markov chain used the maps made in component two, it only considered the predominant community per polygon. Additionally, I created transition matrices for each TMAP type at the community scale to determine whether changes within TMAP types can be attributed to specific communities. The Markov chain and transition matrices were developed using the markovchain and terra packages in R (Spedicato et al., 2023; Hijmans et al., 2024).

2.3.2 Desirability analysis

To find out where in the area conditions have developed in such a way that unwanted communities form, I created a spatial desirability rating map. This map displays changes in the presence and distribution of desirable and less desirable communities, based on ratings from the state forestry service (Table 1). The forestry service indicated that the rating is largely determined by the proportion in which the communities currently occur across the Boschplaat (Jan Meijer, Personal communication, 2024). A grid with 63x63 m cells, determined from the average median polygon areas of 1999 and 2018, was overlaid on both maps. Each grid cell was mathematically assessed (Eq. 1) to calculate a desirability score ranging from 1 to 10. The formula is calculated for every cutoff polygon component within a grid cell. When communities are absent, the formula is multiplied by zero (as 'percentage community' is zero in that case), excluding these communities from the sum. This means I eventually only included the weighted areas of the communities present within that grid cell. Communities lacking a state forestry rating were assigned the average of the other ratings to minimize their influence.

$$Rating\ per\ gridcell = \sum \frac{Rating\ community\ 1 * Area\ polygon\ per\ gridcell * Percentage\ community\ 1}{100} + \frac{Rating\ community\ 2 * Area\ polygon\ per\ gridcell * Percentage\ community\ 2}{100} + \cdots \quad \text{(Eq. 1)}$$

Table 1. *TMAP communities with their code, their full name, their respective TMAP type and the rating from the state forestry service by Jan Meijer. Communities that do not include vegetation are left out in the rating.*

Community code	Community name	TMAP type	Rating State forestry service
HSc	*Schoenus nigricans* type	Dune slack fens	8
SBb	*Bolboschoenus / Schoenoplectus* type	Brackish marsh	8
SBg	Brackish flooded grassland type	Brackish marsh	6
SBm	*Juncus maritimus / Oenanthe lachenalii* type	Brackish marsh	6
SBp	*Phragmites australis* type	Brackish marsh	5
SFl	*Lolium perenne*, *Cynosurus cristatus* and other fresh species types	Fresh grasslands	5
SH_unsp	High salt marsh unspecified	High marsh	6
SHc	*Plantago coronopus*	High marsh	7
SHe	*Carex extensa* type	High marsh	9
SHf	*Festuca rubra* type	High marsh	7
SHg	*Agrostis stolonifera* / *Trifolium fragiferum* type	High marsh	7
SHh	*Atriplex portulacoides* (dominant)	High marsh	6
SHj	*Juncus gerardi* type	High marsh	6
SHl	*Limonium vulgare* / *Juncus gerardi* type	High marsh	9
SHm	*Juncus maritimus* type	High marsh	6
SHo	*Ononis spinosa* / *Carex distans* type	High marsh	7
SHx	*Atriplex prostrata* / *A. littoralis* type	High marsh	6
SHy	*Elymus athericus* type	High marsh	2
SHz	*Artemisia maritima* / *Festuca rubra* type	High marsh	7
SL_unsp	Low marsh unspecific	Low marsh	9
SLa	*Aster tripolium* / *Puccinellia maritima* type	Low marsh	9
SLh	*Atriplex portulacoides* type	Low marsh	7
SLl	*Limonium vulgare* / *Puccinellia maritima* type	Low marsh	9
SLp	*Puccinellia maritima* type	Low marsh	8
Sm	Bare mud or clay in salt marsh systems	Bare mud or clay in salt marsh systems	
SPq	*Salicornia* type	Pioneer zone	8
SPs	*Spartina anglica* type	Pioneer zone	6
Ss	Bare sand or shells in salt marsh systems	Bare sand or shells in salt marsh systems	
Su_unsp	Vegetation not present, disturbed	Vegetation not present, disturbed	
Sw	Open water	Open water	
X.0	Dunes	Dunes	
XEd	*Cakile maritima* type	Beach driftline	7
XEf	*Elymus farctus* type	Beach driftline	7

2.4 Environmental drivers analysis

2.4.1 Data collection

Fieldwork was conducted to evaluate whether environmental characteristics influence the presence of communities, particularly whether certain traits are associated with desired or undesired communities. I selected four communities for both low- and high-desirability, based on the rating by the state forestry service (Table 1). I sampled five plots per community, resulting in a total of forty plots. The low-desirability communities are *Elymus athericus* type (SHy), Brackish flooded grassland type (SBg), *Phragmites australis* type (SBp), and *Juncus gerardi* type (SHj). The high-desirability communities are *Limonium vulgare / Puccinellia maritima* type (SLl), *Salicornia* type (SPq), *Puccinellia maritima* type (SLp), and *Limonium vulgare / Juncus gerardi* type (SHl). Within each desirability group, two communities were chosen in which only plots with consistent vegetation coverage from 1999 to 2018 were selected (SHy, SBg, SLl, and Spq). This approach ensured that these areas were consistently dominated by the same community over time, reflecting stable environmental conditions.

Whilst selecting plots, I focused on polygons with over 70% coverage of the specified community and identified points that were well-distributed. Due to the size and accessibility of the area, I chose to only sample around the first three creeks. These points, along with the total suitable community areas, were exported to the Real-Time Kinematic (RTK) system (TopCon Hiper HR RTK-GNSS (TopCon Systems). This allowed us to locate points easily in the field and to adjust points if the expected community was no longer present or moved. In a few instances, communities shifted slightly, resulting in the community being located next to the expected location. In such cases, the sample points were adjusted accordingly. There was one sample point where the expected SHl vegetation community was no longer present. When this occurred, a new sampling point was selected within the same community type at a different location. The final sample points are shown in Fig. 2.

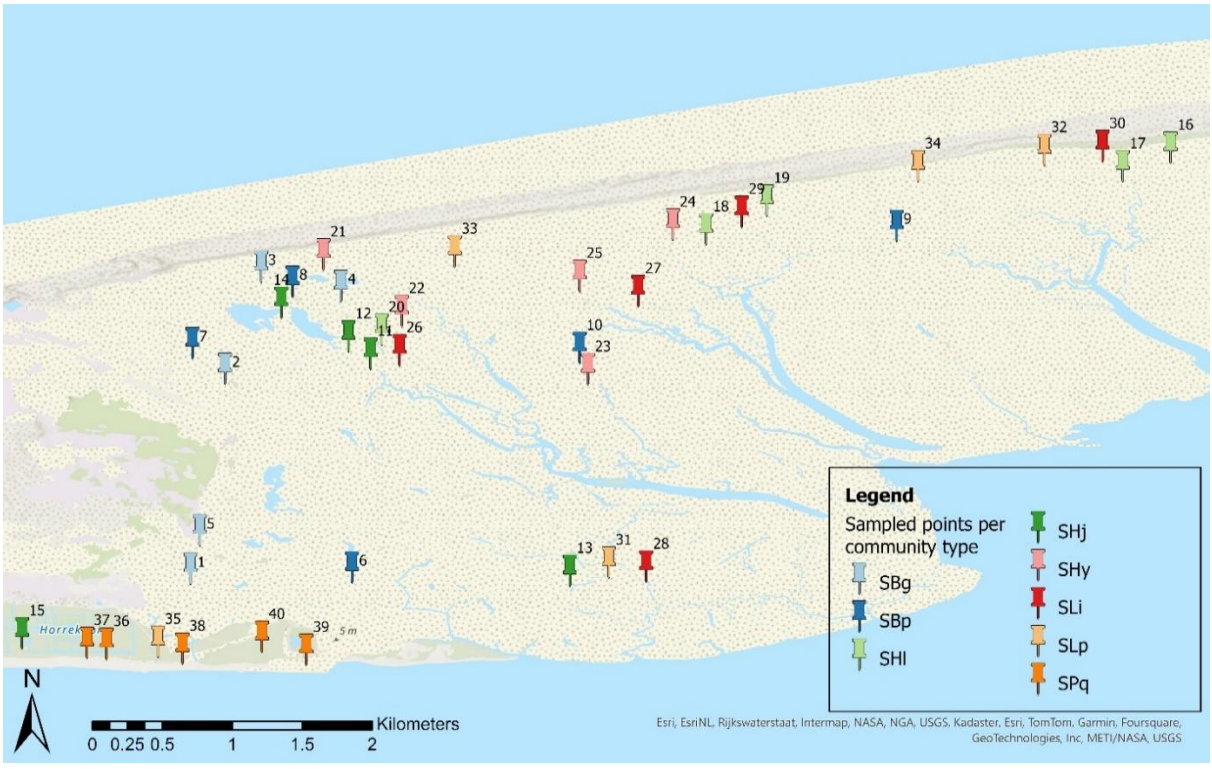


Fig. 2. The locations where samples have been collected. The colours show the communities and the numbers are the plotnumbers.

After locating the exact sites, 1 by 1 meter plots were placed. Within each plot, all species and their estimated coverages were recorded. Additionally, silt depth was measured four times per plot using a soil auger. To make sure this was consistent, silt measurements guidelines were used (Giddings, 2015). Soil elevation was measured using the RTK. Furthermore, samples were collected for laboratory analysis of soil organic matter content and electrical conductivity (EC). Organic matter samples were obtained using 100 cm^3 sampling rings. After removing vegetation, the rings were inserted into the soil using a ring holder and were carefully extracted again with the intact soil. A subsample of 15 grams of dry soil from the centre was used for the loss on ignition (LOI) method. The subsample was heated at 105°C for 2 hours to remove moisture, then again at 550°C for 1 hour to determine organic matter content. For the salinity analysis, the top ten centimetres of soil were sampled from four locations within each plot. From these samples, 8 grams were mixed with 40 mL of deionized water in tubes and shaken for an hour using a vortex mixer. The EC of the resulting solution was measured directly in the tubes using an EC meter.

2.4.2 Data analyses

To answer the question about which environmental drivers explain the spatial variation in vegetation best, an NMDS ordination has been created. The forty plots were all scaled and placed within the ordination using the metaMDS function (k = 2, trymax = 500). This ordination helps visualise the relationship between different plant communities and their preferred environmental conditions. To quantify these relationships, an unconstrained analysis was applied to the NMDS using an envfit function, revealing which environmental variables account for most of the spatial variation. This is all done using the vegan package in R (Oksanen et al., 2024). I also made separate NMDS ordinations for the communities that remained unchanged and the communities that changed between 1999 and 2018. This approach helps determine if specific environmental variables have more influence depending on community stability.

Finally, a binary logistic regression was performed to investigate the association between certain environmental variables and the occurrence of either desirable or undesirable communities. This analysis utilised scaled data and employed the base R glm function with a binomial family.

Results

3.1 Vegetation change analyses

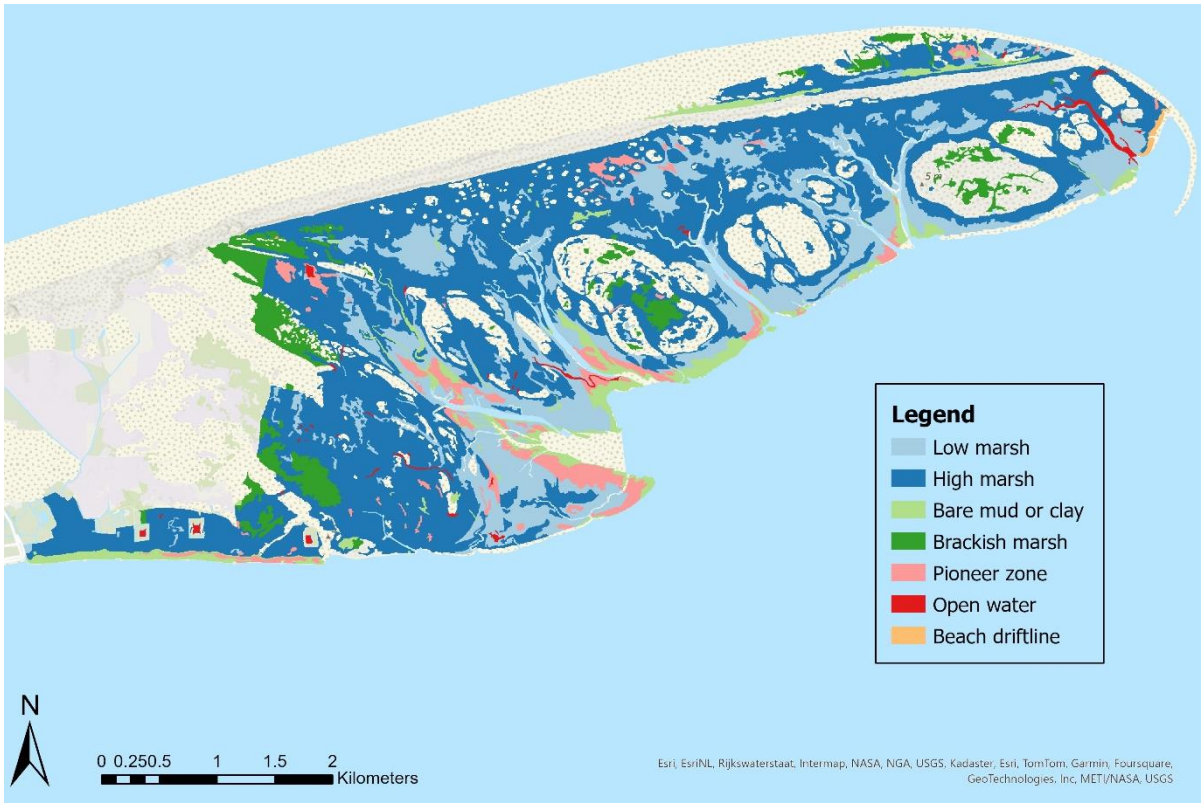
3.1.1 Change analysis

Between 1999 and 2018, beach driftline, brackish marsh, open water, and pioneer zones increased, while bare mud or clay and fresh grasslands decreased. High marsh and low marsh areas remained relatively stable (Table 2). Brackish marsh expanded from the western part of the island and receded around some dunes (Fig. 3). Beach driftline increased at the island's tail and, bare mud or clay partially transitioned to pioneer zones along the south coast. Lastly, the fresh grassland patch in the southwest disappeared. Fig. 4 further explores these TMAP type changes through a Markov chain analysis.

Table 2. TMAP type land cover change in hectares and percentages between 1999 and 2018. The largest changes are underlined

TMAP type	Cover 1999 (Ha)	Cover2018 (Ha)	Change (Ha)	Change (%)	Successional stage
Bare mud or clay	78.15	22.68	-55.53	-71.06	Early
Beach driftline	1.70	34.41	32.71	1922.93	Early
Brackish marsh	61.34	127.94	66.59	108.56	Middle/Late
Dune slack fens		1.29			Early/middle
Dunes	698.80	695.82	-2.98	-0.43	Late
Fresh grasslands	26.44	1.57	-24.87	-94.07	Early/middle
High marsh	791.38	760.83	-30.55	-3.86	Late
Low marsh	335.38	335.05	-0.33	-0.10	Middle/Late
Open water	13.24	17.71	4.47	33.77	
Pioneer zone	87.60	97.22	9.62	10.98	Pioneer

A) *Predominant TMAP type coverage 1999*



B) *Predominant TMAP type coverage 2018*

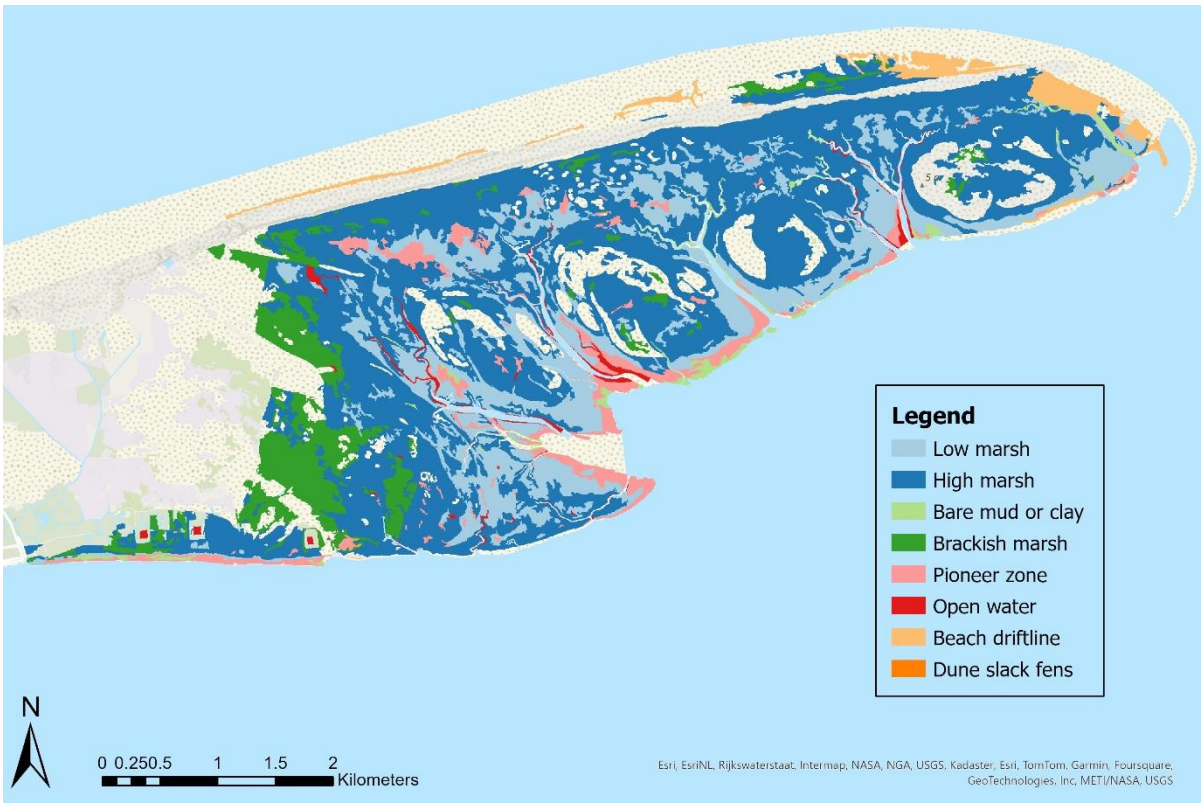


Fig. 3. Predominant TMAP type land coverage in (A) 1999 and (B) 2018. Per polygon the TMAP type with the highest percentage is displayed.

Areas covered with low marsh, brackish marsh and high marsh stayed relatively stable, whilst open water, pioneer zone and bare mud or clay transitioned more to other states. The most prominent changes are bare mud or clay transitioning into pioneer zone (44%), pioneer zone into low marsh (49%) and brackish marsh into high marsh (39%). Part of bare mud or clay also directly changed into low marsh (15%). Furthermore, besides a large part staying stable (57%), 32% of low marsh changed into high marsh. High marsh also stayed stable (72%) with some areas converting into low marsh (13%) and brackish marsh (10%). Furthermore, open water from the creeks transitioned into beach driftline (11%), low marsh (15%), high marsh (17%) and bare mud or clay (26%), only 22% stayed open water (Fig. 4).

Within the high marsh, shifts in community composition occurred. Many of the previously existing high marsh communities transitioned into the *Elymus athericus* (SHy) community (Appendix B). The presence of *Elymus athericus* appeared to have increased over the entire Boschplaat as between 1999 and 2018 an increase of 223.61 ha took place (Appendix A). In 1999 the total coverage of the *Elymus athericus* community was 16.4% whilst in 2018 it turned in to 30.8%, meaning that within those 20 years it almost doubled (Appendix A).

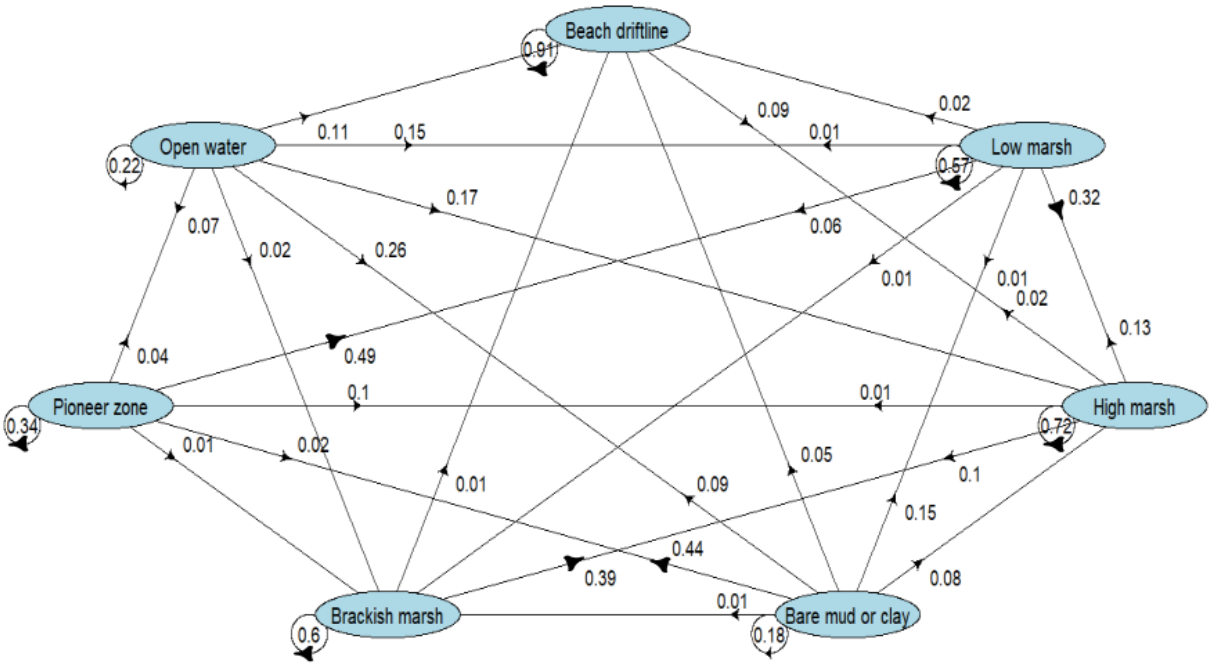
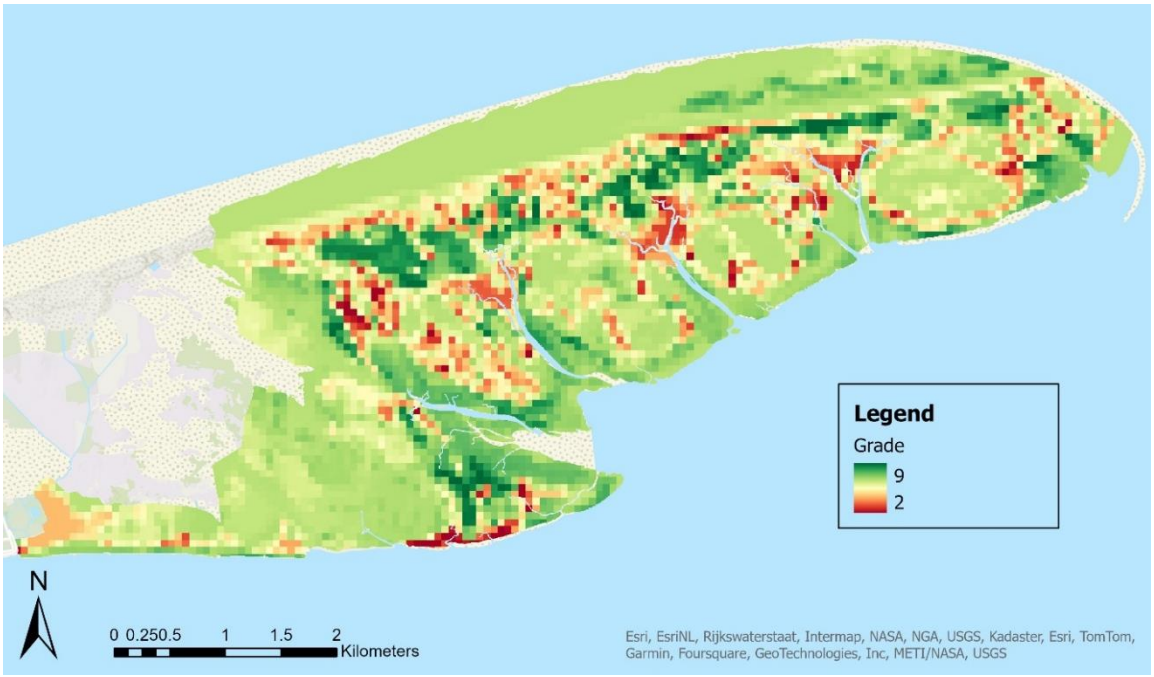


Fig. 4. Markov chain displaying the TMAP types that were both present in 1999 and 2018. Arrows display the proportion changing into or out of a certain state. Arrows circling back to their own state are the proportions of TMAP types that remained the same. Arrows displaying the most change (>0.30) are thicker.

3.1.2 Desirability analysis

The state forestry service has a preference for certain communities on the Boschplaat, primarily those in early successional stages (Jan Meijer, Personal communication, 2024). Based on the ratings per community (Table 1), I created a map that visualises the desirability of each grid cell based on which communities are present and their coverage. This highlights where desired or undesired communities are located across the tail. According to the map, the decrease in desirability is mainly concentrated around the dunes, the southern side of the dike and the creeks, especially near the fourth creek (Fig. 5). This is mainly due to the increase in *Elymus athericus* (SHy) (Appendices B & C). The average grade over the tail changed from a 6.65 in 1999 to a 6.01 in 2018.

A) Desirability rating per grid cell 1999



B) Desirability rating per grid cell 2018

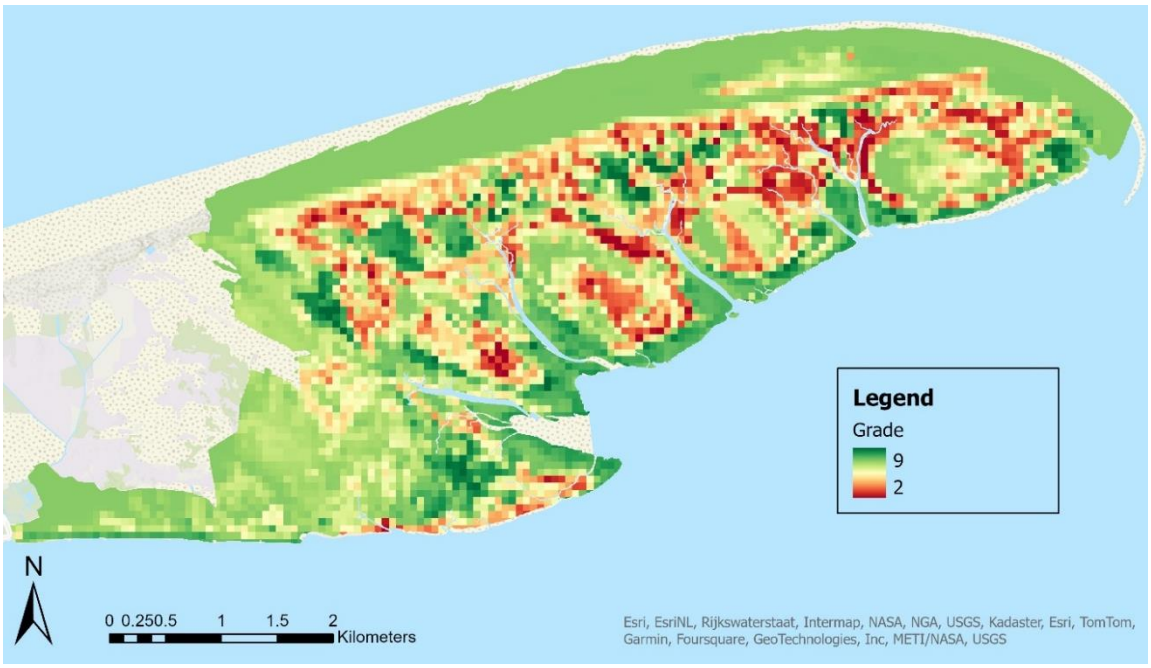


Fig. 5. Desirability rating per grid cell in (A) 1999 and (B) 2018. Eq. 1 mentioned in the methods is used to calculate the average rating per grid cell. Rating is based on grades given per community by Jan Meijer from Staatsbosbeheer.

3.2 Environmental driver analysis

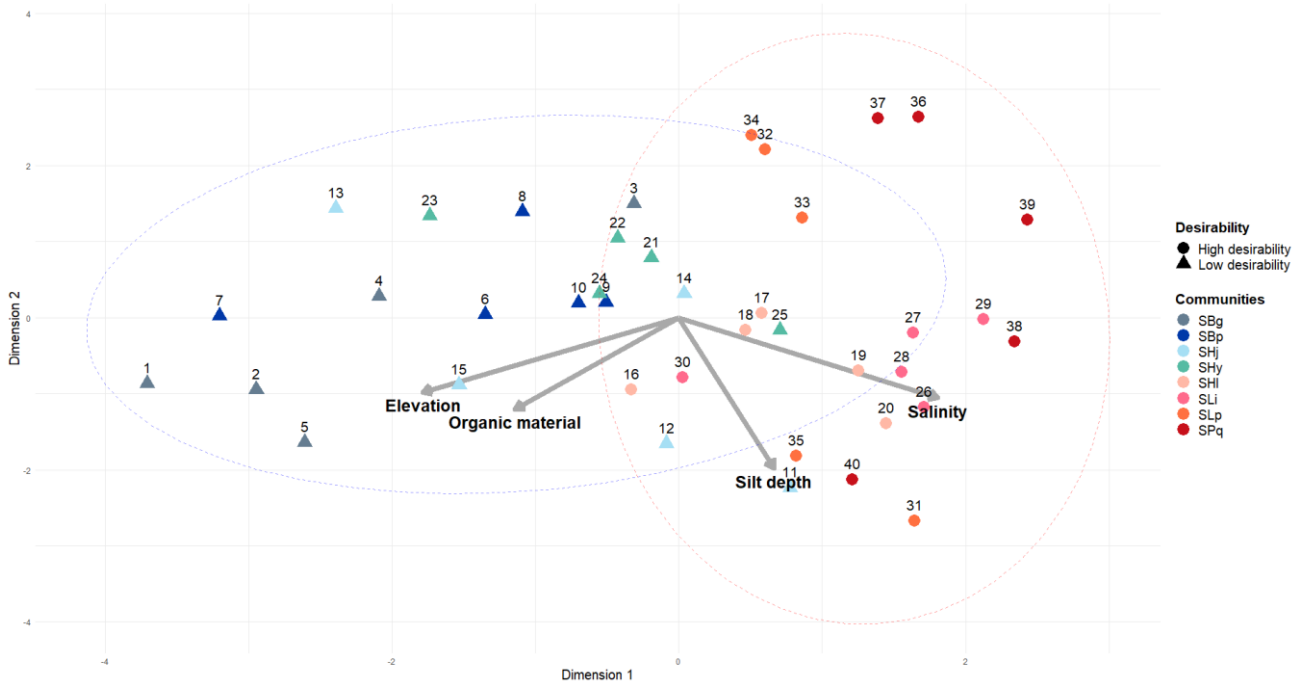


Fig. 6. Nonmetric Multidimensional Scaling (NMDS) ordination plot displaying sampled communities and environmental variables. Different colours represent distinct communities, with numbers indicating plot numbers. High desirability communities are marked with circles, while low desirability communities are indicated by triangles. Red circle is drawn around the desired community plots and blue one around the undesired community plots.

The NMDS shows that Salinity and silt depth overall are higher in desired communities, whilst elevation and organic matter are higher in undesired communities (Fig. 6). An envfit model of the NMDS, assessed the relationship between these environmental variables and the overall structure of community placements in the ordination space. The results indicated that salinity ($R^2 = 0.836$) and silt depth ($R^2 = 0.835$) had the strongest association with community composition, with elevation ($R^2 = 0.814$) closely behind. Organic material also contributed but had a slightly smaller association ($R^2 = 0.663$).

When selecting only the communities that remained unchanged from 1999 to 2018 (underlined in fig. 7), the results differ slightly (appendix D). The association order of the factors changes to elevation ($R^2 = 0.843$), organic material ($R^2 = 0.842$), salinity ($R^2 = 0.839$) and silt depth ($R = 0.447$), all of which are significant ($p < 0.01$). For communities that experienced change (appendix E), the association sequence changes to silt depth ($R^2 = 0.936$), salinity ($R^2 = 0.905$), elevation ($R^2 = 0.883$), and organic material ($R^2 = 0.212$) (appendix D). However, the association with organic material is not significant ($p = 0.104$), while the others are ($p < 0.01$).

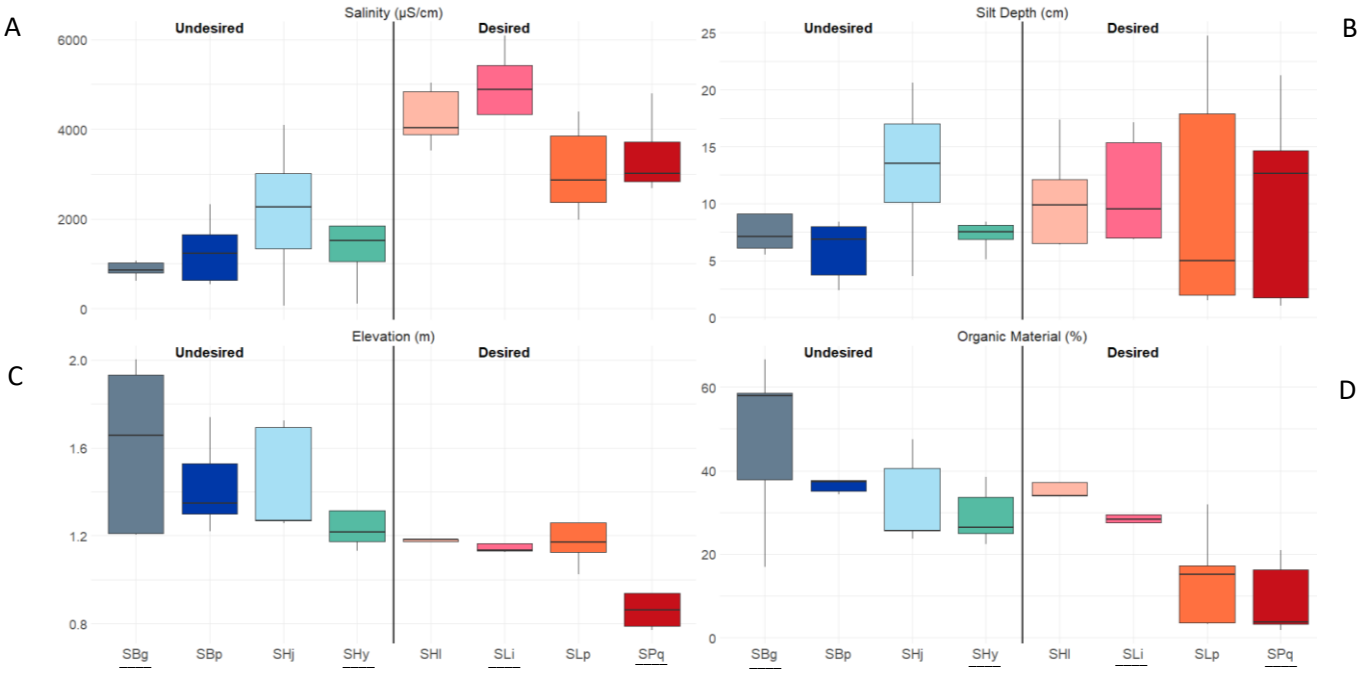


Fig. 7. Boxplots of measured environmental variables within the community plots. The abbreviations of the communities are displayed on the x-axes (full names in Table 1). The lines below half the communities show that the community in the selected plots stayed the same from 1999 to 2018. The environmental variables are al displayed in their own graph: A) Salinity in µS/cm, B) Silt depth in cm, C) Elevation in m, and D) Organic material in %.

In Fig. 7 boxplots are displayed, which show the measured environmental variables within the community plots. It shows that desirable communities have a higher salinity (Fig. 7A). The other variables do not show such a clear trend. The binary logistic regression showed that salinity and organic material are the most significant in explaining desirability. When salinity is higher the chance of the vegetation being desirable are also higher (coef. = 6.071, p= 0.027). When organic material is higher the chances of the vegetation being desirable are lower (coef. = -2.791, p = 0.034).

Discussion

The aim of this study is to explore past changes in vegetation community distribution and diversity on the Boschplaat, along with their underlying drivers, to gain insights into the potential future effects of increased coastal dynamics on the Boschplaat. This is done with the help of the questions: 'How did the spatial distribution and composition of (desired) vegetation change over the period 1999-2018?' and 'Which environmental drivers explain the spatio-temporal variation in (desired) vegetation best?'

The found results show that many of the vegetation types harbouring late successional communities, such as high and low marsh, remained stable. Other late types, like brackish marsh, showed an increase. Within high marsh, most communities rapidly changed in to the climax community *Elymus athericus*. Most of these late successional communities are located around dunes, behind the dike and around the creeks, especially around the fourth creek. Furthermore, all environmental variables are strongly associated with community composition, with salinity as the strongest driver. Higher salinity and lower organic matter are associated with early successional vegetation.

4.1 Main changes (desirable) vegetation distribution and diversity

4.1.1 Main changes vegetation distribution and diversity

As previously expected, the vegetation on the Boschplaat appears to be developing towards late successional stages. This is particularly evident in the Markov chain analysis (Fig. 4), which shows that a large percentage of high marsh, low marsh, and brackish marsh remain in their respective stages, while earlier successional stages such as bare mud and clay, pioneer zone, and the changed part of low marsh, transition into their subsequent stages. Another indicator is that high marsh and low marsh are relatively stable in surface coverage and occupy, together with brackish marsh, the majority of the area.

Although the overall area of high marsh remains largely unchanged, there is a shift within the high marsh type towards the *Elymus athericus* community. Similar patterns were observed in existing literature. Esselink et al. (2009) found no overall increase in high marsh but did observe a shift within the high marsh type towards *Elymus athericus* communities. Here the coverage increased from 15% to 30% between 1991 and 2006. Similarly, Veeneklaas et al. (2013) reported an increase in *Elymus athericus*, from 15-20% in 1999 to 20-30% in 2006. This trend has also been observed on other Wadden Sea islands and along some Dutch mainland coasts. Among the Wadden islands, of which most are embanked with dikes, the most pronounced increase occurred on Terschelling (Esselink et al., 2009). Furthermore, increases in *Elymus athericus* have also been observed across various other European salt marshes (Bockelmann, 2002; Valéry et al., 2004; Veeneklaas et al., 2013; Mueller et al., 2021).

Another sign of late succession is the overall increase of brackish marsh (table 2 & fig. 3), consisting of increases in brackish flooded grassland type (SBg), *Juncus maritimus*/*Oenanthe lachenalii* type (SBm) and *Phragmites australis* type (SBp). Within these types, *Phragmites australis* is an commonly occurring species. Although its increase is less pronounced compared to that of *Elymus athericus*, it is still notable. Similarly, an increase of 10% between 1991 and 2006 in *Phragmites australis* was also observed by Esselink et al. (2009). In Oost et al. (2018) they predict that the western patch of brackish marsh will expand even further in the future.

4.1.2 Trends behind changes in vegetation distribution and diversity

The amount of *Elymus athericus* present is related to marsh age. Normally, its spread varies across marsh sections, with faster expansion in younger areas. As the Boschplaat marsh developed all at once, due to the dike construction, the rate of expansion is equal over the plain (Veeneklaas et al., 2013). This means the plain has been uniformly moving towards higher *Elymus athericus* coverage. In 1999 the coverage of the *Elymus athericus* community was 16.4% whilst in 2018 it was 30.8%, meaning that within those 20 years it almost doubled (Appendix A). This fast increase indicates that the island has not fully reached its final climax stage yet and *Elymus athericus* is still expanding. When no interventions are made, the increase will eventually slow down, as most of the plain will be dominated by *Elymus athericus* by that point (Veeneklaas et al., 2013).

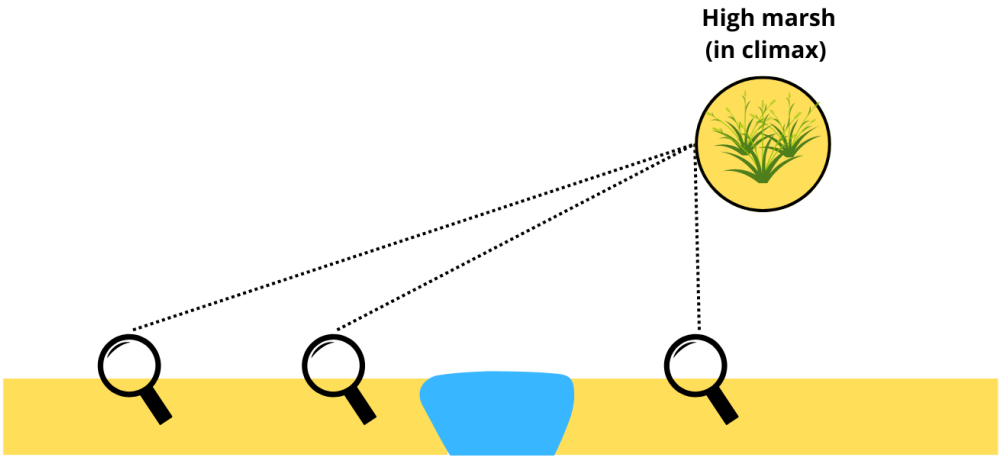
A finding from the literature that was not observed in this research is the impact of silt depth on the presence of either desired or undesired vegetation communities. Because of the dike, there is solely slow inundation from the Wadden Sea, which causes a silt layer to build up (Leendertse et al., 1997). The thickness of the silt is positively related to the amount of nitrogen present (Olff et al., 1997). Oost et al. (2018) states that the increase of nutrients, especially nitrogen, is an important driving factor behind the vegetation succession (Oost et al., 2018, Wijnen & Bakker, 1999) leading to an increase in more late successional species (Wijnen & Baker, 1997). Because of atmospheric deposition due to human influence, nitrogen levels become even higher over the entire plain (Veeneklaas et al., 2013), increasing the succession even further. According to this information, a thicker silt layer would lead to less desirable vegetation communities. This could however not be concluded from my results.

The reason the desirability rating is low behind the dike is that the remaining coastal dynamics from the Wadden Sea no longer occur in this area. A similar process goes on around the dunes, the dunes have high elevation and have become stagnant because of the decreased dynamics. They rarely experience inundation, fresh sediment, or erosion, which leads to older succession stages, such as *Elymus athericus* (Esselink et al., 2009). Furthermore, is the desirability especially bad around the fourth creek. Here the transition is mainly from low marsh to high marsh (fig. 3), with mainly a transition into the *Elymus athericus* type. This indicates a lack of dynamics, however, why the lack of dynamics is especially present around the fourth creek compared to the others remains unclear.

4.2 Key environmental drivers explaining spatio-temporal variation in vegetation

As expected, the unconstrained NMDS analysis revealed that all tested variables, including salinity, silt depth, elevation and organic matter, play significant roles in determining the composition of present communities. These findings align with the concept of Oost et al. (2018), in which coastal dynamics cause various macro-gradients that interact with each other, resulting in unique micro-gradients at each location. According to Oost et al. (2018), a larger range of variations in micro-gradients leads to greater plant diversity. Currently the macro-gradients transition in the same direction, decreasing the micro-gradients available. A simplified representation of these processes is shown in Fig. 8. The binary logistic regression showed that higher salinity leads to more desired early succession communities, whilst organic matter leads to less. These findings, in combination with the late successional vegetation present on the tail, indicate that macro-gradients are moving towards lower salinity and higher organic matter.

A) With restrained coastal dynamics



B) With increased coastal dynamics

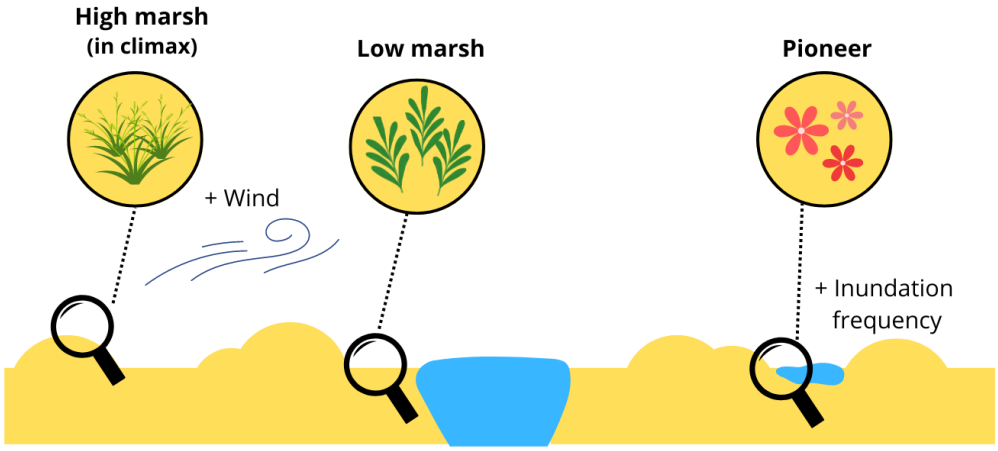


Fig 8. Simplified representation of A) a salt marsh with restrained coastal dynamics and B) a salt marsh with increased coastal dynamics. The increase in coastal dynamics leads to a higher variety in macro-gradients resulting in more micro-gradients per location, leading to an increased variety in communities present and a higher overall plant biodiversity (Oost et al., 2018).

Based upon findings in literature, indicating that elevation and nutrient availability are important drivers of succession (Esselink et al., 2009), I expected that elevation, organic matter and silt depth would be most important in determining vegetation community presence. However, according to the unconstrained NMDS analysis, the main driver is salinity. In other European salt marshes similar results are found. In Ria de Aveiro in Portugal, elevation and hydroperiod are the driving factors of vegetation composition (Gouveia et al., 2023). At the Danish Wadden Sea, elevation is an important factor (Kim, 2017). In a study in Pannonia and the Balkans, vegetation distribution is mainly influenced by salinity and water regime gradients (Elias Jr et al., 2013). In Northern Germany, salinity and depth till anoxic conditions were the most important variables (Schröder et al, 2002). And finally, in a study comparing many plots taken around Europe, researchers classified vegetation based on syntaxonomic units and analysed which environmental variables influenced the presence of each

unit. Salinity, soil moisture, light availability, and soil nitrogen content were identified as key factors. Consistent with our findings, salinity emerged as the most significant explanatory variable (Lubińska-Mielińska et al., 2022).

When I compared communities that changed or did not change between 1999 and 2018, the variables that stayed relevant either way were salinity and elevation, meaning that these factors are always associated with community composition, independent of whether the soil characteristics have been stable for a while or not. Silt is an important influence when vegetation changed between 1999 and 2018 but seemed less relevant when the community remained. This could mean a change in silt depth is often followed by a change in community. However, additional research is needed to actually conclude this.

4.3 Recommendations

4.3.1 Evaluation effectiveness restoration interventions

The goal of the planned interventions on the Boschplaat is to reintroduce coastal dynamics. Based upon this study, I have some recommendations which the state forestry service can take into consideration when further developing these plans.

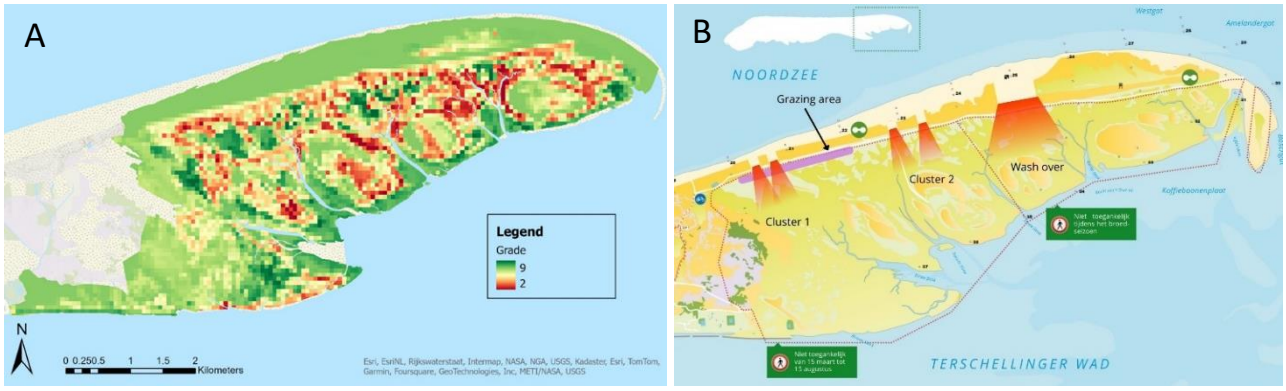


Fig. 9. A) Desirability map and B) interventions planned by state forestry service. These maps are placed next to each other to compare the interventions to the locations where they are most needed.

The planned wash over aims to enhance coastal dynamics through sand drift and storm tide inundation (Jan Meijer, personal communication, 2024). My study found that higher salinity and reduced organic matter favour desirable early-successional communities, and increased inundation and sand drift will help achieve this. While the original plans propose placing the main wash over between the third and fourth creek, my desirability analysis suggests it may be more beneficial to shift it toward the fourth creek. As shown in the desirability map (Fig. 9), this area contains less desirable early-succession vegetation and is therefore most in need of increased dynamics.

One argument for maintaining the current planned wash over position is that the gradient between freshwater and saltwater will decrease if the wash over is positioned directly opposite the creek (Oost et al., 2018). However, since the area currently lacks salinity and the wash over will only experience inundation during storm tides, this may not be a significant issue. Furthermore, there is a risk of the island breaking off due to the force with which the inundation water would reach the creek. An alternative option is to position the opening slightly skewed towards the fourth creek. This would reduce the direct force of storm tide water entering the creek, lowering the risk of island breakage, while still influencing dynamics near the fourth creek. Additionally, a skewed placement could still be

positioned within the thinner part of the dike instead of the thicker part above the fourth creek, making execution easier. Further research using predictive models is needed to evaluate how well this plan would work.

According to literature, adding a wash over seems to be beneficial in increasing coastal dynamics and vegetation diversity. In a research in the Noard-Fryslân Bûtendyks area, they found that after 10 years of de-embankment of the dike there was an increase in characteristics salt marsh species from 35-70% to 75-95%. Especially, an increase at higher elevation, where climax vegetation often occurs, took place from 35% to 75% (Chang et al., 2016). Furthermore in a literature review from Gonçalves (2024) they compared success rates of 'natural', 'assisted' and 'reconstructed' salt marsh interventions. They found that natural interventions worked best and particularly reintroductions of tidal inundations showed a high success rate.

The clusters with small openings are meant to allow fresh sand to drift in to the area again to create a small dynamic dune system (Jan Meijer, Personal communication, 2024). The openings behind the dike are well-placed considering my desirability analysis. Some places behind the dike will not be reached, however, this should not be a problem as it is not the goal to rejuvenate the whole tail but to create a mosaic of different vegetation successional stages (Esselink et al., 2009). The openings will especially work in combination with the grazers, as they get rid of the *Elymus athericus* vegetation, allowing the system to be less fixated and develop again with the help of increased dynamics.

The grazing zone is also placed in such a way that it will help vegetation changing into early successional stages, by combating the unwanted vegetation behind the dike. When looking at the desirability map the grazing zone could be extended further, as there is just as much undesired vegetation below the dike further on the tail. However, if it turns out to be successful on the first half of the tail, the grazing zone can always be extended later. It is importance to monitor the change in vegetation behind the two clusters to evaluate whether the grazing zone plays an important role in determining the vegetation changes.

The area around the last creek is not included in the plan, but does have undesirable vegetation. However, part of the island tail is eroding and a small wash over is already present, so it is possible that these dynamics will increase naturally (Oost et al., 2018; Elias, 2021). Within Oost et al. (2018) they already found a slight increase in early successional species. However, within my results this trend was not visible. Vegetation should be monitored in this area to determine whether early successional vegetation is increasing and to assess if the natural dynamics present may need some further assistance in the future.

The dunes are not directly included in the plans, but do contain undesired communities. The effect of the wash over will probably reach far enough to influence the third dune (Jan Meijer, Personal communication, 2024). Here erosion will lead to younger succession stages in combination with the already present older ones. The sand drift through the smaller openings is estimated to reach about a maximum of 30 hectares behind the dike. This is not far enough to influence the dunes (Jan Meijer, Personal communication, 2024). However, this is not necessarily a bad thing, as sand drift near the dunes would only elevate them further.

The openings within the plan are quite small, which causes there to be a risk of sand accumulating around the edges, which can reduce the size of the opening. If this occurs, the effect of sand drift behind the dike will decrease even further (Oost et al., 2018). Sand accumulation at the edges of the opening should be monitored, and if accumulation takes place, an additional plan should be developed to ensure the openings remain broad enough. Furthermore, creating another wash over could help in adding more dynamics to the dunes. However, this is currently not realistic as the first

part of the tail is too commonly used by inhabitants for recreation (Jan Meijer, Personal communication, 2024).

4.3.2 Recommendations restoration interventions

In summary, based on my research, I predict that the interventions will be beneficial for creating coastal dynamics, leading to an increase in earlier successional stages alongside the existing older stages. I recommend that the location of the wash over be further evaluated, as its effects may be enhanced by slightly shifting it to the right or by positioning it at an angle to better reach the fourth creek. Additionally, some monitoring should be done. First the impact of the grazing zone on dynamics caused by the clusters should be monitored to determine if expanding its boundaries could be beneficial. Furthermore, the vegetation around the fifth creek should be monitored to decide if the present natural dynamics are enough to achieve an increase in early successional vegetation. Lastly, sand accumulation around the edges of the openings should be monitored to ensure they remain wide enough to maintain their effectiveness.

4.3.3 Recommendations further research

For future research, regardless of whether the interventions have occurred, I recommend extending the current dataset. This can be done in two ways. The first is by resampling the same communities at new locations to increase the sample size and enhance the statistical power of the tests. This would help determine whether silt depth and elevation truly have no effect on community composition, or if this result is due to a limited sample size. The second approach is to expand the dataset by sampling additional communities. Currently, only two extremes are studied, leaving many intermediate communities unexamined. To gain a more complete understanding of salt marsh dynamics, it is essential to explore how middle successional stages are influenced by environmental variables. If possible, a combination of the two approaches would be most beneficial.

Furthermore, a comparison should be made between the 2024 VEGWAD map, currently being created, and the 2030 map. If everything goes to plan, the 2030 map will be created after the planned interventions. Repeating the same analyses as in this study, such as generating the predominant TMAP type map, conducting a Markov chain analysis, and performing a desirability analysis, will provide valuable insights into the effects of the interventions. This comparison, especially when aligned with the findings of this research, will offer a clearer understanding of the changes. It would be even more beneficial to continue this process with each new TMAP map created, as it is a cost-effective and relatively simple way of evaluating the process after the interventions.

Another recommendation is to delve deeper into coastal dynamic processes. This study primarily focuses on environmental data in relation to vegetation, whilst making logical assumptions about how these environmental variables come to exist. However, by linking environmental variables to coastal processes, a better understanding of the requirements for certain vegetation types can be achieved. Much of the data needed to understand coastal dynamics is already available, such as remote sensing data and elevation maps. This approach would be particularly valuable in studying the effects of increased coastal dynamics. For example, on the Boschplaat, it could be tested how wash overs and small openings impact environmental variables and, subsequently, vegetation composition.

Partly in contrast to my findings, Kim (2017) found that while environmental factors are important in determining community composition, the existing community plays an even more significant role in shaping future communities. This could explain the wide range of environmental factors observed within a single community in my research (Fig. 7). My results show that environmental variables do

influence community composition. However, in future research, it would be interesting to explore how much of the community composition is explained by environmental variables in comparison to the influence of the previous community. Revisiting my sample points in a few years after interventions could help evaluate whether potential community changes are primarily driven by the preceding community or by shifts in environmental conditions.

Lastly, I have a suggestion for the NMDS ordinations comparing communities that changed between 1999 and 2018, and those that remained the same. The sample locations in this study were selected based on the 2018 map, meaning all communities had already been stable for at least six years when fieldwork was conducted. Therefore, even changed communities can be considered relatively stable. Once the new Boschplaat VEGWAD map for 2024 is published, fieldwork can be conducted using updated locations. This will allow you to more confidently determine whether communities that appeared to change have indeed done so in the last six years, distinguishing them more clearly from those that remained stable and therefore achieving results that are more reliable. Lastly, focusing solely on either changed or unchanged communities reduces the sample size by half, weakening the statistical power of the tests. If possible, it would be better for this test to achieve a bigger sample size in future research.

4.4 Conclusions

This study reveals ongoing succession over the past two decades (1999–2018), with vegetation progressing toward late successional stages, without yet reaching a complete climax. Notably, there has been an increase in the climax species, *Elymus athericus* and *Phragmites australis*. These findings show a continuation of trends previously observed in literature. The succession is especially focused around the creeks, behind the dike and near the dunes. All environmental variables (salinity, silt depth, elevation and organic matter) are important in determining the community composition. Salinity, and thus inundation, turned out to be the strongest driver and is essential in returning desirable early succession vegetation. Decreased salinity and increased organic matter drive late successional growth, suggesting a lack of inundation and sand drift in many areas. These patterns suggest that increased coastal dynamics could likely promote rejuvenation by restoring key variables necessary for early successional communities, creating a mosaic of young and old vegetation and enhancing overall vegetation distribution and diversity. The restoration plan created by the state forestry service is therefore needed to improve salt marsh quality on the Boschplaat.

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Appendix

Appendix A: Changes vegetation community coverage 1999-2018

Tabel 3: Coverage of all communities present on the Boschplaat in 1999 and 2018 and the change between these years in hectares and percentages. Full names of communities are given in Table 1.

Community	TMAP type	TMAP community
HSc	Dune slack fens	Schoenus nigricans type
SBb	Brackish marsh	Bolboschoenus / Schoenoplectus type
SBg	Brackish marsh	Brackish flooded grassland type
SBm	Brackish marsh	Juncus maritimus / Oenanthe lachenalii type
SBp	Brackish marsh	Phragmites australis type
SFl	Fresh grasslands	Lolium perenne, Cynosurus cristatus and other fresh s
SH_unsp	High marsh	High salt marsh unspecified
SHc	High marsh	Plantago coronopus
SHe	High marsh	Carex extensa type
SHf	High marsh	Festuca rubra type
SHg	High marsh	Agrostis stolonifera / Trifolium fragiferum type
SHh	High marsh	Atriplex portulacoides (dominant)
SHj	High marsh	Juncus gerardi type
SHl	High marsh	Limonium vulgare / Juncus gerardi type
SHm	High marsh	Juncus maritimus type
SHo	High marsh	Ononis spinosa / Carex distans type
SHx	High marsh	Atriplex prostrata / A. littoralis type
SHy	High marsh	Elymus athericus type
SHz	High marsh	Artemisia maritima / Festuca rubra type
SL_unsp	Low marsh	Low marsh unspecific
SLa	Low marsh	Aster tripolium / Puccinellia maritima type
SLh	Low marsh	Atriplex portulacoides type
SLl	Low marsh	Limonium vulgare / Puccinellia maritima type
SLp	Low marsh	Puccinellia maritima type
Sm	Bare mud or clay in salt marsh systems	Bare mud or clay in salt marsh systems
SPq	Pioneer zone	Salicornia type
SPs	Pioneer zone	Spartina anglica type
Ss	Dunes	Bare sand or shells in salt marsh systems
Su_unsp	Vegetation not present, disturbed	Vegetation not present, disturbed
Sw	Open water	Open water
X.0	Dunes	Dunes
XEd	Beach driftline	Cakile maritima type
XEf	Beach driftline	Elymus farctus type

Appendix B: Transition matrices high marsh communities

Tabel 4: Transition matrix for high marsh communities showing the transitions between the different high marsh communities between 1999 and 2018 in proportions. If more than half of a community transitions into another this transition is underlined.

Community	TMAP type	Coverage 1999	Coverage 2018	Change (Ha)	Percentage Change
HSc	Dune slack fens		1.285		
SBb	Brackish marsh	4.078	1.672	-2.406	-59.00
SBg	Brackish marsh	55.873	94.387	38.514	68.93
SBm	Brackish marsh		21.216		
SBp	Brackish marsh	1.392	10.673	9.281	666.74
SFl	Fresh grasslands	26.438	1.569	-24.869	-94.07
SH_unsp	High marsh	7.046	7.393	0.347	4.92
SHc	High marsh		5.242		
SHe	High marsh	41.616	11.094	-30.522	-73.34
SHf	High marsh	158.655	33.943	-124.712	-78.61
SHg	High marsh	197.885	76.814	-121.071	-61.18
SHh	High marsh		0.507		
SHj	High marsh	25.577	37.6	12.023	47.01
SHl	High marsh	59.588	39.477	-20.111	-33.75
SHm	High marsh	26.107	27.161	1.054	4.037
SHo	High marsh		1.722		
SHx	High marsh	6.239	17.809	11.57	185.45
SHy	High marsh	228.282	451.896	223.614	97.96
SHz	High marsh	40.282	50.055	9.773	24.26
SL_unsp	Low marsh		4.249		
SLa	Low marsh	43.181	9.487	-33.694	-78.03
SLh	Low marsh	134.682	173.171	38.489	28.58
SLl	Low marsh	131.263	124.449	-6.814	-5.19
SLp	Low marsh	26.219	23.668	-2.551	-9.73
Sm	Bare mud or clay in salt marsh systems	78.149	22.616	-55.533	-71.06
SPq	Pioneer zone	86.801	91.313	4.512	5.20
SPs	Pioneer zone	0.794	5.887	5.093	641.44
Ss	Dunes		202.612		
Su_unsp	Vegetation not present, disturbed		0.064		
Sw	Open water	13.238	17.708	4.47	33.77
X.0	Dunes	698.797	493.203	-205.594	-29.42
XEd	Beach driftline		22.545		
XEf	Beach driftline	1.701	11.861	10.16	597.30

To (2018) → / **From (1999) ↓**	**SHy**	**SHl**	**SHf**	**SHg**	**SHe**	**SH_ unsp**	**SHz**	**SHj**	**SHm**	**SHx**	**Sho**	**SHc**

SHy	0.91	0.01	0.02	0.03	0.00	0.00	0.01	0.00	0.00	0.02	0.00	0.00
SHl	0.68	0.16	0.00	0.01	0.06	0.01	0.03	0.03	0.01	0.02	0.00	0.00
SHf	0.70	0.08	0.01	0.03	0.07	0.01	0.02	0.04	0.02	0.03	0.00	0.00
SHg	0.32	0.01	0.10	0.34	0.01	0.00	0.06	0.13	0.01	0.01	0.01	0.01
SHe	0.61	0.07	0.00	0.00	0.02	0.02	0.04	0.06	0.11	0.03	0.00	0.05
SH_unsp	0.22	0.00	0.00	0.00	0.00	0.00	0.00	0.56	0.22	0.00	0.00	0.00
SHz	0.87	0.10	0.00	0.00	0.00	0.00	0.03	0.00	0.00	0.00	0.00	0.00
SHj	0.74	0.02	0.02	0.11	0.00	0.00	0.00	0.09	0.01	0.01	0.00	0.00
SHm	0.42	0.18	0.00	0.01	0.12	0.00	0.00	0.02	0.24	0.00	0.00	0.00
SHx	0.92	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.08	0.00	0.00

Tabel 5: Transition matrix for high marsh communities showing the transitions between the different high marsh communities between 1999 and 2018 in hectares. All transitions greater than 10 hectares are underlined. The amount of hectares are not exact and only give an indication, as the transition matrix is created based on predominant community present within polygons and not on exact coverage per community.

To (2018) → **From (1999) ↓**	**SHy**	**SHl**	**SHf**	**SHg**	**SHe**	**SH_ unsp**	**SHz**	**SHj**	**SHm**	**SHx**	**SHo**	**SHc**
SHy	208.65	2.97	3.88	5.94	0.23	0.46	1.37	0.23	0.91	3.65	0	0.23
SHl	40.22	9.77	0	0.54	3.52	0.36	1.67	1.73	0.72	1.07	0	0
SHf	111.06	12.69	1.43	4.76	11.11	1.43	2.70	6.03	2.70	4.60	0	0
SHg	62.73	1.98	20.18	67.48	2.37	0.20	11.48	24.93	1.58	1.78	1.98	0.99
SHe	25.14	3.04	0	0.12	0.83	0.67	1.46	2.58	4.49	1.08	0	2.16
SH_unsp	1.53	0	0	0	0	0	0	3.95	1.56	0	0	0
SHz	35.17	3.91	0	0	0	0	1.17	0	0	0.04	0	0
SHj	18.90	0.46	0.49	2.92	0	0.03	0	2.17	0.36	0.28	0	0
SHm	11.07	4.80	0.03	0.21	3.16	0	0	0.52	6.32	0	0	0
SHx	5.72	0	0	0	0	0	0	0	0	0.52	0	0

Appendix C: Changes in *Elymus athericus* type cover 1999-2018

Fig. 10: Change within Elymus athericus type coverage on the Boschplaat between 1999 and 2018. Green shows an increase whilst red shows a decrease.

Appendix D: NMDS Ordination analysis on unchanged communities

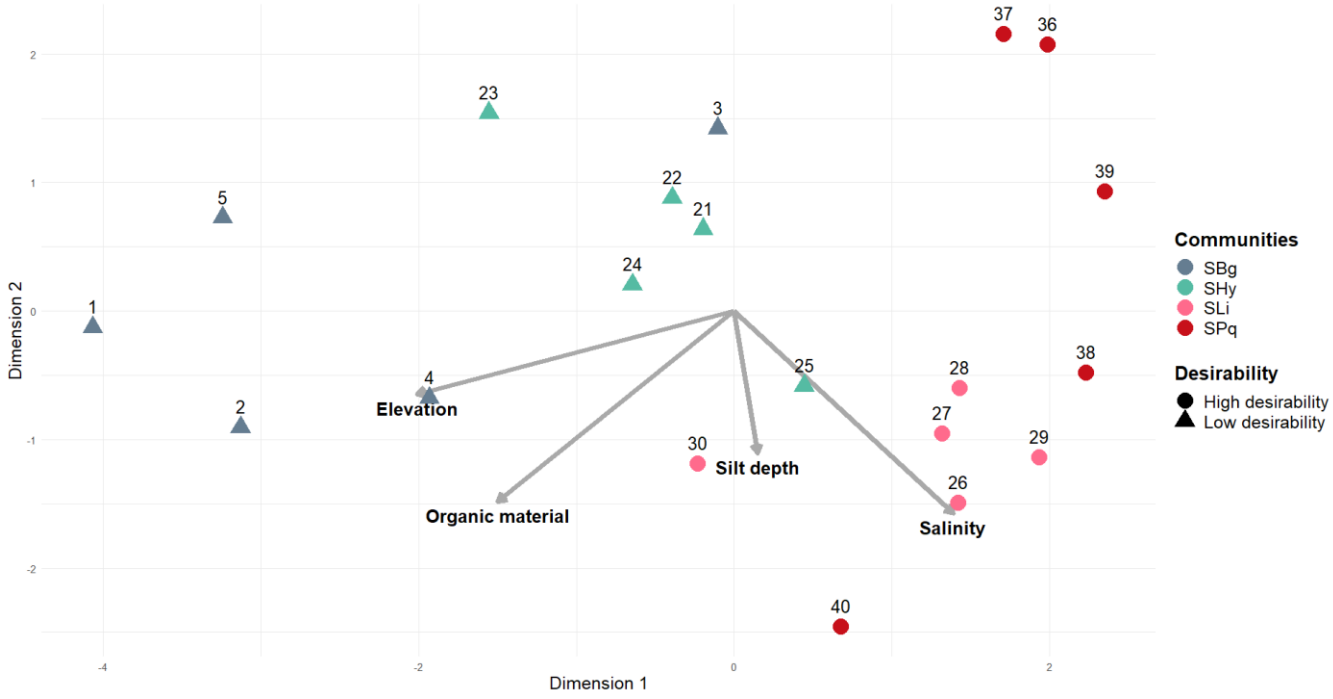

Fig. 11. Nonmetric Multidimensional Scaling (NMDS) ordination plot displaying sampled communities that changed communities between 1999 and 2018 and their environmental variables. Different colours represent distinct communities, with numbers indicating plot numbers. High desirability communities are marked with circles, while low desirability communities are indicated by triangles.

Appendix E: NMDS Ordination analysis on unchanged communities

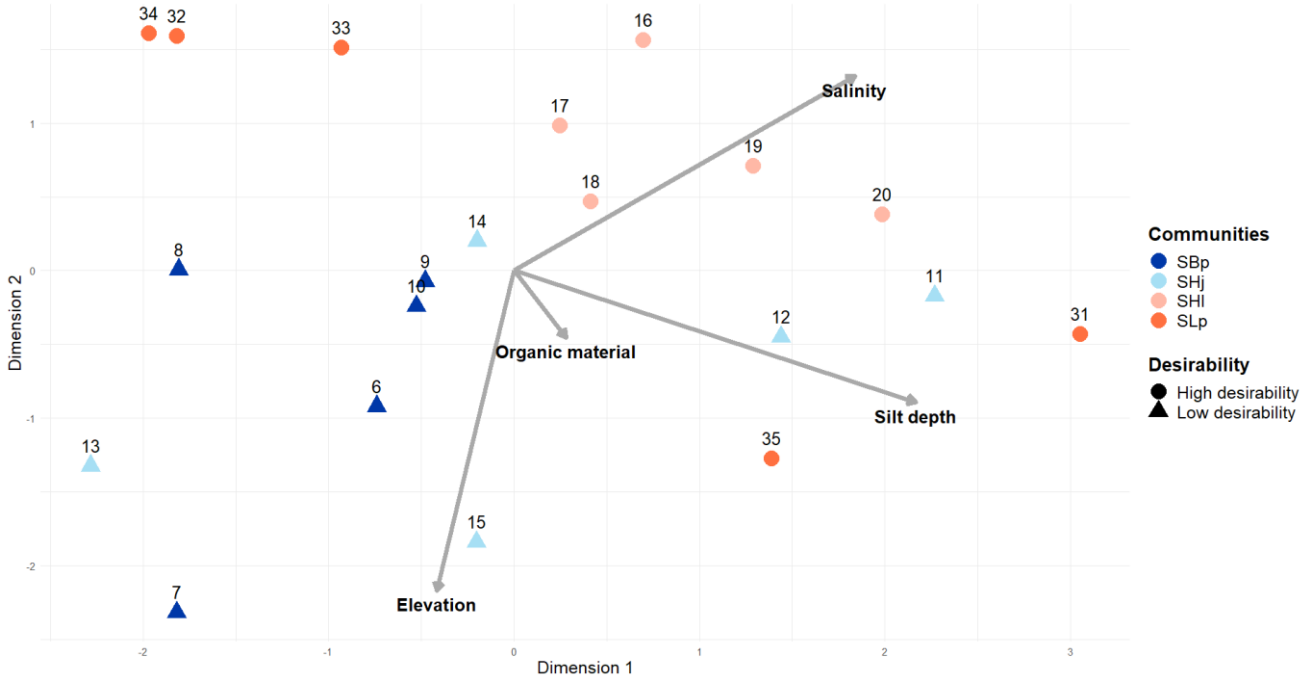

Fig. 12. Nonmetric Multidimensional Scaling (NMDS) ordination plot displaying sampled communities that remained the same communities between 1999 and 2018 and their environmental variables. Different colours represent distinct communities, with numbers indicating plot numbers. High desirability communities are marked with circles, while low desirability communities are indicated by triangles. The displayed plants are characteristic species for salt marsh systems.

Appendix F: Correlations elevation and TMAP types

Tabel 6: The Pearson correlation between elevation and TMAP types from 1999 and 2018. Correlations higher than 0.4 or lower than -0.4 are underlined.

TMAP types	1999	2018
Bare mud or clay	-0.418	-0.278
Beach driftline	0.0368	0.071
Brackish marsh	0.113	0.228
Fresh grasslands	0.129	0.074
High marsh	-0.170	0.049
Low marsh	-0.539	-0.570
No vegetation		0.009
Pioneer zone	-0.436	-0.542
Open water	-0.105	-0.233
Dune slack fens		0.039
Dunes	0.795	0.721
Beach plains		-0.129

To assess whether there is a relationship between elevation and TMAP types, elevation was compared to the TMAP types present in the study area using a Spearman correlation test. I used elevation maps from Actueel Hoogtebestand Nederland (AHN), which are 3D elevation models made with airborne laser technology (Actueel Hoogtebestand Nederland, n.d.). This study employs AHN1 (1996-2003) and AHN3 (2014-2019) (Actueel Hoogtebestand Nederland, 2003; 2019), which align with the vegetation maps' recording periods. Both are used as Digital Terrain Models (DTM) with a 5-meter resolution. I compared AHN 1 data with the 1999 vegetation map and AHN 3 data with the 2018 map (Actueel Hoogtebestand Nederland, 2003; 2019). Then, I calculated the average elevation per polygon to assess whether there is a correlation between elevation and the TMAP types coverage within this polygon. Correlations are examined both by comparing the coverage and the presence of TMAP types to elevations.

The results show a relatively strong positive correlation between elevation and dunes, indicating that dunes are often found at higher elevations. There is also a weak negative correlation between elevation and both low marsh and pioneer zone. Additionally, in 2018, there was a weak negative correlation with bare mud or clay. This suggests that at lower elevations, bare mud or clay, pioneer zone, and low marsh are found. Comparing the elevation to presence/absence data of TMAP types gave similar results

Appendix G: Correlations distance to creeks and TMAP types

Tabel 7: The Pearson correlation between distance to the creeks and TMAP types from 1999 and 2018. Correlations higher than 0.4 or lower than -0.4 are underlined.

TMAP types	1999	2018
Bare mud or clay	-0.147	-0.196
Beach driftline	0.061	0.064
Brackish marsh	0.221	0.343
Fresh grasslands	0.180	0.088
High marsh	-0.127	-0.127
Low marsh	-0.480	-0.487
No vegetation		0.0119
Open water	-0.016	-0.242
Dune slack fens		0.057
Pioneer zone	-0.222	-0.357
Dunes	0.467	0.435
Beach plains		0.136

To assess whether there is a relationship between distance to creeks and TMAP types, distance to creeks was compared to the TMAP types present in the study area using a Spearman correlation test. I compared a map of the creeks to the coverage or presence of these TMAP types. The creek map was created by retaining only the lower parts of the AHN 1 map by using the 'Con' tool and manually correcting it. This map was then used to measure the distance from the creek to the polygons using the 'Near' tool withing ArcGIS Pro. The average distance per polygon was calculated.

To analyse the relationship between distance to creeks and TMAP types, a Spearman correlation analysis was performed. The results show a weak negative Spearman correlation with low marsh and a positive one with dunes, meaning that low marsh lies closer to the creeks and dunes lie further away. Comparing the distance to creek to presence/absence data of TMAP types gave similar results.

Appendix H: Use of AI.

I used ChatGPT to identify mistakes in my R code, to help me find useful packages for the analyses I wanted to perform, and to ask for guidance on tasks in ArcGIS Pro. Additionally, I used ChatGPT to check punctuation and grammar, and occasionally to refine my writing for conciseness as I can be lengthy of text myself. I am fully aware that ChatGPT makes mistakes and I always check somewhere else online or trust my own instincts if something does not seem right. Furthermore, when I struggled with finding articles, I used Elicit. This is an AI-powered search engine for academic articles, which allows you to ask a question instead of using search terms. Whenever I used an article from Elicit, I always verified its presence in traditional search engines, such as Scopus, to ensure its credibility.