FACTORS UNDERLYING THE RECOVERY POTENTIAL OF LITTORAL SEAGRASS IN THE DUTCH WADDEN SEA

PHOTO: Seagrass in artificial saltmarsh works of Groningen © Willem van Duin

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Rijkswaterstaat is opdrachtgever van dit onderzoek. Rijkswaterstaat heeft als natuurbeheerder van de Waddenzee het onderzoek laten uitvoeren om invulling te geven aan de beleidsambities voor zeegras. De groei en ontwikkeling van zeegrasvelden is een belangrijke doelstelling vanuit de Kader Richtlijn Water (KRW) en Natura 2000.

Rijkswaterstaat
Ministerie van Infrastructuur en Milieu

Table of Contents

SAMENVATTING

In de Waddenzee komen twee soorten zeegras voor, namelijk klein zeegras (*Zostera noltii*) en groot zeegras (*Zostera marina*). Beide soorten kunnen een eenjarige en een meerjarige levenscyclus vertonen, waarbij ze respectievelijk met zaden en wortelstokken de winter overleven. Na een periode van zeer lage abundantie, als gevolg van ziekten in de jaren dertig en eutrofiëring in de jaren tachtig, lijkt het zeegras in de noordelijke delen van de trilaterale Waddenzee zich te herstellen, onder meer als het resultaat van een verbetering van de waterkwaliteit. In de zuidelijke delen van de Waddenzee zijn zeegrasvelden echter nog schaars en hebben ze een lage dichtheid. Hoewel zeegras in de Nederlandse Waddenzee enig herstel leek te hebben doorgemaakt, is het huidige oppervlak van de zeegrasvelden (ca. 3 km^2) nog steeds maar een fractie (<3%) van het oppervlak dat geschikt lijkt te zijn voor het voorkomen van zeegras (ongeveer 130 km^2). Dit vraagt om nader onderzoek naar omgevingsfactoren die de uitbreiding van zeegras in de Nederlandse Waddenzee mogelijk beperken.

Zeegras wordt beïnvloed door elke factor die de kwaliteit van water en sediment verandert, wat impliceert dat menselijke invloeden op omgevingsvariabelen zoals zoutgehalte, troebelheid, licht, stroomsnelheid of temperatuur zowel de groei als de overleving van zeegras in gevaar kunnen brengen. Bodemverstoring door baggeren, sedimentwinning en bodemberoerende visserij kan direct (sedimentverstoring) of indirect (bijvoorbeeld via een toename van de troebelheid) de ontwikkeling van zeegras belemmeren. Opwarming van de aarde, toegenomen stormen en zeespiegelstijging kunnen zeegras beïnvloeden via veranderingen in temperatuur, blootstelling en inundatietijd, maar ook via het faciliteren of belemmeren van parasieten en grazers. Verontreinigende stoffen zoals een overmaat aan voedingsstoffen, zwerfvuil op zee, olielozingen en chemisch afval kunnen giftig zijn voor zeegras, in het bijzonder aangroeiwerende verbindingen, fungiciden, insecticiden en herbiciden. Omdat zaailingen en propagules (levensvatbare plantendelen) een andere gevoeligheid kunnen hebben voor omgevingsfactoren dan zaden of volwassen planten, is een beter begrip van de levenscyclus van zeegrassoorten cruciaal voor effectief beheer en herstel van de leefgebieden voor zeegras.

Om te onderzoeken of het mogelijk is om concentratiedrempels vast te stellen in potentieel groeiremmende of groei-vereiste verbindingen voor zeegras is een analyse uitgevoerd op basis van waterkwaliteitsgegevens van Rijkswaterstaat en bekende informatie over het voorkomen van zeegras in de Nederlandse Waddenzee. Op basis van de bevindingen en vergelijkingen met drempels ontleend aan wetenschappelijke literatuur, zou de groei van zeegras kunnen worden belemmerd door hoge concentraties ammoniak en cadmium (met name in het Balgzand-gebied) en zwevende deeltjes (met name in het Eems-estuarium). Omdat de gevoeligheid en toxiciteit van zeegras voor deze verbindingen verband lijkt te houden met de fenologie ervan (bijvoorbeeld het voorkomen van verschillende levensfasen gedurende het jaar) zou verder (experimenteel) onderzoek zich moeten richten op effecten tijdens verschillende levensfasen en hun mogelijke cumulatieve effecten. Ook wordt geadviseerd de waterkwaliteitsstudie uit te breiden naar concentraties in het sediment. De bevindingen dienen vervolgens te worden geëxtrapoleerd naar hoge resolutie data over veldcondities binnen en buiten zeegrasvelden, wat een upgrade van het meetnet met name voor ammoniak, cadmium, kwik en zwevend stof vereist.

Onder de huidige en verwachte toekomstige milieuomstandigheden is de hydrodynamiek waarschijnlijk zeer bepalend voor het voorkomen van zeegras in de Waddenzee. In dit ondiep getijbekken kunnen de sterke getijstromen die de zeebodem eroderen, de mechanische stabiliteit van de zaailingen belemmeren en uiteindelijk zaden verspreiden. Ook kunnen door de wind-gedreven stromingen en golven de bodem omwoelen en zo het leven van zeegras verstoren.

Kleine lokaal gegenereerde golven kunnen destructief zijn, vooral als de effecten worden versterkt door variaties in het waterpeil en getijstromen. Voor een beter begrip van de co-evolutie van interacties tussen zeegras en kwelders is het belangrijk om meer te weten over de koppeling tussen seizoendynamiek van de vegetatie met de omgeving. Kennis van deze belangrijke lokale en korte-termijnverschijnselen, b.v. voor het verkennen van toekomstige (klimaat) scenario's en opties voor het herstel van zeegras, vraagt niet alleen om meer gedetailleerde informatie, maar ook en meer geavanceerde modelbenadering (in tijd en ruimte).

In de kwelderwerken langs de Groningse kust wordt de golfwerking geremd, waardoor een verlaagde erosie en een verhoogde bezinking er netto sedimentatie plaatsvindt. Het effect van het onderhoud van deze kunstmatige sedimentatievelden op het voorkomen van het zeegras *Zostera noltii* is onderzocht aan de hand van gegevens over de milieuomstandigheden in de kwelderwerken en twee verschillende data sets van voorkomen van zeegras. Deze beide datasets hadden echter beperkingen, gedeeltelijk als gevolg van waarnemersbias of gebrek aan gegevens. Al met al kunnen we concluderen dat Z. noltii voornamelijk voorkwam op de lagere delen van de kwelderwerken met een langere inundatieduur en met een beperkte sedimentdynamiek. Zeegras kwam niet alleen voor in sedimentatievelden die onderhouden worden, maar werd ook gevonden aan de randen van de kwelderwerken (waar geen onderhoud meer plaatsvindt) en buiten de kwelderwerken. Er werden geen aanwijzingen gevonden dat (veranderingen in het) onderhoud van de kwelderwerken een impact hadden op de veranderingen in het voorkomen van zeegras aan de kust van Groningen, wat impliceert dat veranderingen in het onderhoud de zeegrasgroei waarschijnlijk niet zullen stimuleren. Onze bevindingen laten daarom niet een-op-een zien dat het onderhoud van de kwelderwerken de aanleg van zeegras heeft bevorderd. Waargenomen herstel binnen de kwelderwerken zou eerder het resultaat kunnen zijn van verbeterde omgevingsomstandigheden die hebben geresulteerd in herstel op grotere schaal in het gehele Waddenzeegebied. De achteruitgang van het zeegrasveld net ten noordoosten van de onderzoeklocatie vraagt echter om aandacht, met name vanwege zijn mogelijke rol bij het leveren van zaden en wortelstokken aan de nabijgelegen kwelderwerken.

Eerdere bevindingen en aannames over het belang van blootstellingstijd, sedimentstabiliteit en ammoniak voor het voorkomen van zeegras in de Nederlandse Waddenzee werden bevestigd en (verder) gekwantificeerd, en er is indirect bewijs gevonden over de extra rol van cadmium en zwevende deeltjes in de beperking van groei van zeegras in verschillende delen van de Waddenzee. Geadviseerd wordt om meer informatie te verzamelen (bijvoorbeeld door middel van experimenten) over de dosis-effectrelaties om eventueel de concentraties van deze verbindingen te verminderen. Daarnaast bleek het belang van seizoensinvloeden en kenmerken van zeegrasvelden bij het bestuderen van de mogelijke effecten van hydrodynamica, sedimentdynamiek en gevoeligheid voor verontreinigende stoffen. Bij het beschermen van zeegras in de Waddenzee moet dan ook rekening worden gehouden met winteroverleving (door middel van zaden of wortelstokken). Zelfs als netto sedimentatie in een langzaam tempo plaatsvindt, kan dit nog steeds schadelijk zijn als de zeegrasvelden lokaal worden beschermd door vaste veen- en klei onderliggende sedimenten als de opslibbing tot een te dikke zandlaag leidt dat het zeegras niet meer kan wortelen in veen/klei. Het verdient daarom aanbeveling om de voormalige kwelders en de veranderingen in de netto sedimentatie in deze gebieden in kaart te brengen, om in de gaten te houden in hoeverre de zandlaag zo dik wordt dat het zeegras niet meer in de stevigere ondergrond kan wortelen. Gezien de waargenomen achteruitgang van het grootste zeegrasveld in de Nederlandse Waddenzee, wordt geadviseerd om mogelijke onderliggende oorzaken (als enkelvoudige en cumulatieve effecten) nader te onderzoeken om deze ongewenste ontwikkeling beter te kunnen begrijpen, kwantificeren en uiteindelijk te kunnen stoppen.

Wat betreft een handelingsperspectief voor beheer van zeegras in de Waddenzee wordt geadviseerd om:

- Bestaande zeegrasvelden zo goed mogelijk te beschermen door een meer gedetailleerde kartering van de zeegrassen zelf, waaronder de overleving in de winter en de eigenschappen van de planten zoals de dichtheid en de morfologie gedurende het groeiseizoen;
- De ontwikkeling van zeegrasvelden zo goed mogelijk te begrijpen door de meest relevante omgevingsfactoren in bestaande en voormalige zeegrasvelden te monitoren, waaronder de hydrodynamiek, de sediment dynamiek en (indien aanwezig) de dikte van een zandlaag op een stevige ondergrond van veen of klei;
- De kans op natuurlijk zeegrasherstel te vergroten door, waar relevant, verstorende menselijke activiteiten zoals bodemberoering en de concentraties van voor zeegrassen giftige stoffen in het water en de bodem in bestaande en potentiele zeegrasgebieden zoveel mogelijk (in ieder geval onder de drempelwaarden) terug te dringen;
- De huidige en toekomstige leefgebieden voor zeegras zo goed mogelijk te identificeren door de ontwikkeling van een dynamische en interactieve habitatkaart op basis van modellering van de interacties tussen zeegras en omgevingsfactoren (inclusief verspreiding van zeegraszaden);
- De omstandigheden voor zeegras verder te optimaliseren door de uitkomsten van het model (b.v. voor verschillende regimes van zoetwater afvoer of bodemberoering) mee te nemen in de belangafweging van alle betrokken in en rond de Waddenzee.

ABSTRACT

The Wadden Sea harbours two species of seagrass, being *Zostera noltii* and *Z. marina*. Both species of these flowering plants can exhibit an annual and a perennial life cycle, with winter survival by means of seeds and rhizomes, respectively. After a period of very low abundances due to diseases in the 1930s and eutrophication in the 1980s, seagrass in the northern parts of the trilateral Wadden Sea appears to recover, which is considered to be the result of (amongst others) an improvement of the water quality. In the southern parts of the Wadden Sea, however, seagrass beds are still scarce and of low density. Although seagrass in the Dutch Wadden Sea appeared to have experienced some recovery, the present surface area of seagrass beds (ca. 3 km^2) is still only a small fraction (< 3%) of surface area that appears to be suitable seagrass habitats (ca. 130 km^2). This calls for further exploration on environmental factors that are potentially limiting seagrass expansion in the Dutch Wadden Sea.

Seagrass is affected by any factor that changes water and sediment quality, implying that human impacts on environmental variables such as salinity, turbidity, light, current speed or temperature can compromised both growth and survival of seagrass. Bottom disturbance due to dredging, sediment extractions and demersal fisheries may directly (sediment disturbance) or indirectly (e.g. via an increase in turbidity) hamper seagrass developments. Global warming, increased storminess and sea level rise may affect seagrass via changes in temperature, exposure and inundation time, but also via facilitating or hampering parasites and grazers. Pollutants such as excess nutrients, marine litter, oil spills and chemical waste can be toxic for seagrass, in particular antifouling compounds, fungicides, insecticides, and herbicides. Because seedlings and propagules can have different sensitivity to external factors than seeds or adult plants, further understanding of the life cycle of seagrasses species is crucial for effective management and restoration of seagrass habitats.

Observational data by on water quality as collected by Rijkswaterstaat was combined with known information about seagrass occurrence in the Dutch Wadden Sea to explore the possibility of establishing concentrations thresholds in potentially growth-hampering or growth-required compounds. Based on the findings and on comparisons with thresholds derived from scientific literature, it appears that seagrass growth may be hampered by high concentrations of ammonia and cadmium (in particular in the Balgzand area), and of suspended particulate matter (in particular in the Ems estuary). Because sensitivity and toxicity of seagrass to these compounds appears to be related to its phenology (e.g., occurrence of various life stages during the year), further (experimental) research should focus on impacts during the various life stages and their possible cumulative effects. These findings should then be extrapolated to high-resolution data on field conditions within and outside seagrass beds, which would require an upgrade of the monitoring network in particular for ammonia, cadmium, mercury and suspended particulate matter.

Under the current and expected future conditions, the Wadden Sea is a hydrodynamically challenging environment for seagrass. As a shallow intertidal basin, the Wadden Sea experiences strong tidal currents that can erode the sea bottom, hamper the mechanical stability of the seedlings and ultimately disperse seeds. Also, wind-driven currents and waves can perturb the bottom, hence disturbing seagrass developments. Small locally generated waves can be destructive, especially if coupled to water level variations and tidal currents. However, the interaction between seasonality and variability of the drivers and vegetation is important to understand the co-evolution of the coupled seagrass-marsh system. Capturing these important local and short-term phenomena, e.g. to explore future (climate) scenarios and options for

seagrass restoration efforts, requires not only more detailed information but critically also advances in modelling approaches (in time and space).

Within the salt-marsh works along the Groningen coast man-made sedimentation fields reduced erosion rates and increased sedimentation rates by reducing wave action. The aim of this study was to determine the effect of these man-made sedimentation fields on the occurrence of the seagrass *Zostera noltii*. We used two long-term datasets that monitor seagrass occurrence along the Groningen coast. However, both datasets had limitations, partially due to observer bias or lack of data. Overall, we can conclude that *Z. noltii* mainly occurred on lower elevations with higher inundation duration and with limited sediment dynamics. Occurrence was not restricted to the 2nd maintained sedimentation fields, but was also present in the no longer maintained 3rd sedimentation fields as well as outside the salt-marsh works. Therefore, we did not find clear evidence that maintenance of the salt-marsh works promoted seagrass establishment. Recovery within the saltmarsh works might be the result of improved environmental conditions that resulted in larger scale recoveries in the entire Wadden Sea area. The decline of the seagrass bed just North-east of the study site, however, calls for further attention in particular due to its potential role in supplying seeds and rhizomes to the nearby saltmarsh works.

In this study, we confirmed and (further) quantified previous findings and assumptions on the importance of exposure time, sediment stability and ammonia for seagrass occurrence in the Dutch Wadden Sea (Table 6.2). Furthermore, we found circumstantial evidence on the additional role of cadmium and suspended particulate matter restricting seagrass growth in several parts of the Wadden Sea; We advise to gather more information (e.g., by means of experiments) on the dose-effect relationships to underline management actions to reduce the concentrations of these compounds. In addition, we illustrated the importance of taking seasonality and characteristics of seagrass meadows into account when studying the potential impacts of hydrodynamics, sediment dynamics and sensitivity to pollutants. We advise to include winter survival (by means of seeds or rhizomes) into account when mapping seagrass in the Wadden Sea. Even if net sedimentation occurs with a slow pace, it might still be detrimental if the seagrass beds are locally protected by solid peat and clay underlying surface sediments because an increase of in sandy layer thickness might reduce the possibility of seagrass to root into the stable underground. We, therefore, advise to map the areas former saltmarshes and the changes in the net sedimentation at these areas. We found no evidence that (changes in the) maintenance of the saltmarsh works had an impact on the changes in seagrass occurrence at the coast of Groningen, implying that changes in maintenance are not likely to stimulate seagrass growth. Given the observed decline of the largest seagrass meadow in the Dutch Wadden Sea, we advise to study potential underlying causes (as single and cumulative effects) in more detail in order to be able to better understand, quantify and ultimately halt this development.

With regard management perspective of conservation of seagrass in the Wadden Sea, it is recommended to:

- Protect existing seagrass beds as much as possible by a more detailed mapping of the seagrasses themselves, including winter survival and the properties of the plants such as density and morphology during the growing season;
- Understand the development of seagrass beds as well as possible by monitoring the most relevant environmental factors in existing and former seagrass beds, including hydrodynamics, sediment dynamics and (if present) the thickness of a sand layer on top of peat or clay;
- Increasing the probability of natural seagrass recovery by, where relevant, reducing disruptive human activities such as soil disturbance and the concentrations of substances

toxic for seagrass in the water and the soil in existing and potential eelgrass areas as much as possible (at least below the threshold values);

- Identify current and future habitats for seagrass as effectively as possible through the development of a dynamic and interactive habitat map based on modelling of the interactions between seagrass and environmental factors (including distribution of eelgrass seeds);
- To further optimize the conditions for eelgrass by including the outcomes of the model (e.g. for different regimes of freshwater discharge or soil disturbance) in the weighing of interests of all those involved in and around the Wadden Sea.

1. INTRODUCTION

Catharina J.M. Philippart & Irene Ballesta-Artero

1.1 Seagrass developments

The area of seagrass beds is regarded as a reciprocal eutrophication indicator and is recorded as a parameter for the European Water Framework Directive (WFD, directive 2008/32/EC). Seagrass is also a parameter for angiosperms (together with saltmarsh vegetation) for the WFD. Being responsible for the water quality of the Dutch part of the Wadden Sea, Rijkswaterstaat safeguards and improves the quality of this ecosystem, including the presence of littoral and sublittoral seagrass beds[1]. Effective management of seagrass beds requires knowledge about the factors that influence the establishment, growth and survival of seagrass as a baseline for determining the suitability of the habitat. This information enables the protection and promotion of seagrass beds by, for example, reducing human activities that hinder natural processes and seagrass recovery at locations where seagrass is already present or could be occurring (Dolch et al. 2017; Zwarts et al. 2018; Folmer 2019).

Seagrasses are marine flowering plants (angiosperm) which appear worldwide (Short et al. 2007; Suykerbuyk 2019). These plants form meadows which are crucial coastal ecosystems, being a feeding, sheltered, spawning and nursery place for many marine organisms (Polte et al. 2005; van Katwijk et al. 2009; Dolch et al. 2017). Although their numbers are globally declining (Duarte 2002; Orth et al. 2006; Waycott et al. 2009; van Katwijk et al. 2016), there are still some resistant populations which can be key to conserve these productive ecosystems (Duarte 2002, Zipperle et al. 2009; Ondiviela et al. 2018). More recently, however, there appears to be local recoveries of meadows of *Zostera* spp. within Europe, which was mostly attributed to management actions including improvement of water quality, reduction of industrial sewage, and anchoring and trawling regulations (de los Santos et al. 2019).

Zostera noltii and *Zostera marina* are the seagrass species present in the Wadden Sea. Nowadays, *Z. noltii* is the more common of the two and is mainly found in the intertidal area (Zipperle et al. 2009, Dolch et al. 2017). *Z. marina* can be found in both subtidal and intertidal areas and has two forms; narrow-leaved (flexible) and wide-leaved (robust). However, after the so-called wasting disease of 1930s (due to a marine slime mould-like protist), the robust type is now extinct in the Netherlands (den Hartog 1987; van Katwijk et al. 2000; de Jong et al. 2005; Dolch et al. 2017).

The Wadden Sea can be divided into three major regions regarding ecosystem processes (Reise 1995; CWSS 2008):

(1) the southwestern Wadden Sea (tidal range is 1.5m to 3m), from the Marsdiep tidal inlet to the Jade tidal inlet, bounded by elongated islands forming a sandy barrier 5km to 15km parallel to mainland;
(2) the central Wadden Sea (tidal range more than 3m), from the Jade inlet to the southern shore of Eiderstedt peninsula, lacking barrier islands and ebb-deltas due to the large volume of tidal water exchange (Ehlers 1988); and
(3) the northern Wadden Sea (decreasing tidal range from 3m to 1.2m in a northward direction), from the north of Eiderstedt peninsula to the Danish Wadden Sea (Skallingen

[1] https://www.rijkswaterstaat.nl/water/waterbeheer/waterkwaliteit/indicatoren-voor-waterkwaliteit/zeegras/index.aspx

Peninsula), consisting of islands and high sand bars that form a seaward barrier from 5km to 25km off the mainland coastline (Philippart & Epping 2010).

Seagrass meadow's distribution differs in density and beds number in these regions (Folmer et al. 2016; Dolch et al. 2017). Northern populations are dense and have expanded until 2015 (based upon the most recent overview of the trilateral Wadden Sea; Dolch et al. 2017). This expansion was possibly due to a reduction in nutrient loads, seed transport to formerly uninhabited but potential suitable areas, and by increasing the suitability of tidal flats in the upper intertidal for *Zostera marina* by *Z. noltii* (Dolch et al. 2017).

Southern seagrass beds are still scarce and with low density since strong eutrophication resulting from intensified riverine nutrient supply that occurred in the 1970s (Hartog and Polderman 1975; Philippart and Dijkema 1995; van Katwijk at al. 2010; Folmer et al. 2016; Dolch et al. 2017). This anthropogenic eutrophication affected more the Southwestern and central Wadden Sea due to its proximity to large estuaries, and might still be limiting present seagrass occurrence (van Katwijk at al. 2000; Folmer et al. 2016; Dolch et al. 2017). Other factors potentially limiting seagrass growth in the southern Wadden Sea are the lack of suitable, sheltered habitats, where hydrodynamic conditions are sufficiently calm and sediments stable, the lack of plants or a 'critical mass' and bioturbation by lugworms.

Based upon seagrass mapping as performed by Rijkswaterstaat[2], the total surface area of three selected seagrass beds in the Dutch Wadden Sea increased from ca. 1.5 km^2 in the early 2000s to around 2.5 km^2 in the late 2000s and early 2010s, with this development mainly due to changes in the largest seagrass bed near the coast of Groningen (Dolch et al. 2017). Furthermore, a modest natural recovery has been reported near the islands of Rottum and Griend (Dolch et al. 2017; Folmer 2019) and, since 2018, resulting from transplanting experiments at Griend[3].

[2] https://www.rijkswaterstaat.nl/water/waterbeheer/waterkwaliteit/indicatoren-voor-waterkwaliteit/zeegras/zeegraskartering.aspx
[3] https://zeegrasherstelwaddenzee.com/2018/07/31/uitbundig-zeegras-bij-griend/

1.2 Seagrass life cycles

The narrow-leaved subspecies *Z. marina* is mainly annual, whereas the wide-leaved *Z. marina* and *Z. noltii* are principally perennial (Zipperle et al. 2009; Dolch et al. 2017). These plants can reproduce both asexually through the extension of rhizomes and sexually by the production of seeds (Figure 1.2). The contribution of both types of reproduction within a meadow varies widely in *Zostera* spp. (Zipperle et al. 2009). There is, for instance, an ancient *Z. marina* clone in the Baltic which persisted more than 1000 years old in a changing environment (Reusch et al. 1999), while the persistence of other meadows is based upon a continuous supply and germination of seeds (Coyer et al. 2004).

In the Wadden Sea, clonal growth through the extension of rhizomes (branching; Figure 1.1) starts around mid-April and stops by the end of July as the result of shortening of the length between rhizome nodes (Philippart 1995), mainly due to the decline of light availability (Vermaat and Verhagen 1996). The flowering season goes from late July to October in *Z. marina* and from late June to September in *Z. noltii* (Hootsmans et al. 1987, Philippart 1995). Seed numbers increase strongly in the sediment at the end of August and at the beginning of September for *Z. noltii* and *Z. marina*, respectively (Hootsmans et al. 1987).

Thus, the Wadden Sea meadows find its maximum extent and cover in August (Dolch al. 2017), with peaks in biomass of both shoots and rhizomes (Philippart 1995). In fall, massive losses happen due to grazing by ducks and geese (Vermaat and Verhagen 1996; Nacken and Reise 2000) and senescence (Philippart 1995). While in winter, survival is mainly due to shoots in *Z. noltii* and to seeds in *Z. marina* (Jacobs 1982; Hootsmans et al. 1987; Vermaat and Verhagen 1996). In Terschelling, *Z. marina* is considered semi-annual because incidental plant survival was also found in winter (van Katwijk et al. 2010).

An important factor to take into account in *Zostera* spp. is that their range of dispersion is limited due to the relative heavy weight of their seeds (Loques et al. 1988; Orth et al. 1994; Zipperle et al. 2009). Most living seeds are found at less than 1000 meters from the originated bed (Costa et al. 1988; Orth et al. 1994). This indicate that when a *Zostera* bed is lost, the recolonization from other beds happens only occasionally. For instance, Folmer et al. (2016) identified locations in the Wadden Sea that may be suitable for seagrass growth, but meadows fail to establish there possible due to the short dispersion range (Dotch et al. 2017). Nevertheless, currents can sometimes transport detached spathes (single floral unit with female and male flowers grouped) and flowering shoots over kilometres (Harwell and Orth 2002; Erftemeijer et al. 2008; Ferber et al. 2008; Zipperle et al. 2009). Van Katwijk et al. (2016) found that recovered seagrass meadows have higher success when the distance to a donor bed is less than 10 km away.

Figure 1.1. The dwarf seagrass Zostera noltii which is anchored into the seafloor with rhizomes and roots, connecting shoots consisting of a stem and groups of two to five strap-shaped leaves which can include spear-shaped lateral stem with separate male and female flowers (www.upload.wikimedia.org)

The overall process of flowering and seed formation takes about 40 days in *Zostera* spp. (De Cock 1980, Alexandre et al. 2006). Moreover, seeds need about 30 days to germinate and from 17-23 to accomplish seedling stage (Alexandre et al. 2006). Lab experiments have shown that there is a large variation in seeds germination success, from 16 to 70%, and only ~10% of them accomplish seedling stage (Alexandre et al. 2006; Zipperle et al. 2009). Moreover, seeds are only viable around 3 years (Zipperle et al. 2009), which is a relative short-time life to recover a meadow from seeds banks. Therefore, seagrass plants have to survive using windows of opportunity at its different phase stages (Bouma et al. 2009).

1.3 Seagrass restoration efforts

Reestablishment of seagrass meadows have shown low chances of success in the last decades (Bouma et al. 2009). Katwijk et al. (2016) calculated a 37% success rate based on 1786 trials of seagrass restoration around the world (trial defined as plant material with the same treatment), 50% of them done with the species *Z. marina*.

The main cause of seagrass degradation is reduction of water quality, both due to turbidity increase and nutrient loadings (Erftemeijer and Lewis 2006). Different authors pointed out some crucial factors for successful restoration practices such as (i) large-scale transplantations (> 100.000 specimens) which increases seagrass survival by 42%, (ii) transplantation in subtidal areas (75% success rate), (iii) manual planting, and (iv) that the transplantation location should previously have had seagrass (van Katwijk et al. 2009, 2016).

Van Katwijk et al. (2016) found that seedlings performed worse than other plant material (sods, rhizome fragments and seeds) used on restoration programs. Plant material with an anchoring improved 84% survival, being the application of weight to rhizome fragments the best technique studied. However, seedlings are still more used (18%) than seeds (9%) for seagrass restoration studies. Bare root transplantations predominated in restoration efforts in the Western Wadden Sea. Although some transplantations with sods have been done, did not perform better than the bare root sediments (van Katwijk et al. 2009).

Summarized, reestablishment of seagrass meadows in the last decades in the Wadden Sea had low success rates so far (Bouma et al. 2009, van Katwijk et al. 2016). In recent years (2018-2020), however, the transplant of *Z. marina* seeds near Griend resulted in a seagrass meadow that increased from 30 hectares in 2018 to 170 hectares in 2020 (with a density of 30 shoots per m^2 for the area where the seeds were planted), but it is not yet clear if this bed is self-sustaining[4].

[4] https://zeegrasherstelwaddenzee.files.wordpress.com/2020/11/nieuwsbrief-zeegras-nov-2020.pdf

1.4 Seagrass habitats

In the **early 1990s**, the distribution of seagrass (*Z. noltii* and *Z. marina*) was found to be related to the period of emersion, sediment type, sediment stability and region (Philippart & Dijkema 1992). The models showed that no seagrass was expected in the proximity of main river estuaries, even under optimal conditions with respect to the other factors. This may point to low salinities limiting seagrass growth and survival, but possibly also to growth-restricting compounds being transported by rivers into the sea, including excess nutrients (Philippart & Dijkema 1992). Within the Dutch Wadden Sea, suitable habitats (ca. 60 km^2) were located at Balgzand, the tidal divide of Terschelling, the mudflats near Griend, and just offshore the mainland of Fryslân and Groningen (Philippart et al. 1992).

In the **mid-2000s**, the habitat suitability of seagrass (*Zostera noltii* and *Z. marina*) was assumed to be related to the tidal exposure, hydrodynamics (current velocity, wave action) and an interaction between salinity and ammonium flux (de Jonge et al. 2005). Based on the outcome of this compilation, presented as a so-called "opportunities map", it was concluded that the Dutch Wadden Sea comprised ca. 20 km^2 that was considered suitable habitats for seagrass. The best areas (ca. 2 km^2) were mainly located north of the mainland, south of the islands and at the mudflats between Lake Lauwersmeer and the Ems estuary (de Jonge et al. 2005).

In the **mid-2010s**, consensus forecasting for seagrass occurrence in the trilateral Wadden Sea region (involving Denmark, Germany and the Netherlands), using hydrodynamic and geomorphological characteristics of the intertidal area as predictors, indicated that extensive areas (211 km^2) in the Dutch Wadden Sea should be suitable for seagrass, and that these areas are mainly located at the tidal divides and close to the mainland of Fryslân and Groningen (Folmer et al. 2016). Further detailed studies on seagrass distribution in the Dutch part of the Wadden Sea, additionally incorporating waves, sediment composition and benthic fauna as predictors, reduced the surface area of potential seagrass habitats to 130 km^2 (Folmer et al. 2019). This was mainly due to a decrease in the area of previously identified locations through a re-evaluation in this report.

1.5 Aim of this study

The actual surface area of the seagrass beds at present (ca. 3 km^2) being, however, still only a small fraction (< 3%) of surface area that appears to be suitable seagrass habitats (ca. 130 km^2) calls for further exploration on environmental factors that are potentially limiting seagrass expansion in the Dutch Wadden Sea. Rijkswaterstaat being responsible for protection and restoration of seagrass (*Zostera spp.*) in the Dutch Wadden Sea, as set by the European Water Framework Directive, commissioned a study to the Royal Netherlands Institute of Sea Research (who invited Wageningen Marine Research to contribute) to further explore thresholds in hydrodynamics, geomorphological dynamics and concentrations of potentially growth-hampering compounds.

This report describes the findings of this exploration, by subsequently providing an overview of potentially harmful human impacts on seagrass (**Chapter 2**), comparing the concentration of potentially toxic compounds within and outside seagrass beds (**Chapter 3**), exploring the various aspects that determine the impacts of wind-driven currents and waves on seagrass (**Chapter 4**), and determining the effects of (management of) man-made sedimentation fields on the occurrence of the seagrass *Zostera noltii* at the coast of Groningen (**Chapter 5**). Finally, all results on are synthesised (**Chapter 6**), including an identification of the most likely factors for hampering seagrass growth and survival in the Dutch Wadden Sea, and options for management to improve suitability of seagrass habitats.

2. HUMAN IMPACTS ON SEAGRASS

Irene Ballesta-Artero & Catharina J.M. Philippart

2.1 Introduction

The trilateral Wadden Sea region has about 3.8 million inhabitants and 10 million tourists every year (Bjarnason et al. 2017). Thus, human activities have a large impact over the landscape, plants and wildlife. Seagrass is affected by any factor that changes water and sediment quality. Consequently, when environmental variables such as salinity, turbidity, light, current speed or temperature are altered due to human impact, both growth and survival of seagrass can be compromised (Figure 2.1). In this chapter, we supply an overview of main human activities affecting seagrass in the Wadden Sea.

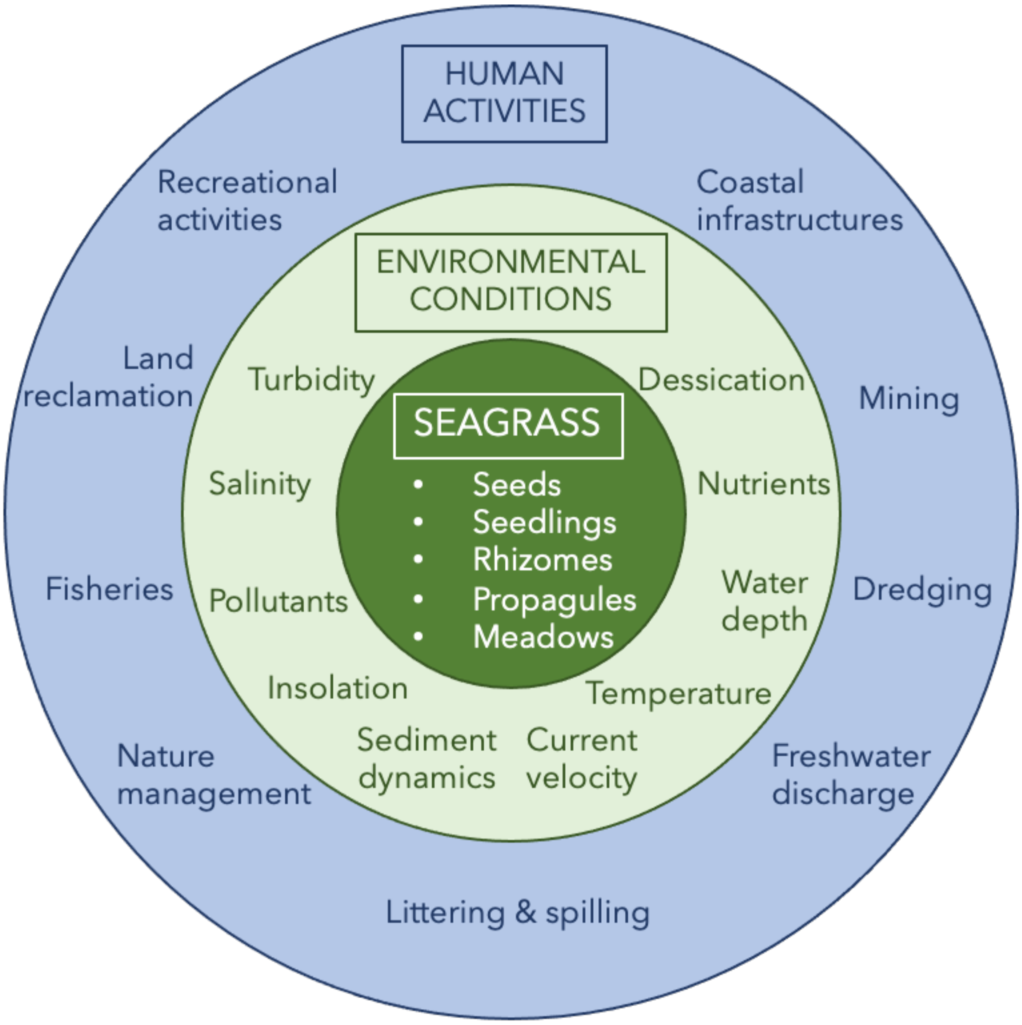

Figure 2.1. Relationships between human activities and environmental conditions determining settlement, growth and survival of seagrass in the Wadden Sea.

2.2 Sediment extraction and dredging

Sediment extractions and dredging have been traditionally deployed for the construction of dikes and roads and is, nowadays, mainly performed for the maintenance and deepening of shipping lanes (Schultze and Nehls 2017).

Within the Dutch Wadden Sea, every year an amount of about 354.000 m^3 sand was been extracted, in particular (290.000 m^3 a^{-1}) in the tidal basin between Vlieland and Ameland (Schultze and Nehls 2017). The three Wadden Sea countries planned to gradually reduce to zero sand and shell extraction between 2016 and 2021, by shifting all sediment extraction activities to areas outside the Wadden Sea, in the open North Sea beyond 15m depth contours (Schultze and Nehls 2017).

Between 2006 and 2013, on average 6 million tons of sediment were dredged and dumped in the Wadden Sea area every year, mainly in the estuaries of Elbe, Weser, Jade and Ems for maintaining the navigation channels (Schultze and Nehls 2017). Within the Dutch part of the Wadden Sea, the annual quantities of dredged and dumped material since 2005 varied between 1 and 10 million tons (Schultze and Nehls 2017), amongst others at locations which are current (and potential) habitats for seagrass (Folmer et al. 2016).

Dredging and sediment extractions can directly and indirectly contribute to loss of seagrass vegetation (Erftemeijer and Lewis 2006). These actions directly remove benthic flora associated with the sediment and often result in serious loss of biomass due to dredging and/or to excessive sedimentation causing (temporal) burial of seagrass plants (Schultze and Nehls 2017). *Z. noltii* and *Z. marina* adult plants, such as other species without vertical rhizomes, experience high mortality (>50%) under low burial levels, 2 to 4 cm, respectively (Vermaat et al. 1997; Mills and Fonseca 2003; Cabaço et al. 2008). Moreover, excessive sedimentation may bury seagrass seeds, precluding seed germination (Hootsmans et al. 1987).

Moreover, they provoke periods of high turbidity and/or and decreases light availability and reduce overall water quality (Yaakub et al. 2014). Consequently, those factors decrease seagrass rhizomes, seeds and seedlings survival (Cabaco et al. 2008). The critical seagrass thresholds for turbidity and sedimentation can be determined in terms of light availability (% of surface irradiance: SI), and vary in *Zostera* spp (Erftemeijer and Lewis 2006). Minimum light requirements for adult plants of *Z. noltii* are lower (2% SI) than for *Z. marina* (11 - 36% SI; Erftemeijer and Lewis 2006). Also, the length of time that *Zostera* spp. are at low light levels is important. Laboratory experiments have shown that *Z. noltii* can survive below their minimum light requirements during a couple of weeks (Peralta et al. 2002).

In addition, indirect adverse effects on seagrass habitats such as temporarily reduced dissolved oxygen concentration, release of nutrients and pollutants from contaminated sediments, and hydrographic changes (bathymetry, current velocities and wave conditions) may also occur due to dredging and sediment extractions, negatively affecting all seagrass life's stages (Jensen and Mogensen 2000; Erftemeijer and Lewis 2006).

Large dredging and sediment extraction operations have, however, been done without causing significant impact on seagrass beds (Erftemeijer and Lewis 2006). In the Ems estuary (the Netherlands), dredging and excavating 250,000 m^3 for the deepening of the gas pipeline has not shown a significant impact on nearby *Z. marina* beds at that time (Erftemeijer 2002; Erftemeijer and Wijsman 2004). That was possible by restricting the disturbance time, applying turbidity plume modelling, and carrying out Environmental Impact Assessment (EIA) programs (Erftemeijer and Lewis 2006). Whilst the population was still thriving in 2003 (covering an area of 285 ha), the seagrass meadows started to decline in 2004 until only a few isolated plants were left in 2012 (Jager & Kolbe 2013).

2.3 Land reclamations

Coastlines are undergoing enormous changes due to human development, including large-scale land reclamations and infrastructural works such as (Yaakub et al. 2014). Both tidal flats (66 km^2 in the 19^{th} century) and saltmarshes have been embanked to provide coastal protection and new land for agricultural exploitation (Dijkema 1987; Bakker et al. 2002). In the Western Wadden Sea, for example, shelter by man-made sand dikes from the 17^{th} century onwards induced a growth of the island saltmarshes of the Dutch Wadden Sea from 17.5 km^2 to 88.5 km^2 in the 18^{th} century, after which these saltmarshes were fully embanked in the beginning of the 19^{th} century (Dijkema 1987). At present, artificial saltmarshes Dutch Wadden Sea are mainly found along the coasts of Groningen and Friesland (Bakker et al. 2002).

Stimulation of artificial saltmarshes decreases local suitability of the area for seagrass growth, whilst common coastal works such as harbours, docks, breakwaters and beach stabilization change sedimentary dynamics and, consequently, affect seagrass habitats (Cabaço et al. 2008). Loss and fragmentation of seagrass meadows occurs due to extraction and burial of adult plants and seeds. The vulnerability of seagrass plants to burial decreases with increasing leaf length and rhizome diameter (Cabaço et al. 2008). *Z. noltii*, for instance, is extremely sensitive to sediment burial, but it is a fast-growing species which can recovery fast if the burial disturbance is not too long (Cabaço et al. 2008). Seagrass beds (adult plants, rhizomes, and seedlings) may also suffer limitation of light availability due to shading from during the construction of coastal infrastuctures (causing local increases in turbidity), and consequently, limitation of photosynthesis and growth (Duarte 2002).

2.4 Demersal fisheries

Bottom-dredging fisheries have a direct impact on the benthic zone and have been recently restricted in the Wadden Sea area (Baer et al. 2017). The Wadden Sea fisheries concentrate on shrimps (*Crangon crangon*) and mussels (*Mytilus edulis*). On a smaller scale, there are manual fisheries on cockles (*Cerastoderma edule*) and oysters (*Crassostrea gigas*; Baer et al. 2017).

Until 2017, there was no clear regulation about the brown shrimp (*Crangon crangon*) fishery which has been increasing its landings since 1960 (maximum landings recorded was 38.613 tons in 2005; ICES 2015; Tulp et al. 2016). Due to the short life span of the species (up to 2 years old), there are no reliable stock size estimates, and thus its management strategies are difficult to establish (Tulp et al. 2016; Baer et al. 2017). While the share of Danish and Germans landings has recently decreased, the Dutch fleet have increased its share from 21% in 1981 to 54% in 2014 (ICES 2015; Baer et al. 2017). The overfishing of shrimp main predators (cod and whiting) have apparently enhanced its populations in the Wadden and North Sea areas. Nevertheless, shrimp stocks are also showing signs of high fishing pressure over the last years. The increased fishing effort is not correlated with an increase of landings (ICES 2015; Tulp et al. 2016; Baer et al. 2017).

The mussel fishery has an opposite trend in the Wadden Sea area. Landings have decreased in Netherlands and Germany since 2005, and due to the relatively small size of the stocks, there has been no mussel fishery in the Danish Wadden Sea since 2008 (Baer et al. 2017). Most mussels from Germany and the Netherlands are transported to special plots in the eastern part of the Oosterschelde (Netherlands), where the mussels recover from transportation and remain for a rinsing period prior to be sold to consumers (Baer et al. 2017).

Mussel seeds are usually caught from the wild spat stock with the use of a mussel dredge (and trawl nets in Lower Saxony; Baer et al. 2017). To reduce the impact on the seafloor, new artificial seed collection technologies, long lines or rope/net seed collectors, are being developed (Baer et al. 2017). Mussel seed fishery is only allowed in subtidal areas, excepting some intertidal areas of Lower Saxony. In the Netherlands, the government agreed that bottom seed fisheries will be reduced (2009-2021; Fig. 7) to enhance alternative seed resources as seed mussel collectors.

In 2010, a trilateral Wadden Sea Plan[5] established the future policies for sustainable fisheries, reducing bycatch and seafloor impact. The goal for the shrimp fishery is to reduce its ecological impact to 50% in 2020, and for the mussel fishery to cease the mussel seed fishing in at least half of the current area by 2022. Moreover, most shrimpers voluntary adopted a trilateral North Sea Brown Shrimp Management Plan in 2015, which achieved the sustainable MSC (Marine Stewardship Council) certification for the North Sea brown shrimp in December 2017. The University of Hamburg, the International Council for the Exploration of the Sea (ICES), and a coalition of eight conservation NGOs helped to develop a harvest control rule to ensure the stable and healthy growth of the shrimp stock, and to minimize the impact of shrimp fishing on the environment[6].

Trawling and anchoring are carried out in vulnerable areas for seagrass. Shrimp fishery is carried out within the 6 miles coastal zone, extending from Sylt to the Dutch-Belgian border and thus, overlapping with current and potential seagrass habitats in the Wadden Sea (Aviat et al. 2011;

[5] https://www.waddensea-worldheritage.org/resources/2010-wadden-sea-plan

[6] www.msc.org

Netherlands Fishing Annual report 2016; Folmer et al. 2016). Shrimp trawl fishing damages the seafloor, eroding the sediment and reducing seagrass biomass (Collie et al. 2000; Baer et al. 2017).

Erosion exposes seagrass roots, which can, then, be colonized by drilling organisms, affecting seagrass survival (Cabaço et al. 2008), and leaving them exposed to waves and currents, provoking uprooting. The extent of the effects of erosion on seagrasses is strongly size-dependent (Cabaço et al. 2008). Balke et al. (2011) found that root length of the seedlings is critical to prevent their dislodgement and thus, assure their survival. Moreover, longer leaves of adult plants have larger loss at hydrodynamic exposed sites (Hermus 1995). Adult plants of *Z. noltii* experiences ~50% mortality at erosion depth of -2 cm (Cabaço and Santos 2007). Moreover, *Z. noltii* experiences a decrease in shoot density and an increase of the internode length due to erosion, suggesting a plant attempt to search for new sediment (Cabaço and Santos 2007). Boese and Robin (2008) showed that erosion removes a portion of perennial shoots of *Z. marina* beds, but to our knowledge, there is no quantitative experimental information of how erosion affect *Z. marina* survival.

2.5 Climate change

Climate change affects all habitats around the world with main effects within the Wadden Sea area on temperature, precipitation, solar radiation and sea-level rise (Oost et al. 2017). These factors will provoke higher evaporation rates and drought, erosion by rising sea level and increased storms (among others), which will trigger deep changes in the marine ecosystem (Duarte 2002; Oost et al. 2017).

By the end of the century, global sea-level is expected to rise between 26 to 86 cm relative to the reference period 1986 to 2005 (IPCC AR5). For the North Sea basin, KNMI'14 scenarios ranged mean sea-level rise similar to the global mean, between 25 to 60 cm considering the low G-scenario, and between 45 to 80 cm according to the high W-scenario (KNMI 14).

Based on the climate scenario "RCP8.5 - MPI-ESM-LR (Run 1) - REMO2009 (EUR-11)", the Wadden Sea atlas projects a mean increase in temperature of 2.6 °C, an increase of 16% in precipitation with an average of 3 more stormy days, and an increase of 2% in mean wind speed until the end of the 21st century (www.coastalatlas.org). These increases will also lead to an average decrease in salinity of the Wadden Sea region (see salinity effect on seagrass below, freshwater discharges).

The Wadden Sea is already affected by changes due to climate change, however, their implications for the abiotic and biotic ecosystems are not yet fully understood (Oost et al. 2017). That is what was adopted for the Tønder Declaration, a trilateral climate change adaptation strategy, in 2014 (CWSS 2014). Because large uncertainties surround climate projections, their management strategies aim to be robust enough to perform well under all weather conditions and flexible enough to enable shifting to alternative management approaches (Oost et al. 2017).

Climate change impacts in the Wadden Sea are expected to vary in space and time. Therefore, some seagrass areas with small increases of temperature and decreases of salinity can be beneficiated, for instance, with higher germination rates (Hootsmans et al. 1987). However, more diseases and parasites can surge due to higher temperature and salinity changes may produce osmotic shocks (Duarte 2002). Special attention should be given to seagrass beds close to their distribution boundaries. Slightly changes in the environmental conditions of those areas will have higher impacts on seagrass beds. Increase of solar radiation may produce, for instance, changes in emersion times, being desiccation lethal for *Zostera* seeds (Hootsmans et al. 1987).

Because of the preference of seagrass for particular emersion times, sea level rise will induce the migration of seagrass meadows towards the coastline (Valle et al. 2014). This migration could be facilitated by moving the boundaries more land inwards, e.g. by opening the dikes and enlarging the Wadden Sea by incorporating former polders[7].

Moreover, phenology such as the seasonal migration, is altered due to global warming. Species wintering in the Wadden Sea have already developed different migration strategies, the greylag goose (*Anser anser*) now departs three weeks earlier and the barnacle geese (*Branta leucopsis*) have postponed their departure by four weeks (Laursen and Frikke 2013; Philippart et al. 2017). These changes may produce phenological mismatches within the coastal foodweb, which may affect seagrass, for instance, the adult plants being grazed before they reach their reproductive stage.

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[7] https://publicwiki.deltares.nl/display/KWI/2.2.3.1.+Wisselpolders

Changes in wind strength and direction may modify wave actions and storms, causing erosion, and producing seagrass loss due to plants uprooting. Moreover, coarsening of the sediment due to an increase in hydrodynamic forces may contribute to the reduction of benthic invertebrate stocks (Bartholomä and Flemming 2007; Dolch and Reise 2010), which may affect symbiotic relationships with seagrass specimens. For instance, mussel beds create benefit shelter and favour seagrass transplant survival (Bos and van Katwijk 2007). Lastly, changes in wind direction may also isolate border seagrass habitats of the Wadden Sea area (Coyer et al. 2004; van Katwijk et al. 2009). Isolation by distance became apparent at distances of more than 100 to 150km (Coyer et al. 2004). Therefore, there is some risk of isolation for the most Western beds of the Wadden Sea due to the predominant Western winds (van Katwijk et al. 2009).

2.6 Freshwater discharges

Freshwater discharges lead to large variation in salinity (as well as pollutants including nutrients, see section below). The major annual freshwater discharges influencing the southern Wadden Sea come from the Rhine, Meuse, Noordzeekanaal, IJsselmeer and Ems, and in the central and northern Wadden Sea from Weser and Elbe (Pätsch and Lenhart 2004). River nutrient inputs, especially phosphorus and nitrogen compounds, are the main drivers of Wadden Sea eutrophication problem (van Beusekom et al. 2017).

Salinity changes due to river discharges can provoke osmotic shocks to seedling and adult seagrass plants (Duarte 2002). Salinity fluctuations between 9 and 31 PSU are tolerated by *Zostera* spp. (Pinnerup 1980; Wium-Andersen and Borum 1984; de Jong et al. 2005). There are records showing that before the 1930s, there was seagrass presence with yearly salinity average of 10 PSU (de Jong et al. 2005; Katwijk et al. 2009). Nevertheless, Bos et al. (2005) showed that seagrass adult plants are rarely encountered in the Wadden Sea when yearly averages are below 18 PSU. Furthermore, according to Kamermans et al. (1999) and van Katwijk et al. (1999), average salinity levels between 22 and 27 PSU are better than 30 PSU for adult plant survival.

De Jong et al. (2005) pointed out that current field observations in the Dutch Wadden Sea only concern the flexible type of *Zostera marina* (see §1.1) which does not occur at salt levels lower than 23-27 PSU (i.e., Kamermans et al. 1999; van Katwijk et al. 1999). The spread of *Z. marina* in the Netherlands suggests that salt tolerance is linked to the morphotype, i.e., robust versus flexible (van Katwijk et al. 2000). For the Baltic Sea, it has been observed that the robust type of seagrass can still grow in areas with a salinity as low as about 10 PSU (Pinnerup 1980; Wium Andersen and Borum 1984).

In addition, lower salinity values stimulate seed germination (Hootsmans et al. 1987; Xu et al. 2016). However, these low levels (< 20 PPT) also had a negative effect on seedling morphology (reduced number and length of leaves) and growth (Fernández-Torquemada and Sánchez-Lizaso 2011; Xu et al. 2016). Xu and coauthors (2016) suggest that the optimum salinity for *Z. marina* seedling establishment and colonization appears to be above 20 PSU.

2.7 Recreational activities

In the Wadden Sea, human wading that inherently involves trampling of the substrate in shallow coastal waters and on tidal flats is a common activity, in particular crossing the Wadden Sea between the mainland of Fryslân and Groningen to the adjacent islands[8]. This activity has been observed to reduce seagrass biomass, with the recovery following a trampling event may take at least seven months (Eckrich & Holmquist 2000) or, if being a more structural activity, result in lower densities and smaller seagrass plants (Travaille et al. 2015).

At present, there are 24 routes described for the Dutch Wadden Sea (including the Ems estuary)[9], of which most follow the tidal divides (generally characterized by long emersion times and muddy sediments). The maximum number of people that are allowed to wade over the mudflats is set at 50.000 per year[10], implying that ca. 2000 people walk over the mudflats per route per year. If these routes are (or could be) inhabited by seagrass beds, then mudflat walking can be expected to locally reduce or prevent seagrass growth and survival.

[8] https://www.visitwadden.nl/nl/bezoeken/wadlopen
[9] https://www.wadgidsenweb.nl/helden/alleoversteken.html
[10] https://decentrale.regelgeving.overheid.nl/cvdr/xhtmloutput/Historie/Fryslân/627849/CVDR627849_1.html

2.8 Mining

In the Dutch part of the Wadden Sea, gas and salt are currently being extracted from several fields that are either fully or partially located underneath the Wadden Sea Area.

Since 2006, the potential impacts of gas extraction at five locations (Moddergat, Nes, Lauwersoog Central, Lauwersoog West, Lauwersoog East and Vierhuizen East) are strictly monitored and gas extraction has to be reduced or stopped if any negative effects on the natural values (in particular on food supply for wading birds) are observed[11]. Between 2007 and 2019, the maximum total lowering of the deep subsurface under the tidal flats ranged between 5 and 8 cm and the average deepening of the tidal basins between 1 mm per year (Zoutkamperlaag) and 2 mm per year (Pinkegat) (Auditcommissie Aardgaswinning 2020).

In 2020, salt extraction started near the city of Harlingen which is expected to result in a maximum lowering of the deep surface of more than 100 cm within 20 to 40 years, implying an average local deepening of 2.5 to 5 cm per year (Auditcommissie Zoutwinning 2020). As for the gas extraction, potential impacts from salt extraction on natural values will be monitored and evaluated.

The lowering of the deep surface is expected to be compensated by enhanced sedimentation, resulting in zero change of the height of the surface of the tidal flats. If so, then mining will not impact seagrass and seagrass habitats via changes in exposure time. If sedimentation results in a change of the sediment composition (e.g. median grain size, silt content), then this development may reduce or enhance (the potential for) seagrass growth (Suykerbuyk et al. 2016).

[11] Rijksprojectbesluit Gaswinning onder de Waddenzee vanaf de locaties Moddergat, Lauwersoog en Vierhuizen, deel 1 en 2, 2006 en Gaswinning binnen randvoorwaarden. Passende beoordeling van het Rijksprojectbesluit over de aardgaswinning vanaf de locaties Moddergat, Lauwersoog en Vierhuizen, 20 januari 2006.

2.9 Pollution

2.9.1 Marine litter

Large amounts of litter are still entering the marine environment, both directly within the Wadden Sea and from adjacent waters (Fleet et al. 2017). In the southern North Sea, mean densities of benthic litter are about 6.35 ± 11.5 kg km^{-2} (2011-2015; Schulz et al. 2015, Fleet et al. 2017). Moreover, the fragmentation of larger plastic items produces microplastics, which are not yet well quantified in most areas. In the Netherlands (Dantziggat), subtidal sediments had a microplastic density of 770 particles kg DW^{-1} Leslie et al. (2013). "Fishing for Litter" is an international initiative which aims to reduce the amount of marine litter at the same time as raising awareness about this problem. This environmental initiative has been running in the Netherlands and Germany since the years 2000 and 2012, respectively, however, Denmark is not yet involved (Fleet et al. 2017). So far, the impacts of plastic pollution of seagrass meadows are poorly described, but cannot be excluded (Bonanno & Orlando-Bonaca 2020).

2.9.2 Oil spills

Oil spills, mostly attributable to discharges from ships, are a threat to marine wildlife (Schulz et al. 2017) including seagrass meadows by smothering the plants and burning the leaves (Jacobs 1980). The monitoring of beached oiled seabirds has been a valuable instrument as indicator of changes in marine oil pollution and it is performed by the Netherlands, Germany and Denmark since 1975 (Camphuysen and Heubeck 2001). From 2008 to 2014, the number of oils spills have decreased in the Wadden Sea waters. The intention of the Wadden Sea countries is to continue the monitoring to be able to identify trends about marine oil pollution and to recognize the success of implemented actions (Lagring et al. 2012; Schulz et al. 2017). Although the number of incidents is low, oil spills still occur in the Dutch Wadden Sea[12] and future spills are therefore be considered as a potential threat[13].

2.9.3 Nutrients

Eutrophication is one of the factors that influence the environmental quality of the Wadden Sea area (van Beusekom et al. 2017). Loadings of nitrogen and phosphorus into the coastal waters of the North Sea, including the Western Wadden Sea, strongly increased from the early 1950s until the early 1980s and decreased since the mid-1980s (van Beusekom et al. 2017). Measures were taken during the 1970s and 1980s to address eutrophication (de Jong 2007) through a reduction of riverine nutrient inputs to the North Sea, which have been effective since the mid-1980s (Radach & Pätsch 1997). This reduction of nutrients was uneven in that P loadings were more effectively reduced than N loadings. This led to a large imbalance in the N:P stoichiometry in the Wadden Sea (Philippart et al., 2007).

Although seagrass growth requires nutrients, eutrophication (nutrient over-enrichment) has been observed to reduce light conditions for seagrass through stimulation of high-biomass algal overgrowth as epiphytes and macroalgae in shallow coastal areas, and as phytoplankton in deeper coastal waters (Philippart 1994, Burkholder et al. 2007). Direct responses to eutrophication include the negative effects of ammonium on several physiological and morphological response variables

[12] https://www.texelsecourant.nl/nieuws/divers/24082/olie-op-diverse-plekken-haven-nog-aanwezig
[13] https://www.waddenzee.nl/themas/veiligheid/oliemorsingen

of seagrass such as a reduction in primary production and significantly decreased shoot, rhizome and root elongation rates, thus affecting plant survival (Brun et al. 2002 & 2008, van der Heide et al. 2008, van Katwijk et al. 1997). Direct toxicity of ammonium on seagrasses has been demonstrated at concentrations as low as 0.02 mmol (van Katwijk et al. 1997; Brun et al. 2002). The thresholds in toxicity for *Zostera noltii* depend on the time of the year with similar doses of ammonium (200 μM) during an experiment resulting in toxic effects in winter and growth enhancement in spring (Brun et al. 2002).

2.9.4 Other pollutants

The Wadden Sea water, sediment and biota is also monitored for chemicals: metals, PAHs (polyaromatic hydrocarbons) and xenobiotics (man-made compounds which are not of biogenic or geochemical origin). In the period 1996-2007, metal concentrations (Cd, Cu, Hg, Pb, Zn) remained at the same level as in 1995 or were decreasing at a moderate rate. Concentrations of some metals as mercury and lead in the sediments still posed a risk to the Wadden Sea ecosystem in the majority of sub-areas studied (OSPAR 2009, Bakker et al. 2009). The rivers Elbe and Weser and Lake IJsselmeer are the three most important contributors of metals to the Wadden Sea. The available data on natural organic micropollutants (PAHs) did not show a significant trend and its concentrations in Wadden Sea biota (blue mussel) were not at risky levels for the ecosystem (Bakker et al. 2009).

Most of the well-known xenobiotics have reached a basic levelled-off concentration in the sediments and biota of the Wadden Sea (PCB, Lindane, DDTs, HCB, TBT; data until 2006; Bakker et al. 2009). However, new compounds are being continuously developed, and although the EC regulation on chemicals and their safe use aims to guarantee environmental safety, many of the compounds may exert their environmental effect by synergism. New xenobiotics are mainly compounds disrupting endocrine processes such as BFRs, PFOS and PFOA, Alkylphenols, Bisphenol-A, and Phthalates; and compounds disrupting ecological processes such as pharmaceuticals, Polycyclic Musk Fragrance, Irgarol and other herbicides. There are no monitoring data available for most of these compounds and the attention given to them and their effects in the environment is still limited (Bakker et al. 2009).

The Trilateral Monitoring and Assessment Program (TMAP), which covers the entire Wadden Sea Area, wants "to reach background concentrations for natural compounds and zero-discharges for man-made substances" (Bakker et al. 2009). However, the standardization of methods to improve comparability and quality of information, as well as the quality and availability of data stored still requires further progress. Moreover, many newly developed xenobiotics have a wide occurrence in the Wadden Sea ecosystem, but are not yet monitored in the TMAP framework (Bakker et al. 2009). Specific details about chemicals monitoring in the Wadden Sea area can be found in Bakker et al. (2009).

Antifouling compounds, fungicides, insecticides, and herbicides have an impact on seagrass growth and survival and have already been detected in roots and leaves of *Zostera* spp. (Scarlett et al. 1999; Haynes et al. 2000; Lewis and Devereux 2009; Fernandez and Gardinali 2016). Chemical toxicity leads to chronic effects on photosynthesis, reducing energy reserves at plant and population level, and consequently reducing the resilience of seagrass meadows (Diepens et al. 2017). Diverse studies have shown reduction of seagrass growth and length and changes in photosynthetic pigments ratios due to herbicides such as Glyphosate, Bentazone and MCPA (e.g., Nielsen and Dahllof 2007; Diepens et al. 2017). Furthermore, antifouling compounds such as Irgarol 1051 and Diuron, used as alternatives for tributyltin (TBT) in antifouling boat paints (due to

TBT ban on 2003), also provoke significant reduction in *Zostera* spp. growth (Lamoree et al. 2002). Nevertheless, the effect of mixture toxicity is yet poorly understood at all stages of the life cycle of seagrass.

2.10 Overview of scale, disturbance and potential of reducing threats

Based on the literature described above, we compiled an overview of the temporal scales (e.g. irregular events, continuous activities or irreversible changes), spatial scales (from local if activities take place within a subarea of a tidal basin to the entire Dutch Wadden Sea) and management options for reducing for the types of potential disturbances (from reducing the impacts by adjusting the timing of the activities with respect to the tide to reversing historical activities) created by various activities that may affect seagrass and seagrass habitats in the Dutch Wadden Sea.

Table 2.1. Overview of scale, disturbance and potential for management actions to reduce threats to seagrass settlement, growth and survival.

Activity	**Disturbance**	**Temporal scale**	**Spatial scale**	**Management options**
Sediment extraction & dredging	Seagrass removal	Irregular to continuous	Local	Reducing activities in seagrass habitats
	Habitat destruction	Irregular to continuous	Local	
	Increased turbidity	Irregular to continuous	Larger than local	Timing of activities
Land reclamations	Seagrass destruction	Irreversible	Larger than local	Reducing and reversing activities
	Habitat destruction	Irreversible	Larger than local	
	Increased turbidity	During construction	Larger than local	Timing of activities
Demersal fisheries	Seagrass removal	Irregular to seasonal	Local	Reducing activities in seagrass habitats
	Habitat destruction	Irregular to seasonal	Local	
	Increased turbidity	Irregular to seasonal	Larger than local	Timing of activity
Climate change	Increasing temperatures	Structural	Wadden Sea	Reducing other impacts
	Changes in wind	Structural	Wadden Sea	Reducing other impacts
	Sea level rise	Structural	Wadden Sea	Enlarging WS area
	Changes in precipitation	See freshwater discharges		
Freshwater discharges	Mean salinity	Irregular to seasonal	Local to tidal basin	Taking seaward impacts into account
	Variation in salinity	Irregular to seasonal	Local to tidal basin	
Recreational activities	Seagrass removal	Irregular to seasonal	Local	Reducing activities in seagrass habitats
	Habitat destruction	Irregular to seasonal	Local	
	Increased turbidity	Irregular to seasonal	Larger than local	
Mining	Habitat change (?)	Continuous (?)	Local (?)	Reducing activities (?)
Pollution	Smothering (oil & litter)	Incidental & continuous	Local	Preventing spills & reducting inputs
	Toxication	Continuous	Tidal basin to WS	

3. SEAGRASS AND WATER QUALITY

Sonja M. van Leeuwen

3.1 Introduction

Knowledge on local concentrations of pollutants and on dose-effect relationships should be considered for future conservation and recovery strategies of seagrass in the Wadden Sea. The effect of mixture toxicity is yet, however, poorly understood at all stages of the life cycle of seagrass. In this chapter, the thresholds in single and multiple pollutions for seagrass growth are explored by comparing concentrations of pollutants in areas with and without seagrass being present. This analysis was limited to those pollutants which were expected to have negative impacts on seagrass (see Chapter 2) and for which sufficient data were available.

3.2 Material & methods

3.2.1 Seagrass data

Information about seagrass occurrence in the Dutch Wadden Sea was taken from Folmer (2019). This concerns two species of seagrass, *Zostera marina* and *Zostera noltii*, as reported by Rijkswaterstaat monitoring programs and the SIBES monitoring program by NIOZ. Folmer (2019) builds on previous work and considers both physical and biological factors in determining areas that might be suitable for seagrass within the Dutch Wadden Sea. Therefore, the focus here is mainly on the chemical environment that may allow seagrass occurrence or not. The main aim is to establish thresholds for chemical compounds (like nutrients and pollutants) that would further identify conditions for natural seagrass growth and survival, where possible. The known locations where intertidal seagrass was found according to Folmer (2019) are listed in Table 3.1.

For each location of known seagrass occurrence (based on Folmer, 2019) a Rijkswaterstaat long-term monitoring station was selected as close as possible within the same basin. For this analysis, we did not distinguish between coverage ranges nor selected for a minimum surface area (ha), but used all three categories and all occurrences in order to find the envelope allowing seagrass development (starting from 1 plant only). However, some stations were decommissioned in 2009, resulting in a data gap compared to the years for which seagrass data is available (1972-2017). For instance, on Griend *Zostera noltii* was observed in 2015, yet the relevant Rijkswaterstaat station of Blauwe Slenk oost only has data until 2009. The same occurs for the location of Schiermonnikoog, where seagrass has been observed from 2011 onwards, but station Zoutkamperlaag was discontinued for main monitoring in 2009. Table 3.1 shows the selected seagrass locations and the used monitoring stations per seagrass location. According to Folmer (2019), not all selected sites have occurrences of both types of sea grass: only *Zostera marina* has been observed at Groningerwad, while *Zostera noltii* is the sole seagrass observed at Griend so far.

Table 3.1. Seagrass locations (Folmer 2019) and their associated nearest and long-term monitoring stations. Zostera marina and Zostera noltii occur at all sites except Groningerwad (Zostera marina only) and Griend (Zostera noltii only). Occurrence years at each location may differ between the species. See Figure 3.2 for locations of the seagrass and sampling stations for water quality of Rijkswaterstaat (RWS)

Seagrass location	RWS nearest stations	RWS long-term stations
Balgzand	Amsteldiep, Den Oever spuisluizen	Marsdiep noord
Bocht van Watum	Bocht van Watum zuid	Bocht van Watum
Eemshaven	Eemscentrale, Robbenplaat, Eemshaven stroommeetpaal	Bocht van Watum Noord
Griend	West Meep, Blauwe Slenk west	Blauwe Slenk oost
Groningerwad	Eilanderbalg, Groningerwad	Zuid Oost Lauwers oost
Lauwersoog	Oort (zuidrand brakzand), Zoutkamperlaag	Lauwersoog spuisluis buiten
Noordpolderzijl	Noordpolderzijl, Ra	Zuid Oost Lauwers oost
Rottumerplaat	Lauwers, Eilanderbalg	Rottumerplaat 3 km uit de kust
Schiermonnikoog	Zoutkamperlaag zeegat, Gat van Schiermonnikoog	Zoutkamperlaag
Terschelling	Noord Meep oost, Oost Meep west	Vliestroom
Valom	Ra, Doekegat	Huibertgat oost

3.2.2 Compounds

3.2.2.1 Rijkswaterstaat monitoring stations

Rijkswaterstaat has maintained an elaborate monitoring system within the Dutch Wadden Sea in the past. However, throughout time stations have been axed so that now only a few stations remain. These are not necessarily in or near places of known seagrass presence, as the species studied here are found in intertidal areas and Rijkswaterstaat monitoring focusses on subtidal areas. Figure 3.1 shows station activity through time for two compounds, used as examples for a widely monitored variable (here the nutrient ortho-phosphate; PO_4) and a less monitored variable (here the metal lead; Pb). Data was obtained from a data portal which is set up and maintained by Rijkswaterstaat[14]. Figure 3.2 shows the locations of the selected stations.

[14] https://waterinfo.rws.nl

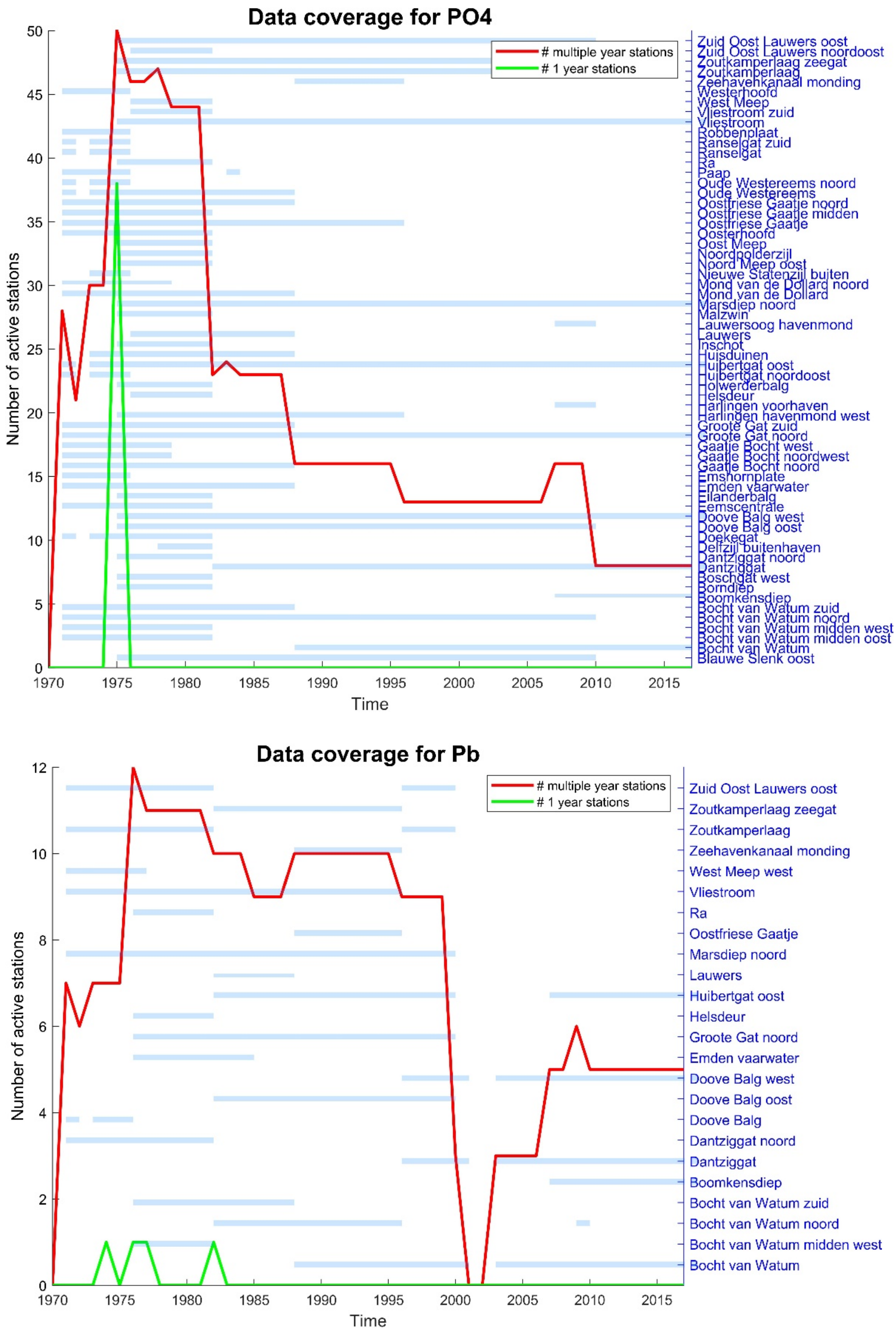


Figure 3.1. Active Rijkswaterstaat monitoring stations monitoring ortho-phosphate (above, PO_4) and lead (below, Pb) from 1970 to 2017.

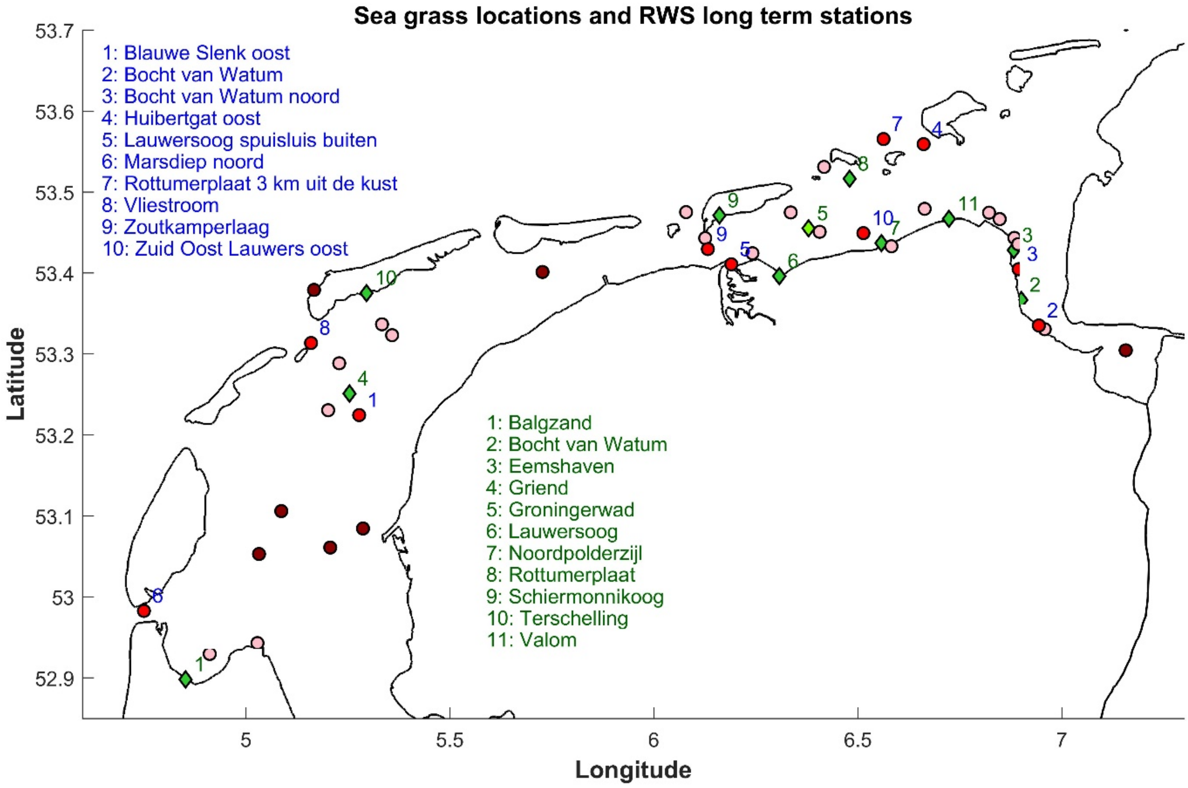


Figure 3.2. Locations of observed seagrass (numbers and text in green, locations indicated by green diamonds) and the associated longer-term monitoring stations (numbers and text in blue, locations indicated by red dots). Extra (near) monitoring stations associated with seagrass locations are identified with pale pink dots. The dark red dots indicate long-term monitoring stations that are not linked to a seagrass location.

Data for the period 1970-2017 was used, to coincide with the seagrass data period from Folmer (2019). But the coverage over time is clear: from the peak of monitoring in the 1970's and early 80's, there are now only a handful of stations (10 for NO_3, 6 for Pb) left representing the entire Dutch Wadden Sea. There are no current monitoring stations in the data portal within the Friesche zeegat (inlet between Ameland and Schiermonnikoog) and Lauwers (inlet between Schiermonnikoog and Rottumerplaat) basins for water quality at all, hindering identification of suitable seagrass conditions along the Groninger coast (Lauwersoog, Noordpolderzijl).

Please note that selected locations for seagrass occurrence were used (Figure 3.2): in reality (see Folmer, 2019) the seagrass will cover varying patches in the surrounding area. For instance, the locations of Lauwersoog, Noordpolderzijl, Valom and Eemshaven are separate here as they belong to 2 different basins and have varying presence years. But in some years, seagrasses were observed along the entire north Groningen coast from Lauwersoog to Eemshaven. The same applies to Bocht van Watum, with varying locations in the Eems bend, and Balgzand, with separate occurrences of seagrass along different places on the Western boundary of the sea-land interface of the Balgzand area. For details of the spatial occurrence see Folmer (2019).

3.2.2.2 Selection of compounds

Compounds with potential negative effects on seagrass survival include the herbicides glyphosate, bentazone and MCPA, as well as antifouling compounds irgarol 1051, diuron and tributyltin (TBT)

(Chapter 2). The latter occur in boat paints, with irgarol and diuron replacing TBT after use of it was banned in the EU in 2003 due to negative effects on shellfish reproduction (Waldock et al. 1986, Champ 2003). For this initial study only surface water values are considered. Note that high metal concentrations are mainly a problem within the sediments, whereas for this study only surface waters have been considered. An overview of the studied compounds is shown in Table 3.2. Where applicable, the dissolved fraction was used, i.e. after filtration. Only quality-approved data (flagged with "normale waarde") were selected.

Table 3.2. Overview of the data for all compounds, observations from Waterinfo (https://waterinfo.rws.nl), Rijkswaterstaat. The "RWS code" refers to name as used by Rijkswaterstaat in the data portal. Minimum and maximum values are shown to supply the full range in concentrations as has been observed in the Dutch Wadden Sea.

Compound	RWS code	Number of stations	Number of observations	Period	Minimum	Maximum	Unit
Herbicides							
Glyphosate	glyfst	1	2	2017-2017	<0.01	<0.01	ug/l
Bentazone	bentzn	8	253	2009-2017	<0.01	<0.01	ug/l
MCPA	MCPA	8	253	2009-2017	<0.05	<0.05	ug/l
Antifouling toxins							
Irgarol	irgrl	15	1349	2003-2017	0.0002	0.0055	ug/l
Diuron	Durn	14	583	2009-2014	0.0003	0.02	ug/l
Tributyltin	TC4ySn	10	448	2008-2013	5.0	5.0	ng/l
Nutrients							
Nitrate	NO3	72	17552	1971-2017	0	14.58	mg/l
Total nitrogen	Ntot	106	19373	1971-2017	0.05	57.1	mg/l
Orthophosphate	PO4	107	20458	1971-2017	0	5.4	mg/l
Total phosphorous	Ptot	107	19752	1970-2017	0	17	mg/l
Ammonium	NH4	107	26153	1971-2017	0	45.1	mg/l
Silicates	SiO2	53	3852	1974-1987	0	8.28	mg/l
Metals							
Cadmium	Cd	31	2613	1971-2017	0.01	11.9	ug/l
Lead	Pb	32	2589	1971-2017	0	42	ug/l
Mercury	Hg	31	2403	1971-2017	0	1.1	ug/l
Copper	Cu	31	2501	1971-2017	0.1	31	ug/l
Iron	Fe	8	492	1974-2017	0.001	0.184	mg/l
Zinc	Zn	31	2406	1971-2017	0.07	650	ug/l
Xenobiotics							
bis(2-ethylhexyl) ftalaat	DEHP	7	743	2009-2017	1	20	ug/l
Hexahydrohexamethylcyclo pentabenzopyran (Polycyclic Musk Fragence)	HHCB	1	2	2011	0.016	0.028	ug/l
Tonalide (Polycyclic Musk Fragence)	AHTN	1	2	2011	0.0050	0.0076	ug/l
Perfluoroctaan-zuur	PFOA	2	44	2010-2017	0.0015	0.010	ug/l
4-tertiair-octylfenol (Alkylphenols)	4ttC8yFol	7	822	2007-2017	0.0050	0.33	ug/l
som 4-nonylfenol-isomeren (vertakt) (Alkylphenols)	S4C9yFol	7	593	2010-2017	0.10	0.13	ug/l
Other							
pH	pH	125	27810	1971-2017	3.6	9.8	-
Suspended matter	ZS	112	23531	1973-2018	0.30	7690	mg/l
Salinity	SALNTT	107	43607	1975-2017	0.10	36.86	PSU

The tested herbicides all show observations that were below the detection limit for those compounds. As such, these are not deemed to be a problem for seagrass occurrence. The same applies to tributyltin (TC4ySn). For many new xenobiotics, measurements are few and far between, and knowledge regarding impact on seagrasses is lacking: their values have been included here for reference only.

3.3 Results

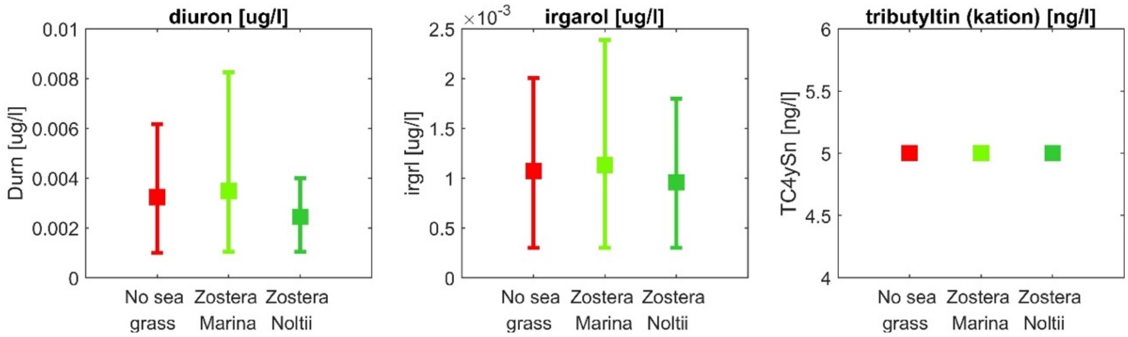
3.3.1 Compound concentrations with and without seagrass present

The stations associated with seagrass occurrence were used to identify observations in time and place linked to the presence of either *Zostera marina* or *Zostera noltii*. Figure 3.3 show the resulting values. Due to the presence of detection limits, the observations can be seen as left-censored data. However, most compounds studied here displayed only a very low percentage of data at/below the detection limit (generally < 0.1%, results not shown). Exceptions were DEHP (the only phthalate in the data), 4ttC8yFol and S4C9yFol (both alkyl phenols), which displayed percentage data below detection limits of 93%, 72% and 99.8%, respectively: these compounds are therefore excluded from further analysis here. Iron (Fe) displayed 40% of values at or below detection limit, while Irgarol and PFOA showed ~ 2% of data below the detection limit. When data was below detection level the detection limit itself was used as value, as the percentages were deemed too low to warrant estimation of the missing part for most compounds. Results for Fe should therefore be treated with care.

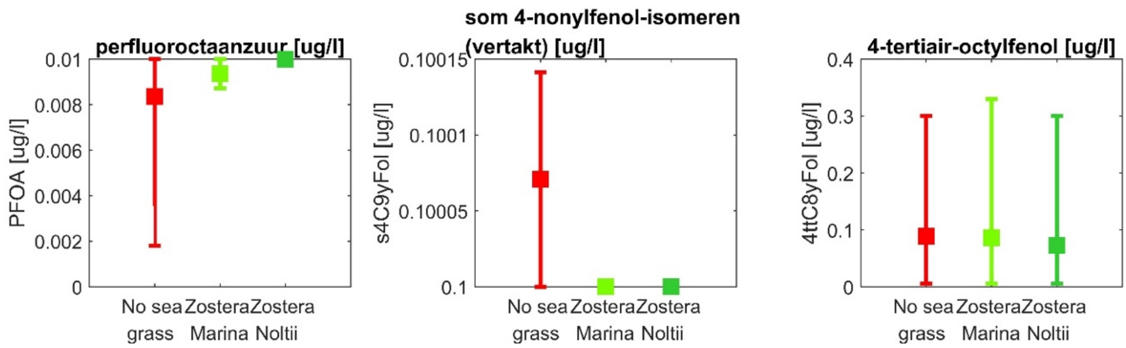
The results presented in Figure 3.3 show the mean value plus the 10^{th} and 90^{th} percentile values. The data is not distributed normally, so we use the 10th and 90th percentiles to get an indication of the range of values tolerated by sea grass, assuming extreme values might only be tolerated for short exposure times and thus not be representative for seagrass-suitable conditions. Note that seagrass presence is known, but seagrass absence is usually not known. Although labelled "no seagrass", this category refers to all data that is not linked to a location in time and space with observed seagrass. Thus, it contains data for years not included in Folmer (2019), as well as data for known seagrass years for locations without positive seagrass observations. As such, the "no seagrass" category merely provides an envelope for the range of values found throughout the Wadden Sea for the selected compounds, and cannot be seen as mutually exclusive with the seagrass categories.

In general, nutrient levels show lower mean values (and 10^{th} and 90^{th} percentile levels) when sea grass is present (Figure 3.3). For metals, seagrass mean values are lower than without observed seagrass, with the exception of lead (Pb) where the mean and 90^{th} percentile of *Z. noltii* is equal, and the iron (Fe) where the mean and 90^{th} percentile of both seagrass species is higher. Thus, these two species of seagrass seem to thrive in areas with lower (than average Wadden Sea) nutrient concentrations, lower metal concentrations (except for lead and iron) and lower than average suspended matter concentrations. The latter strongly reduces the underwater light climate, hindering plant growth. The results for PFOA are derived from 44 observations spread over 2 stations (Table 3.2) and are therefore not deemed representative.

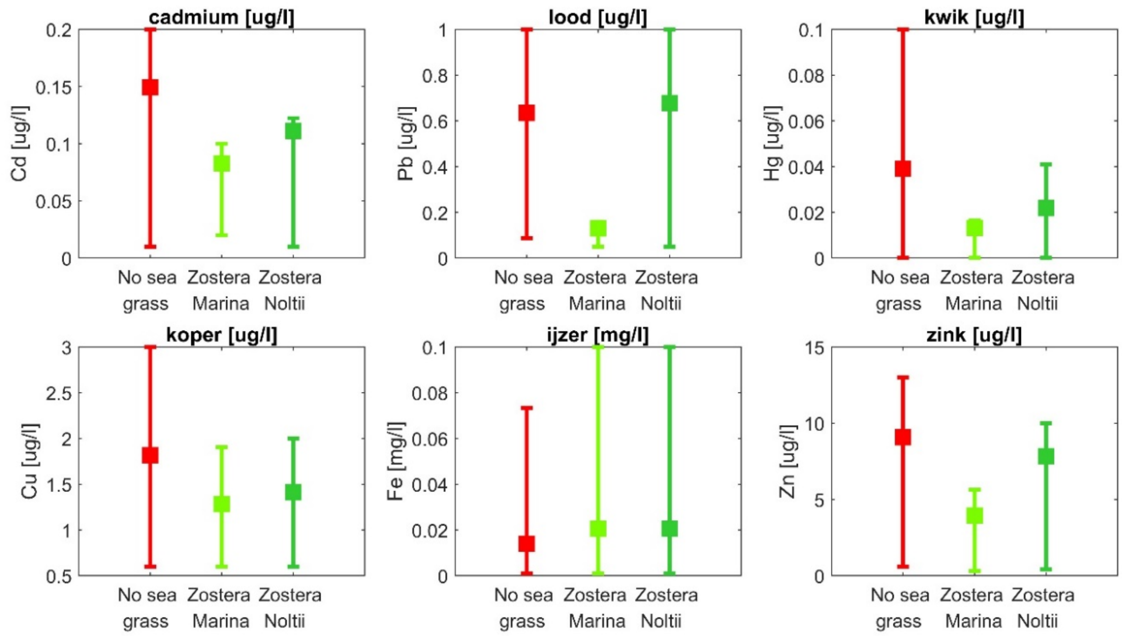
a. *Anti-fouling compounds. Tributyltin only has values below 5.0 ng/l, which is the detection limit.*



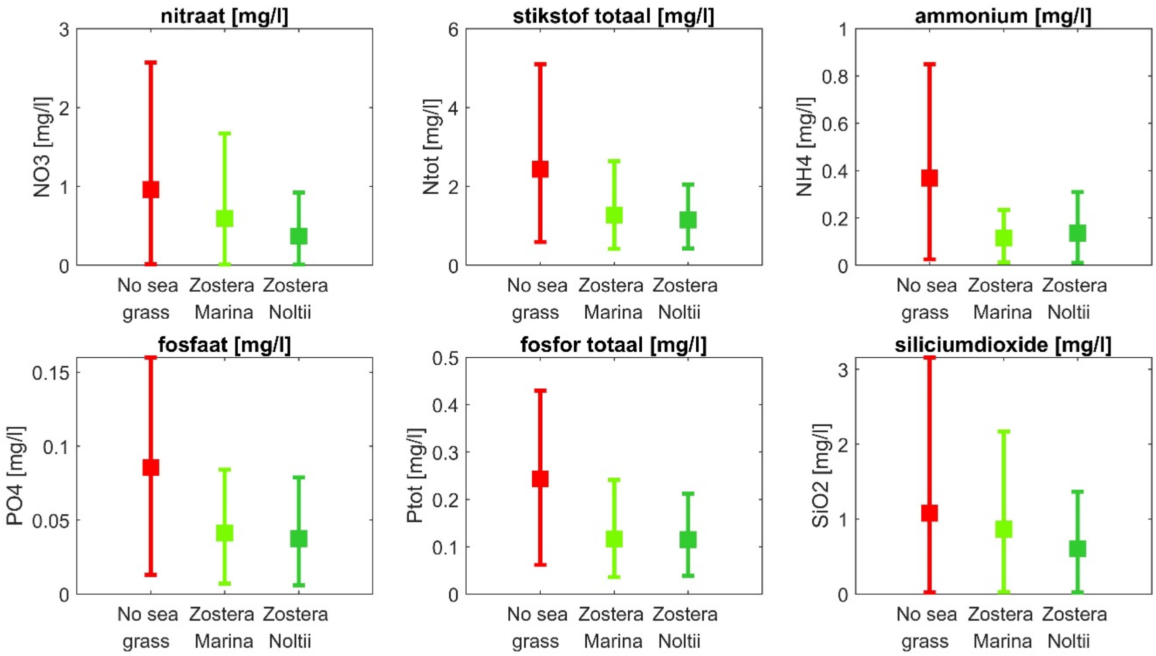
b. *Xenobiotic compounds, where "perfluoroctaan-zuur" is perfluorooctanoic acid, and "4-tertiair-octylfenol" and "som 4-nonylfenol-isomeren (vertakt)" are two types of alkylphenols.*



c. *Metals, where "cadmium" is cadmium, "lood" is lead, "kwik" is mercury, "koper"is copper, "ijzer" is iron and "zink" is zinc.*



d. Nutrients, where "nitraat" is nitrate, "stikstof totaal" is total nitrogen, "ammonium" is ammonium, "fosfaat" is orthophosphate, "fosfor totaal" is total phosphorous and "siliciumdioxide" is silicate.



e. Other environmental conditions, where "zwevende stof" is suspended particulate matter, "zuurgraad" is acidity and "saliniteit is "salinity". The maxima for suspended matter are 7690, 890 and 1033 mg/l for the no seagrass, Zostera marina and Zostera noltii respectively.

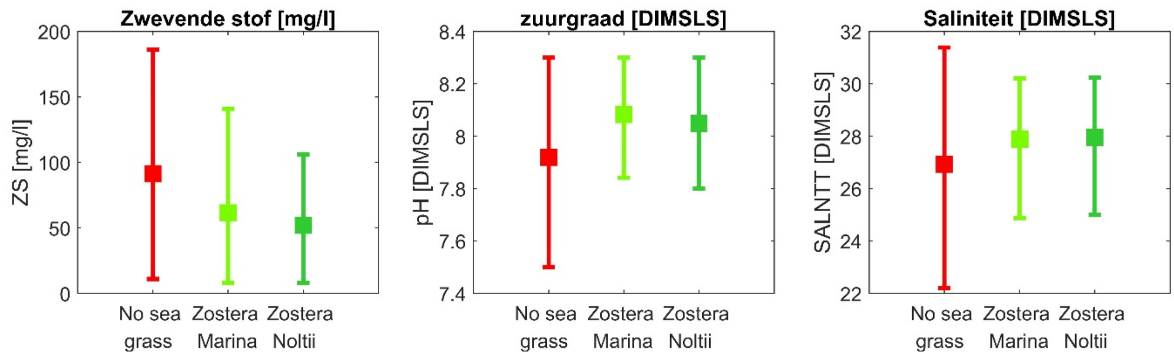


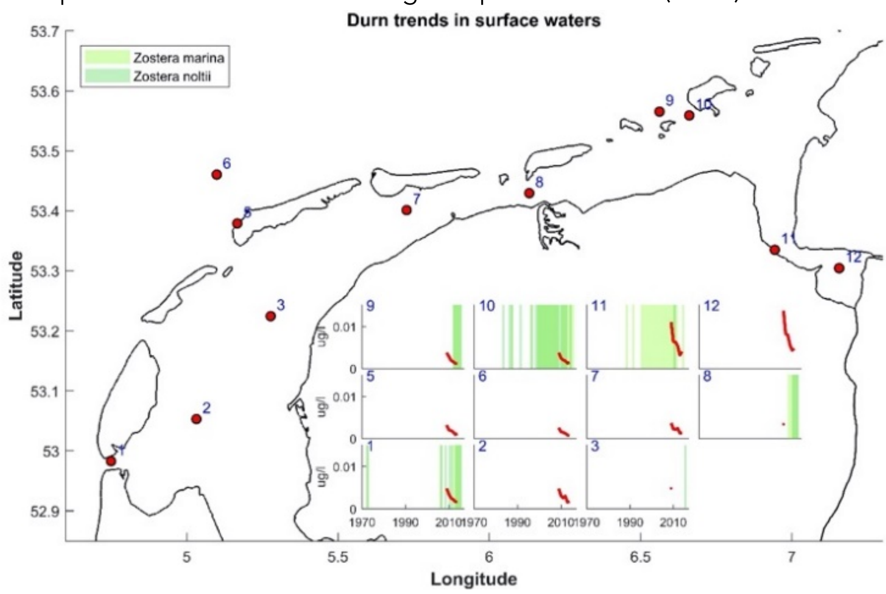
Figure 3.3. Results for nutrients, potentially toxic compounds and environmental factors where seagrass (Zostera marina, Z. noltii) was present or absent. The squares indicate the mean values, coloured bars the 10th and 90th percentile values. The Dutch names refer to the names as used by Rijkswaterstaat in the data portal.

3.3.2 Spatiotemporal variation in concentrations with and without seagrass present

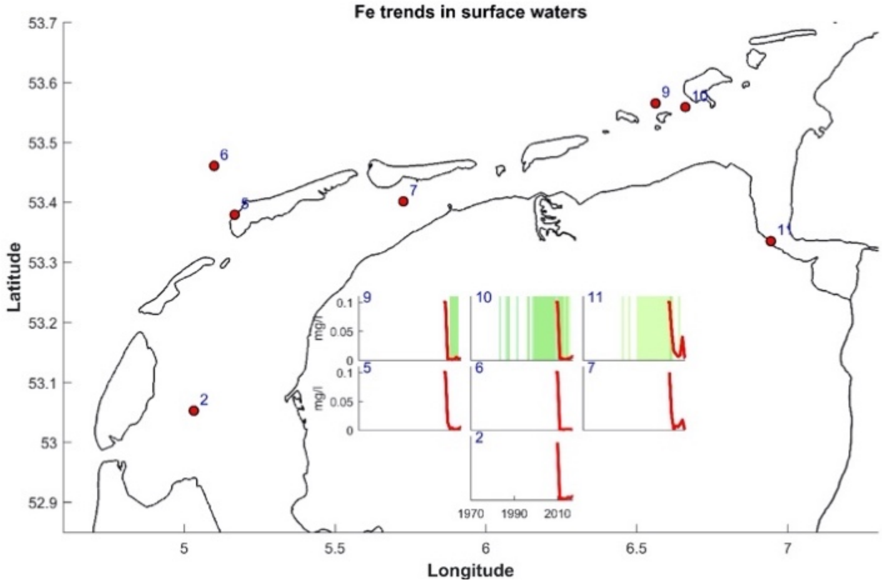
Based on Figure 3.3 and literature (Chapter 2), we will focus our attention on the following compounds: Diuron (Durn), all metals, ortho-phosphate (PO_4), nitrate (NO_3), ammonium (NH_4), and suspended matter (ZS). The xenobiotic compounds do not have enough observations to allow for a meaningful analysis: most compounds within this range only have a limited amount of unique values, likely due to the measurement techniques (e.g. PFOA has 20 points with 5 different values for the no seagrass situation, and less for those with seagrasses). Total nitrogen and total phosphorous are expected to exhibit results very similar to NO_3 and PO_4. Silicate results are limited by the observations being mainly from 1982-1987, which has only a small overlap with the years seagrasses were observed: we therefore do not consider it further. Nevertheless, the results presented here indicate that some of these compounds may influence seagrass growth.

Figure 3.4 shows the spatial trends within the Wadden Sea for the selected compounds for long-term monitoring stations. Where stations are associated with seagrass occurrence, the relevant subplot has been coloured green to indicate presence of *Zostera marina*, *Zostera noltii* or both. Metal levels have decreased since 1970 in the Dutch Wadden Sea, but recent rises have occurred in some areas for copper and cadmium. Iron levels have dropped off sharply. The anti-fouling agent Irgarol shows a peak and subsequent decline in the period 2000-2010, while Diuron shows a decline in the recent, limited observations. Nutrient levels remain high in the Eems-Dollard region, but ortho-phosphate levels have reduced across the Dutch Wadden Sea since the mid 1980's (phasing out of phosphates in detergents). Suspended matter is high in the Eems-Dollard, as is well known, but also shows increasing values in the central Dutch Wadden Sea. Both the suspended matter and metal levels could threaten seagrass occurrence, as they seem to prefer below average concentrations for the Wadden Sea. The drop in the levels of iron (Fe) could also hinder seagrass growth, as they seem to prefer high iron levels.

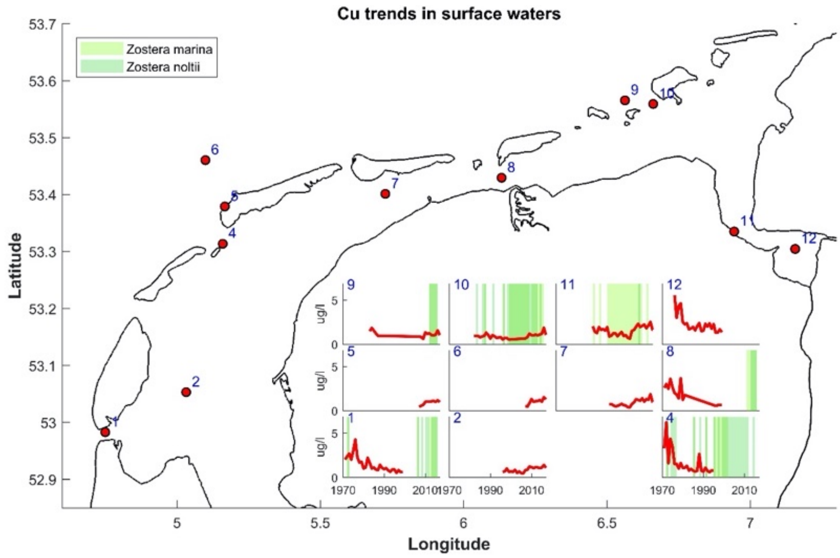
a. Spatiotemporal trends in the antifouling component Diuron (Durn).



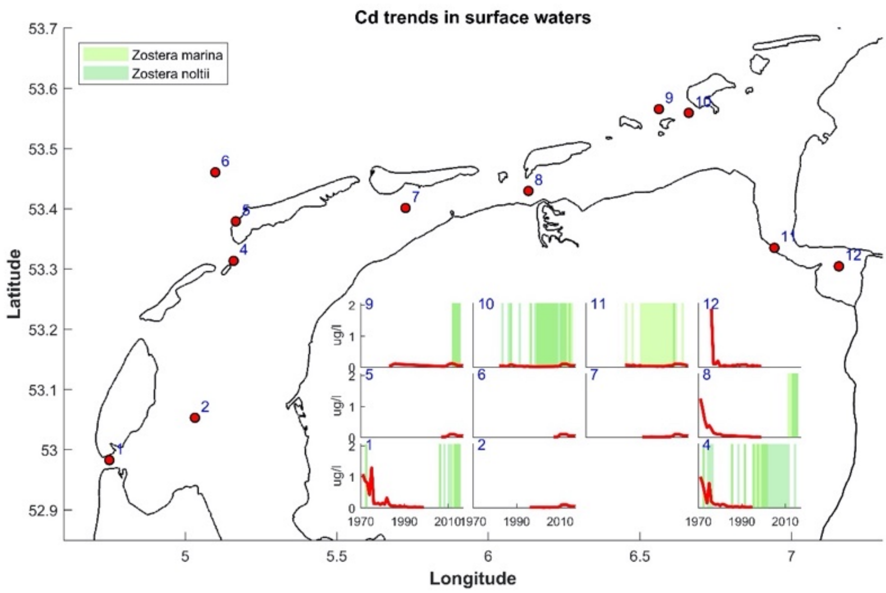
b. Spatiotemporal trends in the metal iron (Fe).



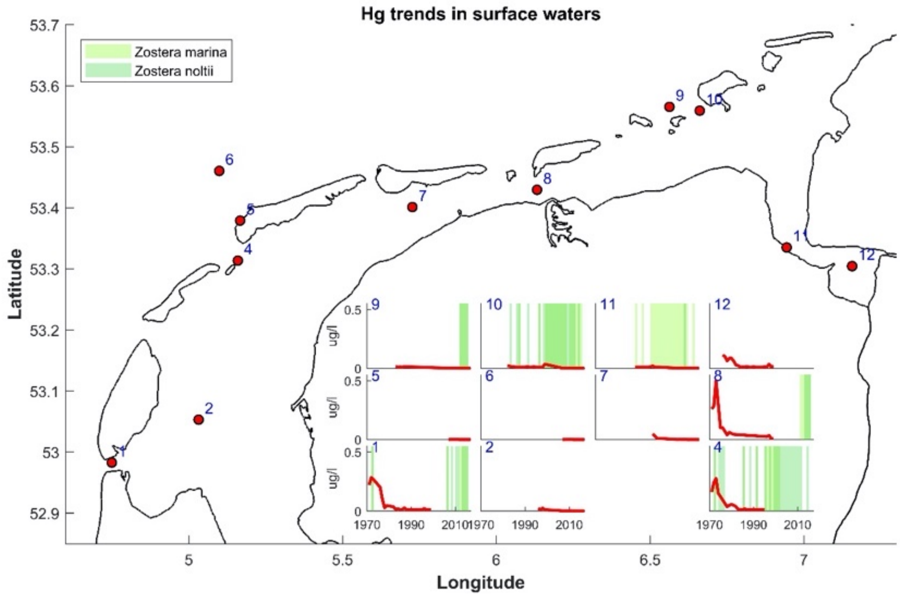
c. Spatiotemporal trends in the metal copper (Cu).



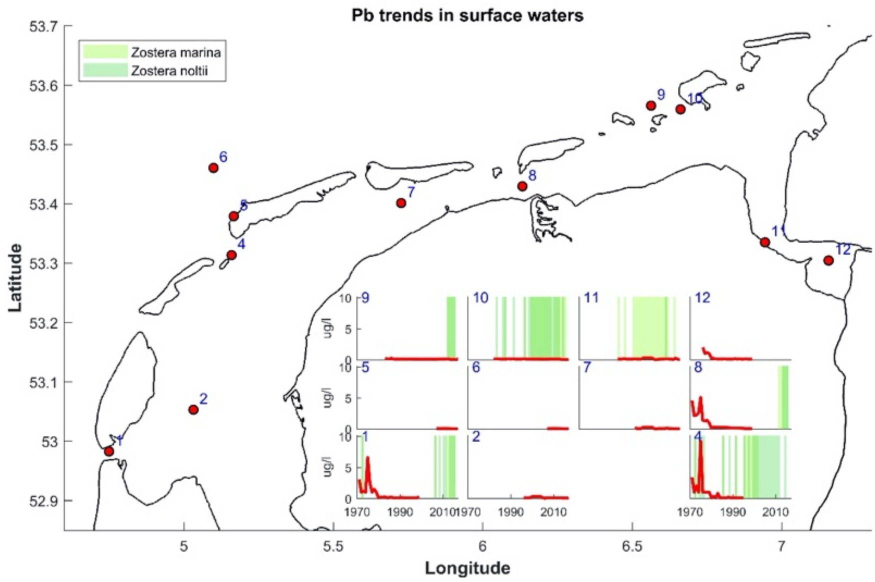
d. Spatiotemporal trends in the metal cadmium (Cd)



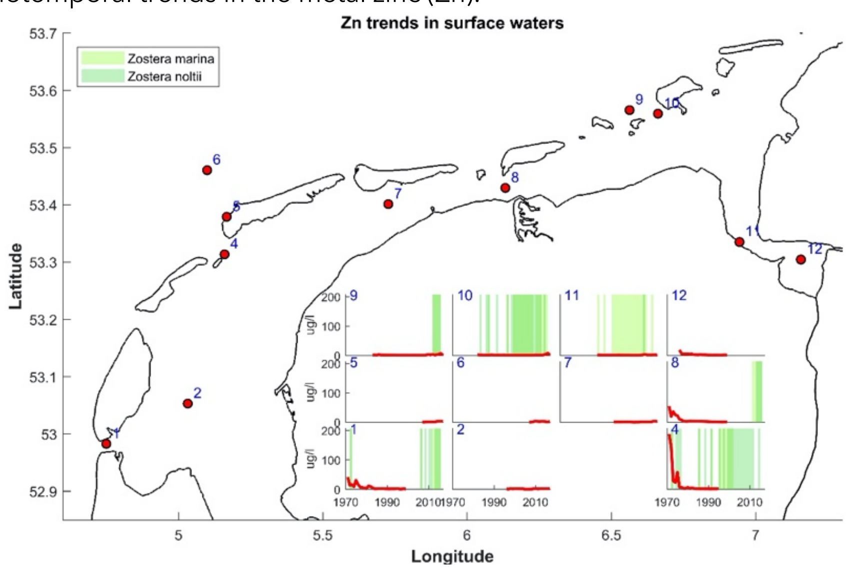
e. Spatiotemporal trends in the metal mercury (Hg).



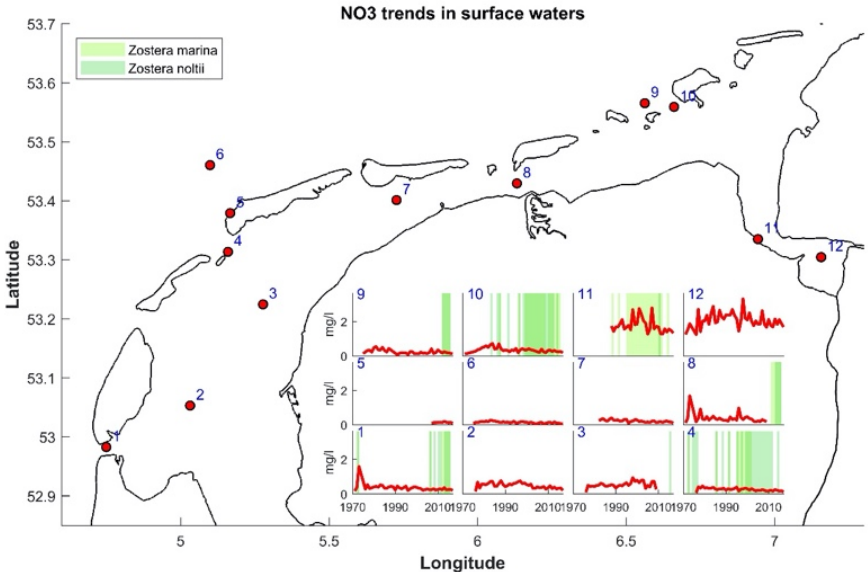
f. Spatiotemporal trends in the metal lead (Pb).



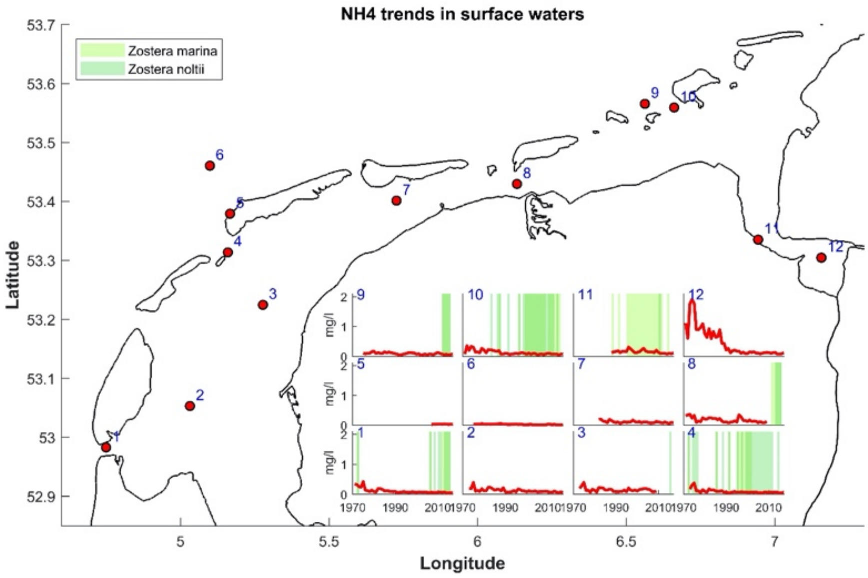
g. Spatiotemporal trends in the metal zinc (Zn).



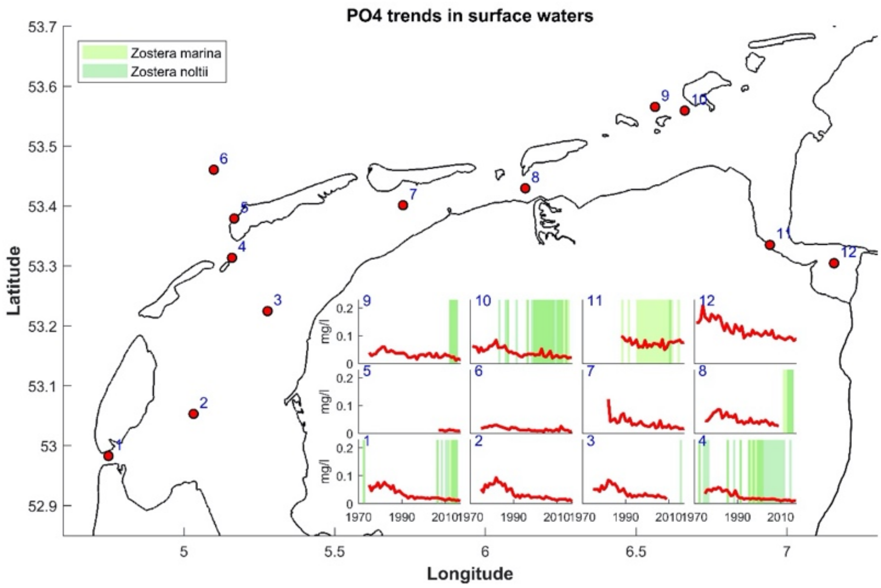
h. Spatiotemporal trends in the nutrient nitrate (NO3).



i. Spatiotemporal trends in the nutrient ammonium (NH4).



j. Spatiotemporal trends in the nutrient ortho-phosphate (PO4).



k. Spatiotemporal trends in particulate suspended matter (ZS = “zwevende stof”).

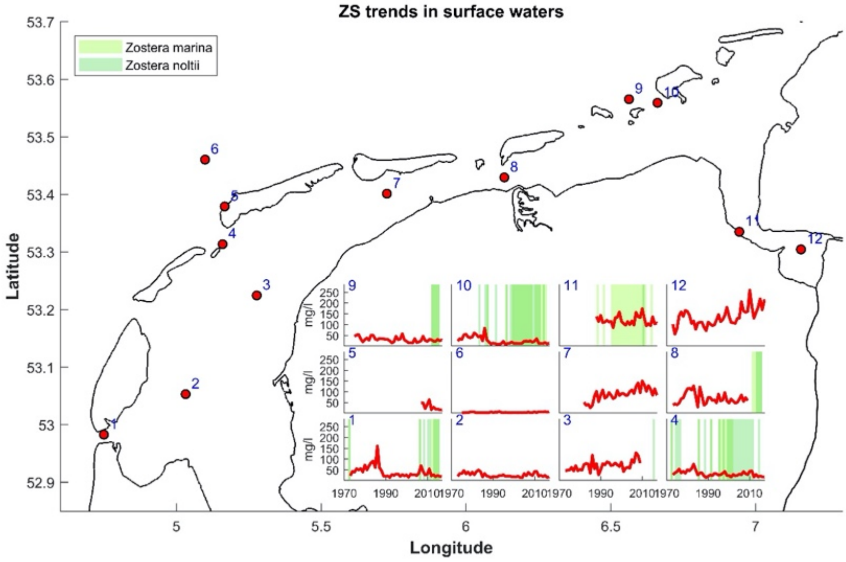


Figure 3.4 a-k: Spatiotemporal trends in nutrients, toxic compounds and environmental conditions (red lines). The green colours indicate seagrass presence at (associated) long-term monitoring stations.

3.3.3 Potential thresholds for seagrass presence

Seagrass can be absent in spite of favourable circumstances with respect to potentially growth-reducing compounds. This implies that statistical analyses of concentrations of these compounds with and without seagrass present cannot reveal thresholds. The information on the 90th percentile in areas with and without seagrass might, however, give an impression if compounds there might be limiting seagrass growth in the Dutch Wadden Sea. Table 3.3 shows the 90th percentile per compound for all data available. Table 3.4 shows the same but per seagrass location, using only the associated observational stations (see Table 3.1).

The results on the overall data set for the Dutch Wadden Sea (Table 3.3) suggest that for the antifouling compounds, the 90th percentile concentrations in observations without seagrass present are more or less comparable to those measured close to or in seagrass beds. With respect to nutrients, the concentrations in observations without seagrass were 80% (total phosphate) to almost 300% (ammonium) higher than those close to or in seagrass beds. For several metals (e.g. lead and iron), the concentrations were comparable with or without seagrass. For other metals (mercury and cadmium, respectively), the observational data without seagrass were 100% to 150% higher than those with seagrass presence. With respect to other environmental conditions, the 90th percentile concentrations of suspended particulate matter were more than 30% higher for observations without known seagrass presence compared to those where seagrass was known to be present at the time in the area.

The results focusing on the seagrass locations only (Table 3.4) suggest that the concentrations at the Bocht van Watum area without seagrass exceed potential thresholds for seagrass growth the most (4 out of 17 compounds considered), in particular for the nutrient ammonium. At the Balgzand area, metal concentrations (cadmium, mercury and copper) near seagrass were highest of all locations.

Based on these findings, we suggest that seagrass growth at a Wadden Sea scale (Table 3.3) might be locally hampered by exceeding thresholds in ammonium, cadmium and mercury. At a local scale (Table 3.4), seagrass growth might be restricted due to high concentrations of nutrients, in particular ammonium, in the Bocht van Watum area.

Table 3.3. The 90th percentile of the concentrations of compounds with and without seagrass present. Colours in "no seagrass" column indicate if the 90th percentile are higher (light blue) or at least 2x (dark blue) higher than 90th percentile with seagrass present. Light-green colour in "seagrass" columns indicates the highest values of all compounds where seagrass was present which might indicate a threshold in concentration for that specific compound.

Compound	RWS	Unit	No seagrass	*Zostera marina*	*Zostera noltii*
Antifouling toxins					
Irgarol	irgrl	µg/l	0.0021	0.0023	0.0018
Diuron	Durn	ųg/l	0.0063	0.0083	0.0040
Nutrients					
Nitrate	NO3	mg/l	2.57	1.67	0.92
Total Nitrogen	Ntot	mg/l	5.10	2.64	2.05
Ammonium	NH4	mg/l	0.85	0.23	0.31
Orthophosphate	PO4	mg/l	0.16	0.08	0.29
Total Phosphate	Ptot	mg/l	0.43	0.24	0.21
Silicates	SiO2	mg/l	3.14	2.17	1.37
Metals					
Cadmium	Cd	ųg/l	0.20	0.10	0.10
Lead	Pb	ųg/l	1.00	0.16	1.00
Mercury	Hg	ųg/l	0.10	0.01	0.04
Copper	Cu	ųg/l	3.00	1.91	2.00
Iron	Fe	mg/l	0.08	0.10	0.10
Zinc	Zn	ųg/l	13.00	2.26	10.00
Other					
pH	pH	-	8.30	8.30	8.30
Suspended matter	ZS	mg/l	186	141	106
Salinity	SALNTT	PSU	31.39	30.21	30.23

Table 3.4. The 90th percentiles per compound for all seagrass locations. Blue indicates local values with "no seagrass" that are higher than the 90th percentile found for areas with seagrass throughout the Dutch Wadden Sea in this table (considered to be potential thresholds), with dark-blue being the highest value found. Green colours in the "seagrass" columns indicate 90th percentile concentrations found with seagrass present within this table. Yellow colour indicates the lowest salinity with seagrass.

Location			Balgzand			Bocht van Watum			Eemshaven		
Compound	**RWS**	**Unit**	**NS**	***ZM***	***ZN***	**NS**	**ZM**	**ZN**	**NS**	**ZM**	**ZN**
Antifouling toxins											
Irgarol	irgrl	µg/l	0.0016	0.0011	0.0016	0.0014	0.0033	0.0039	0.0024	0.0024	0.0023
Diuron	Durn	µg/l	0.0059	0.0026	0.0034	0.0064	0.0110	0.0096	0.0110	0.0110	-
Nutrients											
Nitrate	NO3	mg/l	0.852	0.701	0.729	2.660	2.892	3.154	2.568	2.656	2.618
Total Nitrogen	Ntot	mg/l	2.800	1.728	1.458	5.570	4.329	4.617	4.051	4.390	4.168
Ammonium	NH4	mg/l	0.259	0.200	0.150	0.900	0.278	0.347	0.640	0.277	0.263
Orthophosphate	PO4	mg/l	0.073	0.027	0.027	0.160	0.123	0.125	0.150	0.107	0.073
Total Phosphate	Ptot	mg/l	0.190	0.110	0.110	0.340	0.392	0.320	0.330	0.364	0.339
Silicates	SiO2	mg/l	0.626	-	-	3.240	-	-	2.854	2.930	-
Metals											
Cadmium	Cd	µg/l	1.00	1.90	1.90	0.14	0.09	0.07	0.08	0.22	-
Lead	Pb	µg/l	2.0	1.0	1.0	1.0	0.3	0.2	0.2	0.1	-
Mercury	Hg	µg/l	0.10	0.66	0.66	0.10	0.01	0.00	0.03	0.02	-
Copper	Cu	µg/l	3.1	8.2	8.2	4.4	2.3	2.8	2.2	1.8	-
Iron	Fe	mg/l	-	-	-	0.05	0.10	0.10	0.10	0.10	-
Zinc	Zn	µg/l	21.9	40.7	40.7	7.2	1.9	2.7	4.3	2.0	-
Other											
pH	pH	-	8.4	8.4	8.4	8.0	8.3	8.2	8.1	8.2	8.2
Susp. matter	ZS	mg/l	77.5	52.5	62.2	142.0	212.7	331.0	160.4	134.9	134.3
Salinity	SALNTT	PSU	31.01	31.20	31.16	24.34	25.06	24.34	27.30	30.17	30.17
SUM "Highest"			**0**	**3**	**3**	**4**	**2**	**3**	**1**	**1**	**0**
TOTAL SCORE per AREA					**3**			**9**			**1**

Location			Noordpolderzijl			Rottumerplaat			Schiermonnikoog		
Compound	**RWS**	**Unit**	**NS**	***ZM***	***ZN***	**NS**	**ZM**	**ZN**	**NS**	**ZM**	**ZN**
Antifouling toxins											
Irgarol	irgrl	ug/l	0.0027	0.0019	0.0021	0.0014	0.0010	0.0010	0.0026	-	-
Diuron	Durn	ug/l	0.0040	-	0.0040	0.0045	0.0018	0.0018	0.0044	-	-
Nutrients											
Nitrate	NO3	mg/l	0.934	0.879	0.989	0.822	0.550	0.512	0.730	-	-
Total Nitrogen	Ntot	mg/l	2.400	1.854	2.271	1.670	1.050	1.048	2.300	-	-
Ammonium	NH4	mg/l	0.450	0.371	0.400	0.240	0.137	0.137	0.336	-	-
Orthophosphate	PO4	mg/l	0.120	0.112	0.112	0.070	0.036	0.034	0.090	-	-
Total Phosphate	Ptot	mg/l	0.360	0.242	0.291	0.220	0.107	0.101	0.280	-	-
Silicates	SiO2	mg/l	1.030	-	1.332	0.891	-	-	0.922	-	-
Metals											
Cadmium	Cd	ug/l	0.16	0.03	0.18	0.09	0.10	0.10	0.08	-	-
Lead	Pb	ug/l	1.0	0.1	5.4	0.1	0.1	0.1	0.2	-	-
Mercury	Hg	ug/l	0.10	0.05	0.06	0.02	0.00	0.00	0.02	-	-
Copper	Cu	ug/l	4.5	0.9	3.6	1.7	1.3	1.3	1.3	-	-
Iron	Fe	mg/l	-	-	-	0.10	0.00	0.00	-	-	-
Zinc	Zn	ug/l	5.5	0.7	19.6	3.4	4.4	3.3	3.1	-	-
Other											
pH	pH	-	8.3	8.3	8.2	8.4	8.2	8.2	8.3	-	-
Susp. matter	ZS	mg/l	225.4	110.6	157.0	88.1	59.3	59.8	136.0	-	-
Salinity	SALNTT	PSU	31.20	31.29	31.05	31.71	32.61	32.70	32.29	-	-
SUM "Highest"			**0**	**0**	**1**	**0**	**1**	**0**	**0**		
					1			**1**			**0**

Location			Terschelling			Valom		
Compound	**RWS**	**Unit**	**NS**	***ZM***	***ZN***	**NS**	**ZM**	**ZN**
Antifouling toxins								
Irgarol	irgrl	ųg/l	-	-	-	0.0007	0.0011	0.0013
Diuron	Durn	ųg/l	-	-	-	0.0041	0.0028	0.0040
Nutrients								
Nitrate	NO3	mg/l	0.720	0.786	0.663	1.010	0.859	0.873
Total Nitrogen	Ntot	mg/l	1.448	1.220	2.200	2.320	1.310	1.410
Ammonium	NH4	mg/l	0.190	0.150	0.400	0.380	0.172	0.192
Orthophosphate	PO4	mg/l	0.066	0.037	0.050	0.110	0.052	0.059
Total Phosphate	Ptot	mg/l	0.150	0.102	0.143	0.310	0.098	0.110
Silicates	SiO2	mg/l	0.597	0.402	0.402	1.470	1.476	1.390
Metals								
Cadmium	Cd	ųg/l	1.00	1.00	1.00	0.10	0.10	0.10
Lead	Pb	ųg/l	2.0	1.0	6.1	1.0	0.1	0.1
Mercury	Hg	ųg/l	0.10	0.22	0.22	0.02	0.00	0.01
Copper	Cu	ųg/l	2	2.2	6.1	6.0	1.2	1.2
Iron	Fe	mg/l	-	-	-	0.00	0.10	0.10
Zinc	Zn	ųg/l	44.8	173.0	108.0	5.1	1.7	1.8
Other								
pH	pH	-	8.3	8.4	8.3	8.3	8.3	8.3
Suspended matter	ZS	mg/l	63.6	55.2	61.0	175.0	37.7	39.0
Salinity	SALNTT	PSU	32.52	32.39	32.13	31.23	31.49	31.48
SUM "Threshold"			**0**	**1**	**1**	**0**	**0**	**0**
SUM "High"					**2**			**0**

3.4 Discussion & conclusions

3.4.1 Consistency in data sets

For our analyses, we assumed that all data were consistently sampled, analysed and processed in time and space. Based on a previous exploration, however, it is known that the Rijkswaterstaat time series in the Western Wadden Sea has undergone several methodological changes in time (Philippart et al. 2013). For example, the water samples were taken irregularly with regard to the tidal phase from 1973 up to 1977, approximately 2 h before local low tide between 1978 up to 1989 (Waterloopkundig Laboratorium 1991) and/or 2 h after local high tide from 1990 onwards (Bot & Colijn 1996). Furthermore, sampling depth changed from 2 m up to 1990 and to 1 m below the water surface since 1991 (Dronkers 2005). The decrease in maximum values of suspended particulate matter in the early 1980s (results not shown) suggest that another change in sampling and/or analyses procedures has occurred. However, an in-depth analysis of observational consistency is outside the scope of this work. For most compounds, the use of the 90th percentile enhances the time series' consistency.

3.4.2 Seasonal dynamics

With respect to salinity, seagrass occurred between 26.9 (Bocht van Watum) and 34.20 (Noordpolderzijl) PSU (Table 3.5) with the highest salinity with seagrass present in the Dutch Wadden Sea being 35.5 (Table 3.4). Salinity (in areas without and without seagrass) varies, however, strongly in time, which is predominantly due to variations within a year (e.g. tides and seasons; van Aken 2008). This variation is most conspicuous in the salinity data (because of the large size of this data set), but most probably present in other data sets (in particular those of nutrients and suspended particulate matter). The tolerance of seagrass to exposure to particular compounds will not only rely on the concentrations and thresholds of these compounds, but also on the duration (e.g., intermittent versus continuous; Handy 1994) and the timing of this exposure (e.g. in summer during peak of vegetative biomass or in winter on seed banks; Phillips 1976). With respect to salinity, for example, seagrass might profit from low salinities for seed germination in spring, but be stressed by these conditions during seedling development hereafter (Xu et al. 2016). To fully understand the potential impacts of compounds on seagrass growth and survival, seasonal variation in dose-effect relationships should be taken into account.

3.4.3 Thresholds

Based upon the comparisons between local concentrations and the occurrence of seagrass, it appears that the most likely candidates for compounds hampering seagrass growth are ammonium, cadmium, mercury and suspended particulate matter.

Although ammonium is part of the nutrients required for seagrass growth, negative effects of ammonium on several physiological and morphological response variables of seagrass have been observed, including a reduction in primary production and significantly decreased shoot, rhizome and root elongation rates, thus affecting plant survival (Brun et al. 2002 & 2008, van der Heide et al. 2008, van Katwijk et al. 1997). Direct toxicity of ammonium on seagrasses has been demonstrated at concentrations as low as 0.02 mmol (van Katwijk et al. 1997; Brun et al. 2002). The thresholds in toxicity for *Zostera noltii* depend on the time of the year with similar doses of ammonium (200 μM) during an experiment resulting in toxic effects in winter and growth enhancement in spring (Brun et al. 2002). Within the Dutch Wadden Sea, the maximum ammonium concentrations were 45.1 mg l^{-1} (3.21 mmol; on 1978-12-05 at 10:41:00 in station Groote Gat zuid), an area without seagrass. Highest 90th percentile ammonium concentrations (0.9 mmol) were found at the Bocht van Watum (Table 3.5). On average, ammonium concentrations in the Ems-Dollard estuary appear to be declining (Figure 3.4), suggesting that local seagrass revival might be more likely.

Cadmium is identified as a priority hazardous substance for non-inland surface waters, with environmental quality standards of an annual average concentration (AAC) of 0.2 µg l^{-1} and a maximum allowable concentration (MAC) of 1.5 µg l^{-1} (Bakker et al. 2009). Within the Dutch Wadden Sea, the maximum concentrations observed was 11.90 µg l^{-1} (on 1976-01-07 at 10:59:00 in station Groote Gat noord), which is almost 10x as high as the MAC. Within our study, the 90th percentile concentration at locations without seagrass present was 0.2 µg l^{-1}, which is in the same order of magnitude as the AAC (Table 3.4). These findings suggest that 0.2 µg l^{-1} may indeed be a threshold concentration for the occurrence of seagrass. At the Balgzand seagrass area, cadmium concentrations declined since the 2000s (as was observed for the trilateral Wadden; Bakker et al. 2009) with seagrass reoccurring when these concentrations fell below the AAC of 0.2 µg l^{-1} around 2005 (Figure 3.5a). At the Noordpolderzijl seagrass area, measurements of cadmium concentrations stopped before 2000 and were at that time 0.3 µg l^{-1} so just over the ACC (Figure 3.5f). If cadmium concentrations declined hereafter as well, then this may have contributed to the reappearance of seagrass. At Valom, cadmium concentrations remained below 0.2 µg l^{-1}, so below AAC level.

Present concentrations of mercury, with environmental quality standards of an annual average concentration (AAC) of 0.05 µg l^{-1}, are considered to be a risk for large parts of the Wadden Sea ecosystem (OSPAR 2009, Bakker et al. 2009). (Bakker et al. 2009). Although concentrations of mercury in the river Elbe were strongly reduced in 1994, yearly averaged mercury concentrations between 1994 and 2006 are still over 10 times higher in the Elbe, Weser and Ems, than in Lake IJssel and Eider (Bakker et al. 2009). Within our study, the 90th percentile of mercury concentrations was higher than the ACC in most of the seagrass locations (Table 3.4). High concentrations of mercury have been observed to limit the growth of *Zostera marina* (Lyngby & Brix 1984). Furthermore, the ability of seagrass to accumulate mercury might facilitate the transfer of this toxic metal from abiotic elements of the marine environment to higher levels of the trophic chain (Beldowska et al. 2015).

High suspended particulate matter (SPM) concentrations are considered to be harmful to seagrass growth by reducing their light available for photosynthesis. Within the Dutch Wadden Sea, the maximum concentrations of SPM were more than 7.5 g l^{-1} (Table 3.2). It should be noted, however, that SPM concentrations are intrinsically highly variable and that the observed variations in SPM measurements (including peaks) are most likely influenced by changes in protocols (Philippart et al. 2014). In the 2000's, the average SPM concentrations ranged between (0.1 * 264 =) 26 mg l^{-1} at Balgzand (Figure 3.5a) and (0.5 * 264 =) 132 mg l^{-1} at the Eemshaven (Figure 3.5b). Assuming a linear relationship between the light attenuation coefficient (k_D; m^{-1}) and SPM (mg l^{-1}) of k_D = 0.08596 + 0.06729 SPM (Devlin et al. 2008), then the attenuation coefficient at Balgzand and Eemshaven would have been 1.8 and 9.0 m^{-1}, respectively. Light conditions at a particular depth (z; m) can be calculated from the light conditions just under the water surface determined as photosynthetic active radiation (PAR_{-0m}) and the light attenuation coefficient (k_D; m^{-1}) according to $PAR_z = PAR_{-0m} \exp^{-KD*z}$). For the Dutch Wadden Sea, the range in proportions of the remaining light conditions at a depth of 0.5m ($PAR_{-0.5m}$) would then be from 1% near the Eemshaven to 60% at Balgzand. In addition, growth might not only be hampered when the seagrass is submerged but possibly also during low tide if high turbidity of the water results in covering the seagrass leaves with a layer of fine sediment.

3.4.4 Conclusions

In conclusion, the results of the analyses suggest that seagrass growth may be hampered by high concentrations of ammonia, cadmium, mercury and suspended particulate matter in the Dutch Wadden Sea. Concentrations outside seagrass beds are not only much higher than inside seagrass beds, but also higher than the thresholds found during previous experiments. Because sensitivity and toxicity of seagrass to these compounds appears to be related to its phenology (e.g., occurrence of various life stages during the year), further (experimental) research should focus on impacts of cadmium, ammonium and suspended particulate matter during various life stages and their possible cumulative effects. The potential of harmful effects of high nutrient and metal concentrations in the sediments should also be investigated. The findings should then be extrapolated to high-resolution data on field conditions within and outside seagrass beds, which requires an upgrade of the monitoring network in particular for ammonia, cadmium, mercury and suspended particulate matter.

4. SEAGRASS AND HYDRODYNAMICS

Paolo Stocchi & Adam S. Candy

4.1 Introduction

Seagrass in the Wadden Sea is represented by two species of the genus *Zostera* that are generally located at different depths with respect to the local water level:

1. *Zostera noltii* is perennial and grows in the intertidal zone (hence it is exposed to air and wind during local low tide). It is characterised by small and narrow leaves.
2. *Zostera marina* is largely perennial and grows below the local low-water level (hence it is always submerged). It is characterized by rigid bases and broad leaves. Furthermore, a smaller morph of *Z. marina*, which is a mostly annual and characterized by narrower leaves (Bos et al. 2007), often occurs together with *Z. noltii* in puddles which remain filled with water at low tide.

Seagrass beds and the communities they form are well known for their ability to alter their local hydrodynamic environment, reducing current velocities and altering turbulent structure in and around the canopy (Fonseca and Koehl 2006). Also, by interacting with suspended sediment and its erosion and deposition, Seagrass provides shelter for sediments to settle and therefore alters the morphology. Accordingly, seagrass beds have a positive effect on the stability of shorelines (Keyzer et al. 2020). The geomorphological role of seagrass beds (and aquatic vegetation in general) is particularly important for the stability of salt marshes. Here, in fact, seagrass:

- decreases the near-bed shear stresses, thus reducing the sediment flux to the salt marsh platform;
- dissipates the wave energy acting on the salt marsh scarp (Brampton 1992; Moller et al. 1999, Suzuki and Klaassen 2011), thus reducing boundary erosion;
- increases sediment deposition (especially during summer time) via complex ecosystem engineering (Jones et al. 1997; Bouma et al. 2005).

However, the very same physical processes from which seagrass offers protection, can also contribute to the demise of seagrass beds. Seagrasses are extremely sensitive to hydrodynamics (currents and waves), desiccation as well as to extreme changes in temperature and salinity (Dolch and Reise 2009; Folmer et al. 2016). Also, seagrass beds require sediment stability, i.e. low rates of erosion/transport/deposition. The latter is also an important factor that can limit seagrass recovery (Philippart 1994; Schanz and Asmus 2003; Dolch and Reise 2009; Suykerbuyk et al. 2016). Overall, Seagrasses respond quickly to changing environmental conditions (Frederiksen et al. 2004ab).

In the Wadden Sea, most of the current seagrass beds are found in the mid to upper tidal zone along the leeside of islands and high sand bars, as well as along the parts of the mainland coast that are sheltered from prevailing storms. This suggest that low hydrodynamic regimes (and the associated sediments dynamics) are preferred by seagrass. It is important, therefore, to consider the relationship between seagrass and the flow of the surrounding water, air as well as sediment.

4.2 Seagrass and hydrodynamics: modelling and field experiments

4.2.1 Benthic boundary layers

Seagrass is anchored to the seabed, where water flow is affected by the nature of the bottom. In fact, when a fluid is in motion against a solid boundary such as the seabed, friction arises between the two. This friction initially affects only the fluid motion in direct contact with the bed, but over time these effects reach higher elevations in the flow. The region of fluid that is closest to the bed and influenced by frictional effects is termed benthic boundary layer (Figure 4.1). The mean horizontal velocity within the boundary layer increases from zero at the bed (the no-slip condition) to a maximum value at the top of the boundary layer. The mean horizontal flow velocity varies as a function of the elevation above the bottom and defines the so-called velocity profile (Figure 4.1). When a fluid begins to flow over the bed the boundary layer is initially laminar, i.e. it is characterized by very thin layers of non-mixing moving fluids. Its thickness grows slowly over time, therefore with distance travelled. In most coastal settings laminar flow is short-lived, and the boundary layer develops through the transitional regime to become a turbulent boundary layer. Turbulent flow is characterized by a prevailing flow direction, but with random lateral and vertical deviations through the fluid body.

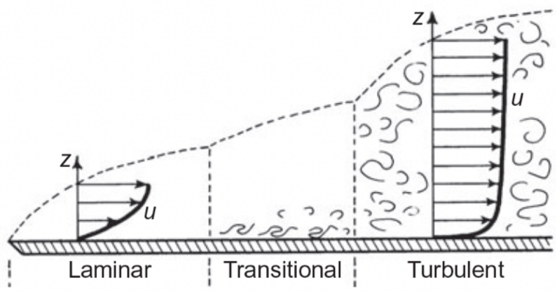


Figure 4.1. A growing boundary layer (transformation from laminar to turbulent flow) and related vertical velocity profile for a stationary uni-directional flow (Allen 1985; Masselink et al. 2011).

The shear stress is the tangential force (τ) per unit area at any level in the fluid, according to:

$$\tau = \mu \, d_u / d_z$$

where μ is the molecular viscosity of the fluid, which is the resistance to deformation provided by molecular forces within the fluid. The molecular viscosity is the link between the shear stress and the velocity gradient (d_u / d_z). The bed shear stress is the tangential component of stress occurring on the fluid plane that is in contact with the bed. It is positively related to the velocity gradient. The bed shear stress under a turbulent boundary layer is higher than under a laminar boundary layer, because of the steeper velocity gradient. Accordingly, eroded material can be lifted from the bed into the flow through turbulent mixing. A hydraulically smooth beds (mud or very fine sand) are overlain by a viscous sublayer of laminar flow (Figure 4.2). A hydraulically rough bed, instead, offers more friction because of the coarser elements that protrude up through the fluid layer (Figure 4.2). Seagrass beds, and aquatic vegetation in general, contribute to the roughness of the sea bed. Hence, dissipation of energy through turbulence is expected.

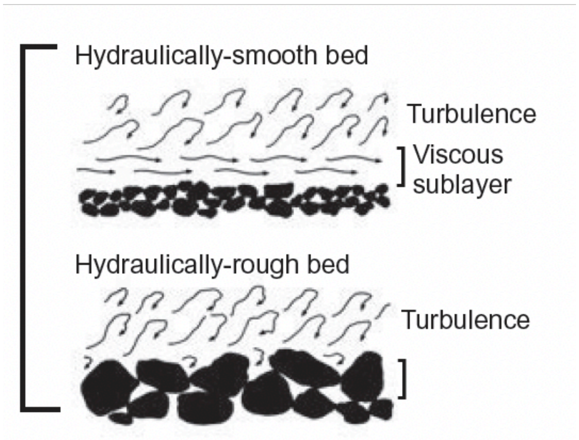


Figure 4.2. Flow and bed condition in the presence (top panel) and absence (bottom panel) of a viscous sublayer (modified from Allen 1994; Masselink et al. 2011).

Isolated clumps of vegetation act as small obstacles disturbing the flow velocity. Larger stands of vegetation more significantly change the shear velocity profile (Figure 4.3). The uppermost surface of the vegetation acts as a false benthic boundary layer, termed the zero-plane displacement. This is typically located around two-thirds of the stand height, depending on vegetation type and spatial density over the bed. Flow strength within the vegetation is very low, facilitating sediment deposition. As flow strength increases, the vegetation stand is progressively flattened and the zero plane is located closer to the bed.

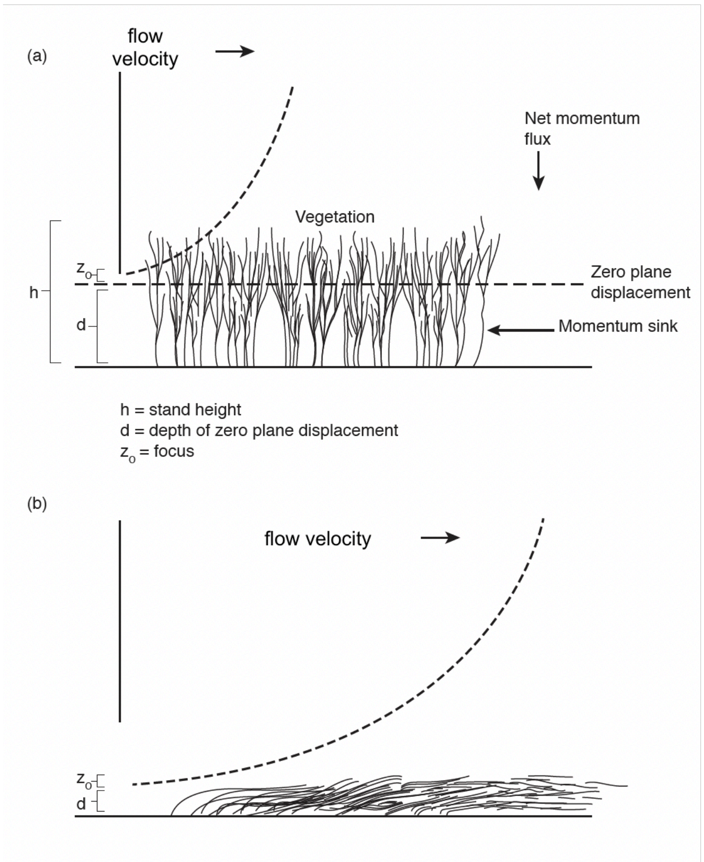


Figure 4.3. Flow velocity profiles over vegetation stands at relatively low (top panel) and fast (bottom panel) flow velocities (modified from Carter 1988, Masselink et al. 2011).

4.2.2 Benthic boundary layers under oscillatory flow (surface gravity waves)

In shallow water all water motion consists of horizontal movements to-and-fro which are uniform with depth and greater than the wave height (Figure 4.4). When the waves orbital motions are able to disturb the seabed, sediment movement then becomes possible. The to-and-fro motion can lead to sea bed disturbance, increased sediment mobility and size sorting. These processes are accentuated as water shallows (Figure 4.5). Where the sea bed is sloping, which is the situation as waves approach the coast, sediment can be brought into suspension within the water column, accumulate in depressions on the sea bed, and/or undergo net transport towards the coast in the direction of wave energy transfer. Wave-influenced bed forms such as ripples may develop.

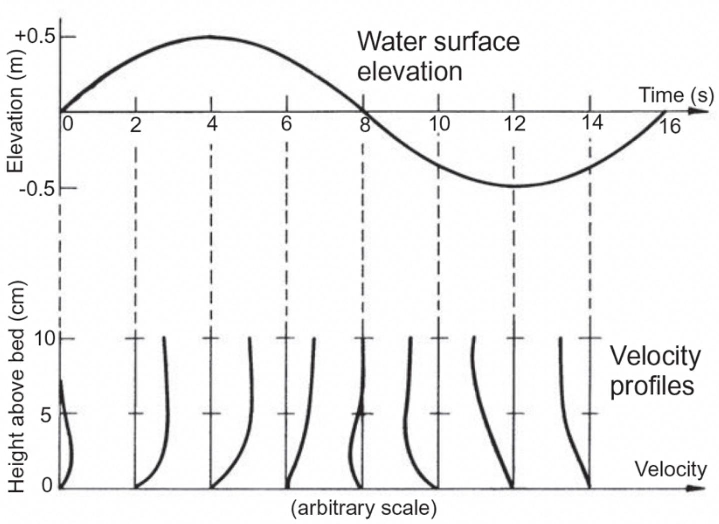


Figure 4.4. Current velocity profile (velocity of the water at different depths) in an oscillatory flow due to a wave with an amplitude of 0.5m passing within 16 seconds (Sleath 1984; Masselink et al. 2011).

In most of the available numerical models for regional hydrodynamics (e.g. see SWAN and Deltares products such as Delft3D and XBeach), vegetation is represented by vertical rigid rods. This spatial discretization follows the Dalrymple (1984) parametrization of bed roughness and energy dissipation. In these models, the spatial distribution of different vegetation species can be specified, as well as a schematization in vertical sections per plant species. The occurrence of these rigid static objects results in wave attenuation by damping and wind-wave driven water level set-up (Figure 4.6). Accordingly, vegetation contributes to bottom rugosity and roughness and, eventually, to friction and shear stress. The latter dissipates wave energy and current velocity, generating variable pressure fields which, in turn, affect transport of suspended and bottom matter such as sediment.

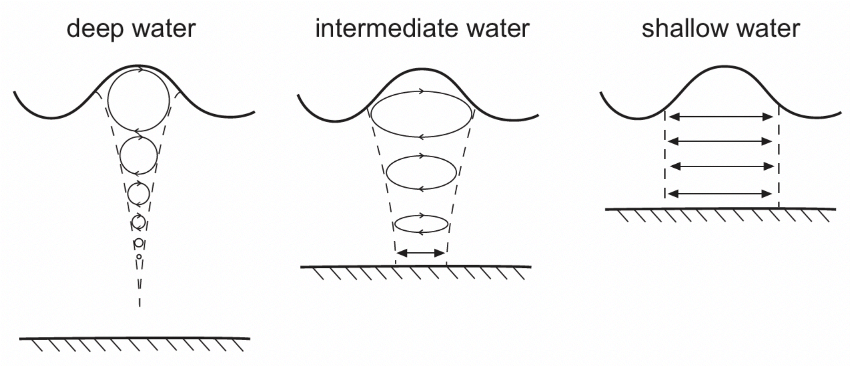


Figure 4.5. Motion of water particles under surface gravity waves at different water depths (Masselink et al., 2011).

These models have been used by Chen et al. (2007) to show that larger seagrass bed width in the direction of wave propagation results in higher wave attenuation and less energy on the shoreline. The total force acting on the bottom in the whole domain decreases as the seagrass bed is moved offshore. Also, relative wave attenuation and reduction in bottom stress increase with incoming wave height. However, seagrass presence varies spatially, seasonally, and inter-annually in temperate environments, whereas shoreline erosion is usually associated with wave events that occur episodically (Wilcock et al. 1998) over annual or decadal time scales (Kamphuis 1987). Timing between wave events and seagrass growth likely influences the potential for seagrass beds to protect shorelines. Without knowing this timing, it is difficult to evaluate the net influence of seagrass on shoreline protection based on the results presented here.

Following the implementation of wave dumping due to vegetation of Figure 4.6, Carr et al. (2018) have used a three-point dynamic model (hence coupled to the hydrodynamics) to investigate how seagrass might affect the behaviour of coupled marsh-tidal flat systems. The authors have shown that the presence of seagrass beds (see Chapter 1) has two main effects:

- reduction of near-bed shear stress and consequent decrease of the sediment flux to the salt marsh platform, and;
- reduction of the wave energy directly impacting on the salt marsh scarp and consequent decrease of boundary erosion.

Differences due to the presence or absence of seagrass and stochastic vs. constant drivers lead to the emergence of complex behaviours in the coupled salt marsh-tidal flat system. In intertidal areas without seagrass, small tidal flats are unlikely to expand and provide enough sediment to the salt marshes to combat sea level rise. However, as the tidal flat expands, the concurrent increase in sediment supply due to wave-induced processes allows for the salt marsh to maintain pace with sea level at the expense of salt marsh extent. Therefore, the occurrence of seagrass provides an overall stabilizing effect on the coupled marsh-tidal flat system.

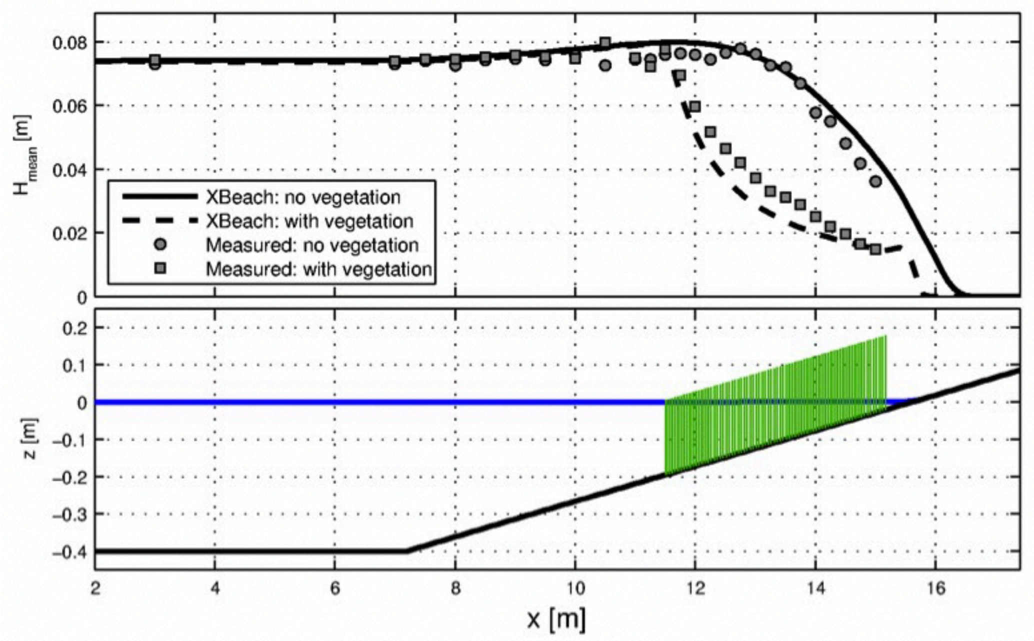


Figure 4.6. Top panel shows the predicted (straight and dotted line, based upon XBeach model) and observations (circles and squares) effects of vegetation on the significant wave height (H_{mean}; m) based upon a sediment profile (height z in m, transect x in m) and height of the vegetation when present (green) as depicted in the bottom panel (Deltares, 2014).

Hence, seagrass adjacent to a salt marsh may impact long term morphological behaviour under constant and stochastic forcing for different external sediment supply and rates of sea level rise. System behaviour differed between constant and seasonally varying stochastic drivers, indicating that the interaction between seasonality and variability of the drivers and vegetation is important to understanding the co-evolution of the coupled seagrass-marsh system (see 4.2.1). On the other hand, currents affect the vegetation via the advection of nutrients and (in)organic suspended matter, as well as the local light climate; moreover, the current and wave climate plays a crucial role in whether or not an area is favourable for pioneering vegetation.

Suzuki and Klaassen (2011) have investigated the hydrodynamics on seedlings of halophytic plants around a salt marsh cliff by flume experiment and a numerical model. From this study it is found that high waves and long period waves (such as from fully developed swell) produce vortices which can be dangerous to the seedlings. Measurements reveal the existence of a vortex in front of a salt marsh cliff. The vortex occurs because of the flow separation on the stepped bottom. The vortex might give negative impact to the seedlings of salt marsh plants.

With regard to sea level rise and increasing storm frequencies due to climate change, higher waves and long period waves can be expected to occur near marsh cliffs. This could have profound effects on salt marsh ecosystem stability and potential for recovery worldwide and also in the Wadden Sea. Within the study of Suzuki and Klaassen (2011) introduced above, the hydrodynamics on seedlings of halophytic plants (in general) around a salt marsh cliff are investigated by flume experiment and a numerical model. Particle tracking velocimetry (PTV) measurements reveal the existence of a vortex in front of a salt marsh cliff. The vortex occurs because of the flow separation on the stepped bottom. The vortex might negative impact the seedlings of saltmarsh vegetation, therefore, the strength and position of the vortex is investigated by a numerical model. From this study it is found that high waves and long periods wave produce vortices which can be lethal to the seedlings.

More recently, the numerical simulations by Le Minor et al. (2019) for mangrove seedlings (Figure 4.7) showed that a downward flow associated to a horseshoe vortex enhances scour in front of the plant seedling and vortex shedding keeps the sediment in suspension or re-suspends the sediment in the rear of the mangrove seedling. Thus, a seedling has a significant influence on the flow pattern and sediment transport: the higher the flow speed, the less stable the sediment bed. Additionally, these findings could help to better understand how the settlement of mangrove/ seagrass seedlings and sediment dynamics affect mangrove and seagrass establishment and why the colonization or restoration of tidal flats is successful or not.

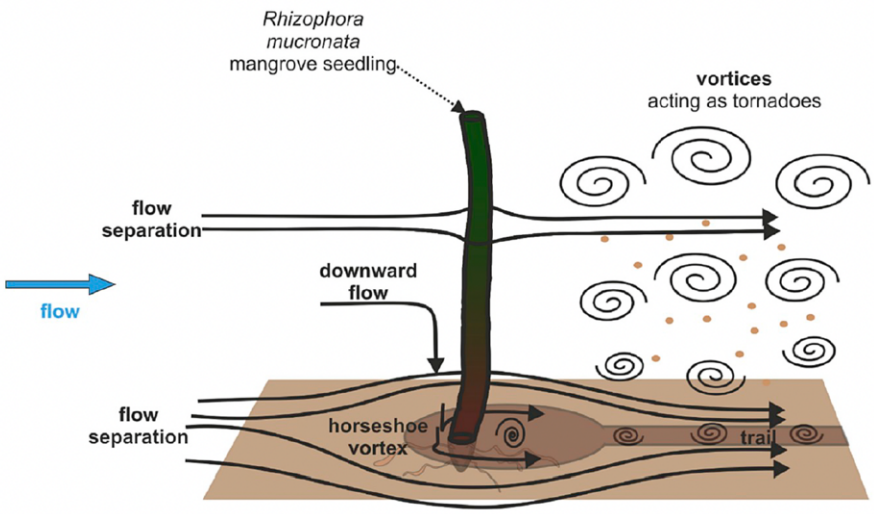


Figure 4.7. Interpretation scheme of the processes occurring when a unidirectional flow encounters a single mangrove seedling (Le Minor et al. 2019).

4.2.3 Flexible vegetation

The studies considered so far assumed the vegetation is rigid, i.e. they did not include/ consider the motion of vegetation. However, most aquatic vegetation is flexible and moves with and in response to the flow (as shown earlier in Figure 4.3). This adaptation to the hydrodynamic forcing affects the effective plant height and the drag that is exerted on the vegetation. Therefore, the flow-induced movement of the vegetation eventually affects the water flow itself and has implications for sediment stability and transport.

By means of flume experiments, Paul et al. (2012) have determined the contribution of the mechanical characteristics of vegetation in the attenuation of waves (Figure 4.8):

a) blade stiffness,
b) shoot density, and
c) leaf length.

Results show that wave attenuation is positively correlated with blade stiffness and for a given wave in shallow water, attenuation is dependent on a combination of shoot density and leaf length, which can be described by the leaf area index. Furthermore, the presence of a tidal current strongly reduced the wave-attenuating capacity of seagrass mimics, and this reduction was most pronounced at high shoot densities. Thus, most studies that have been carried out considering only waves will structurally overestimate wave attenuation for tidal environments. This emphasises that tidal currents need to be taken into account in future studies on wave attenuation by vegetation.

Since the seminal work of Dijkstra (2008) the flexibility of aquatic plants has been formally implemented larger-scale hydrodynamic and morphodynamic models (Dijkstra and Uittenbogaard 2010). These feedbacks are modelled in a research-tool called DYNVEG that takes into account the biomechanical parameters of the modelled plant species. It allows for the assessment of the behaviour of complex plants (plants with leaves and or buoyancy structures) in complex flow and waves and can be used as a pre-processor for further calculations using the rigid vegetation approximation. These new developments in the modelling of water-vegetation interactions will improve our understanding of complex physical feedbacks that can either boost or destroy the seagrass beds.

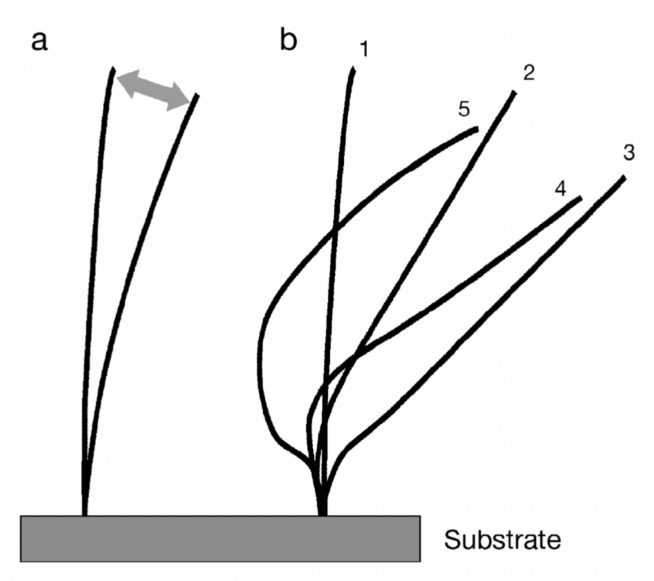


Figure 4.8. Schematic representation of mimic movement. (a) The stiff material moves back and forth like a cantilever, and (b) the flexible material moves in a whip-like motion (from Paul et al. 2012).

4.3 Potential physical threats to seagrass

4.3.1 Sediment stability (erosion/transport/deposition)

Sediment stability is an important condition for the growth of seagrass. It does not grow in areas with high sediment turnover, erosion or deposition, as may happen during storm surges (Cabao and Santos 2007). High sediment turnover can be caused by strong currents, storm surges, dredging and dumping of sediments, deepening of gullies and rivers as shipping lanes and through land claim operations in the nearshore zone. In particular, the main sources of sediment instability are wave exposure or high current velocity, which in addition, are known to have direct adverse effects on seagrass (Fonseca and Bell 1998; Schanz and Asmus 2003; van Katwijk and Wijgergangs 2004).

Seagrass cannot tolerate strong erosion neither being buried by sedimentation (Cabao and Santos 2007; Daniel et al. 2008). Elevated sand accretions with a generally oblong structure are called sand waves or mega-ripples and are widely observed on the tidal flats of the Wadden Sea. These large sandy bedforms may be formed by strong currents during storm surges and occur in extensive fields. These may be regarded as indicators of increased sediment mobility. Long-term studies near the island of Sylt, in the Nordfriesland district of Germany, have shown that seagrass beds have been replaced by areas with sand waves (Dolch and Reise 2009).

For the Western Wadden Sea, it was suggested that seagrass predominantly occurs in places with a low sedimentation rate and therefore does not occur at the Frisian coast where sedimentation rates are very high (van der Graaf and Wanink 2007). In the intertidal zone of the Northfrisian Wadden Sea, where more seagrass grows than in all the other regions of the Wadden Sea, large seagrass beds are found where surface sediments are underlain by solid peat and clay in which seagrass rhizomes and roots get a fair hold (Reise and Kohlus 2008). Both, the spatial pattern and a recent decrease in storminess suggest that sediment stability is the key factor for seagrass dynamics in this tidal area. On exposed sand, high sediment mobility may be limiting and along the sheltered mainland shore land claim activities with high accretion rates may cause a scarcity of seagrass (Reise and Kohlus 2008).

4.3.2 Sea-level rise and storm surges

The sea level is expected to rise by 0.5 to 1.4 m until the end of this century in response to global warming (Rahmstorf 2007; IPCC 2013). It is not clear to what extent natural sediment accretion could compensate for such an increase in water levels, especially in the face of the fixed coastline, but it is assumed that at least in the larger tidal basins the sediment supply may lag behind and consequently the duration of tidal submergence will increase (CPSL 2005). With higher water levels above seagrass beds, storm surges will have stronger effects on sediment stability. This could affect the seagrass directly. Extrapolating winter storm surge levels observed at tide gauges over the last four decades (Weisse and Pi 2006) into the next 40 years, water levels would rise by about half a meter, irrespective of any acceleration in global sea level rise. The reason for the recent increase in seagrass bed coverage in northern parts of the Wadden Sea could be a relaxation from an associated increase in hydrodynamics that would diminish seagrass beds in the long term (Reise and Kohlus 2008). With regard to sea level rise and increasing storm frequencies due to climate change, higher waves and long period waves can be expected to occur near marsh cliffs. This could have profound effects on salt marsh ecosystem stability and potential for recovery worldwide

(Reise and Kohlus 2008). It can be expected that habitats which are just marginally sheltered and suitable, such as in the more open Southwestern Wadden Sea, will be affected most.

4.3.3 Seed dispersal

As said above, seed dispersal of plants is essential for their long-term survival. In the Wadden Sea seagrass has difficulty re-establishing because, due to the local hydrodynamics, the natural dispersal of seeds towards potentially suitable habitats is limited.

4.4 Conclusions

Seagrass bed coverage in the Wadden Sea is assumed to be below its potential extent but estimates are affected by large regional variability, thus indicating a need for research and better definition on this subject. Under the current and expected future conditions, the Wadden Sea is a challenging environment for seagrass. Being a shallow intertidal basin, the Wadden Sea experiences strong tidal current that can erode the sea bottom, hamper the mechanical stability of the seedlings and ultimately disperse seeds. In addition, wind-driven currents and waves can perturb the bottom, hence disturbing the life of seagrass. Although small, locally generated waves can be destructive, especially if coupled to water level variations and tidal currents. However, the interaction between seasonality and variability of the drivers and vegetation is important to understanding the co-evolution of the coupled seagrass-marsh system.

Summarized, recent studies show evidence of the potential for hydrodynamics to affect this in multiple ways. Moreover, there is the potential for hydrodynamics to have a leading order effect on where seagrass meadows can establish. With the Wadden Sea being a highly evolving and dynamic area, there is an urgent need for further information to better understand and quantify this – if reestablishment is to be planned for. In order to get more grip on present and future options for the Wadden Sea as a hydrodynamically suitable habitat for seagrass (to better quantify the hydrodynamic processes and their interaction with seagrasses, their settlement and establishment), it is recommended to further improve the existing probability map by gathering and including more information on:

- Characteristics of seagrass meadows (blade stiffness, shoot density, leaf length) to allow for modelling of complex plants (with leaves and buoyancy structures) in complex flows and waves;
- Wind and waves (both distant and locally-generated wind waves), as a base-line for the potential impacts of hydrodynamics on seagrass meadows and habitats;
- Sediment availability, sedimentation rate and the sediment budget in general, as a base-line for the potential impacts of sediment dynamics on seagrass meadows and habitats;
- Higher-resolution data (in time and space) on water flow-vegetation-sediment interactions and feedbacks (in particular for seagrass meadows, a biogeomorphological approach);
- Data and modelled potential for seagrass seed dispersal in the Wadden Sea region; and
- Local relative sea level change as a combination of tides, wind set-up, global sea-level rise, local subsidence and local sediment compaction.

Such information can be gathered through two core efforts. Firstly fine-scale modelling studies of individual seagrass plants, similar to Le Minor et al. (2019) but for the species native to the Wadden Sea. This is important for the development and validation of accurate parameterisations of their behaviour relative to local hydrodynamic conditions. The above can then be gathered by means of more detailed regional models (possibly with higher resolution in areas where seagrass is already present and is most likely to occur) which are fed with high-resolution data on seagrass and the main structuring environmental factors.

Once calibrated and validated, such models can be used to identify potential hotspots (which can then be protected), for estimating the impacts of various climate scenarios, and for exploring the potential of various seagrass restoration efforts.

5. SEAGRASS IN THE SALT-MARSH WORKS OF GRONINGEN

Catharina J.M. Philippart, Marinka E.B. van Puijenbroek & Kelly Elschot

5.1 Introduction

One of the most important sites within the Dutch Wadden Sea where dwarf eelgrass appears to be slowly recovering is offshore along the northern coast of Groningen (Dolch et al. 2017, Elschot et al. 2020). Along a part of the coast of Groningen former land-reclamation works are present, which are created by man-made brushwood groynes and drainage ditches. These have resulted in semi-natural salt marshes (Dijkema et al. 1988, 2013).

So far, it is not clear whether the increase in dwarf eelgrass meadows in these salt-marsh works is due to larger-scale changes underlying the European-wide recovery (Dolch et al. 2017, de los Santos et al. 2019) or due to management influencing local conditions, i.e. protection against high energy waves and storms by increased maintenance of brushwood dams (Dijkema et al. 1988, Elschot et al. 2020). Dam maintenance may have created the essential Windows of Opportunity (WoO) for seagrass establishment: the mudflats reached an optimal bed level for successful settlement under the influence of reduced sedimentation and erosion rates combined with protection against strong hydrodynamic currents and waves during the most vulnerable germination and seedling stages.

The aim of this chapter is to study the relationship between the occurrence of *Z. noltii* and that of environmental factors that potentially affect its successful establishment within the salt-marsh works. This study is based upon two long-term ongoing monitoring datasets (2009-2018) along the northern coasts of the Groningen 1) long-term monitoring of salt-marsh works along the Groningen coast and 2) seagrass surveys in the Wadden Sea performed by Rijkswaterstaat. In this study, the occurrence of *Z. noltii* is related to the environmental factors (sediment height, change in sediment height and inundation). The temporal factor 'year' and the spatial factors 'sedimentation field' and 'polder' were taken into account as possible long-term and large-scale drivers for seagrass occurrence.

5.2 Methods

5.2.1 Study site

Along the Dutch coast, salt-marsh works consist of man-made sedimentation fields constructed in the first half of the 20th century to stimulate the settlement of sediment followed by the colonization of salt-marsh vegetation (Dijkema et al. 1988, Bakker et al. 2002). Brushwood groynes delineate each sedimentation field, which are maintained to prevent erosion of the accumulated sediment, and are designed following the Schleswig-Holstein method (Dijkema et al. 1988, 1990). Maintenance of the brushwood groynes surrounding the third and outer sedimentation field seized between 1990 and 2005 along the coast of Groningen (Elschot et al. 2020).

Within the sedimentation fields ground dams and drainage channels were constructed according to a fixed pattern (Figure 5.1, Dijkema et al. 1988). Main drainage channels were located every 200 m perpendicular to the dike, primary ditches were constructed every 100 m parallel to the dike and secondary (smaller) ditches every 10 m (draining into the primary ditch). From 1960 onwards, Rijkswaterstaat installed a monitoring network of 25 measurement sections spread over the mainland marshes, 12 along the Frisian and 13 along the Groningen coast to monitor variations in bed-level and the establishment of vegetation (Figure 5.2). Each measurement section consists of a series of three sedimentation fields, from the dike to the mudflats. A sedimentation field measures approximately 400 x 400 m and consists of on average 16 subsections of 100 x 100 m each. In summary, each measurement section covers approximately 48 subsections divided over three sedimentation fields.

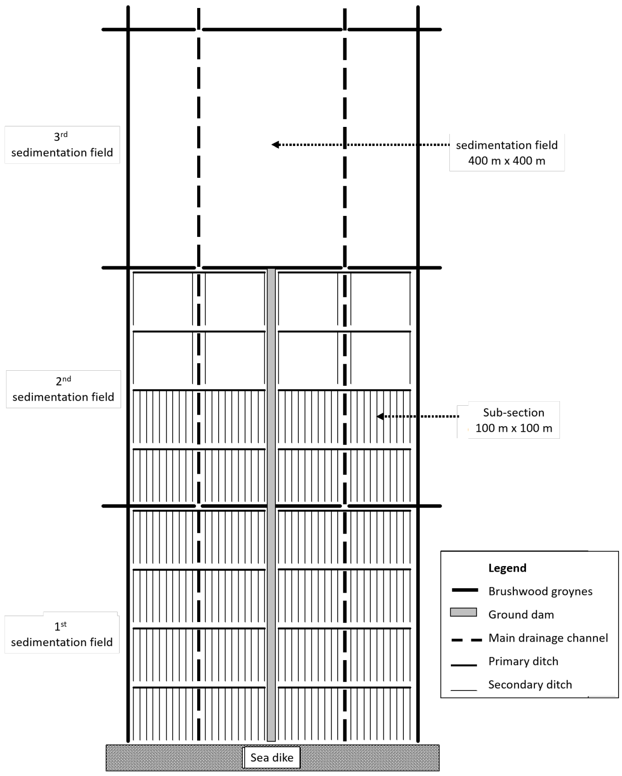


Figure 5.1. Schematic compartmentation of one measurement section with three sedimentation fields from the seashore (sea dike) at the bottom to the mudflats at the top, each being divided into sub-sections of 100 x 100 m (see Kamps 1956 and Dijkema et al. 1988 for more details).

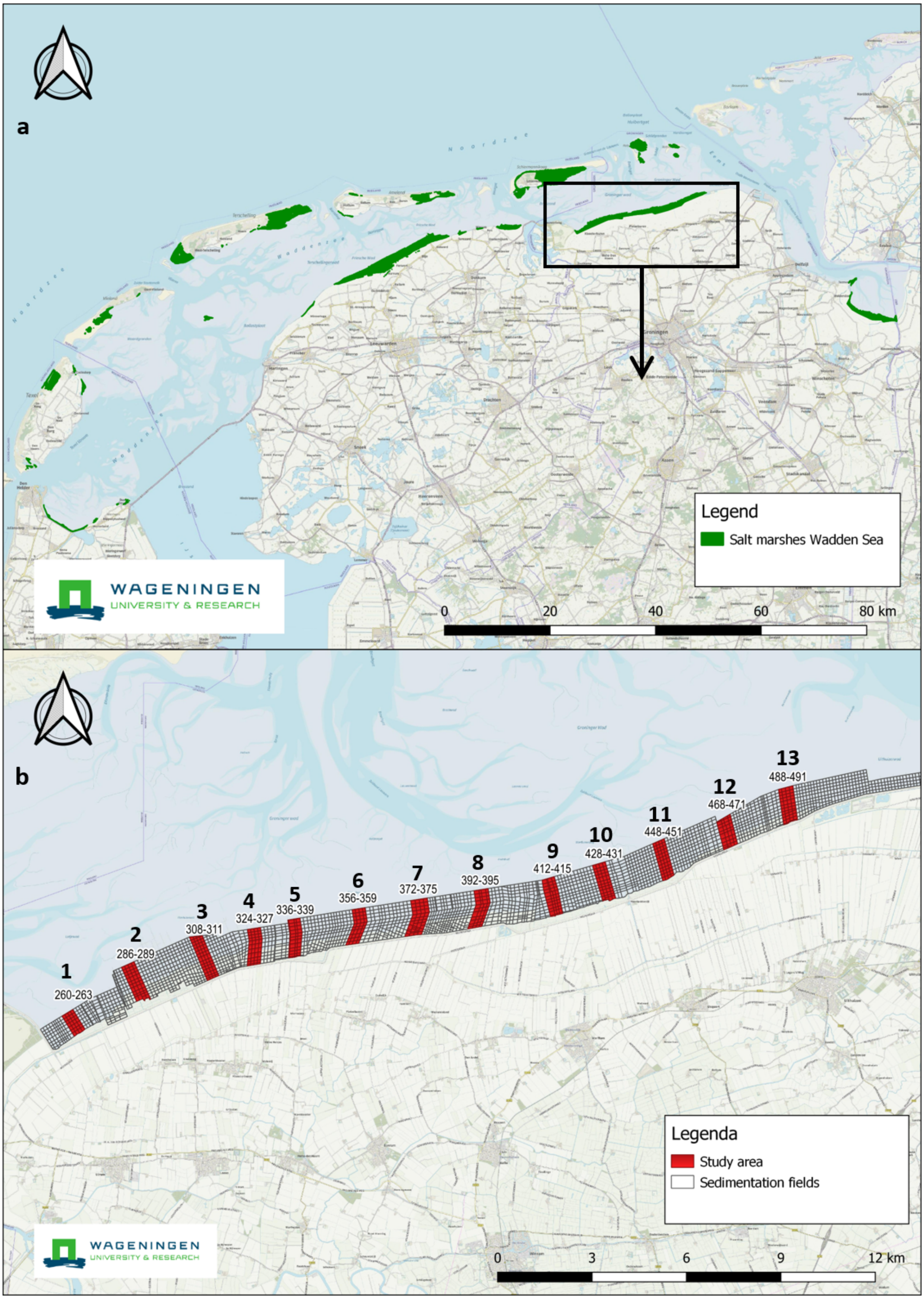


Figure 5.2. Study site. a) Overview of saltmarshes of the Dutch part of the Wadden Sea (in green). b) Close-up of the salt-marsh works along the Groningen coast with 13 measurement sections used in this study (in red). The individual number of each measurement field is indicated in bold, numbers of transects referred to in previous studies (e.g. 260-263) are also provided (Elschot et al. 2020).

5.2.2 Conceptual model

With respect to exploring the presence/absence of seagrass in saltmarsh works, our analysis was based upon the working hypothesis that seagrass settlement, growth and survival is influenced by:

1. Sediment height of the area (mm relative to NAP)
2. Annual change in sediment height (mm / yr)
3. Inundation
   a) Frequency (events per day; 1 April-31 Aug)
   b) Duration (hours per day; 1 April-31 Aug)
   c) Maximum inundation-free period (days; 1 April-31 Aug)
4. Sedimentation field (gradient from dike to sea and maintenance)
5. Measurement section (gradient from west to east; e.g. in sedimentation rate and nutrients)
6. Year (long-term trend and/or year-to-year variation in large-scale environmental conditions)

Although the impacts of other environmental conditions such as wave energy and water quality (e.g. nutrients, toxic compounds and suspended particulate matter) on seagrass performance cannot be excluded, these factors were not included because no data of sufficient quality (temporal and spatial resolution) were available to perform such an analysis.

5.2.3 Seagrass data sets

Data on sediment height (and annual change in sediment height) were derived from the monitoring database of the Groningen saltmarsh works (see 5.2.4). Indices for inundation were calculated from sediment height and Rijkswaterstaat water level data (see 5.2.4.3).

To explore the presence of seagrass in relation to these environmental conditions, we have analysed the data with three different datasets on the presence of seagrass (*Zostera noltii*) within the study site, being:

1. the Groningen saltmarsh works monitoring of subsections of sedimentation fields (2009 – 2018), and
2. the Rijkswaterstaat seagrass survey within subsections of sedimentation fields, divided into two periods, being
   a. between 2006 and 2009, and
   b. between 2010 and 2017.

As these three datasets had different methods and effort in the seagrass monitoring, they were analysed separately. For the second and third dataset, only the sedimentation fields were selected that were included during the surveys.

5.2.4 Long-term monitoring of salt-marsh works along the Groningen coast

5.2.4.1 General description

For thirteen measurement sections present in the salt-marsh works along the Groningen coast, the coverage percentage of thirty types of salt-marsh plants were recorded annually in each subsection of approximately 1 ha (Figure 5.1). The sediment height in each measurement section was measured in transects parallel to the coast, in the middle of each 1-ha sub-section using an RTK-DGPS. Between 2009-2013, the frequency of measurements was every 4-years. After 2013, this has been adjusted to once every three years. The length measured per measurement section differs because the salt marsh is not consistently the same width everywhere and the distance between the dike and the mudflats varies in time.

Before 2005, all measurements were carried out by Rijkswaterstaat and since 2005 by external parties. Up to this day, part of the second and the third sedimentation field furthest from the dyke remained unvegetated, except for the establishment of *Salicornia* sp., *Spartina anglica* and *Zostera noltii* (Elschot et al. 2020).

5.2.4.2 Sediment height and change in sediment height

Sediment height in the Groningen salt-marsh works was extrapolated linearly between the years it was measured to calculate an annual sedimentation height. From these annual sediment heights, the yearly change in sediment height was calculated by subtracting the heights for two consecutive years. Unfortunately, the sediment height was not measured for all subsections. This mainly occurred in the third sedimentation field furthest from the dike on the mudflats. For the second (middle) sedimentation field in 15% of the subsections the sediment height was not measured, whereas for the third sedimentation field (furthest from the dike) approximately 40% of the data are missing.

5.2.4.3 Inundation indices

The water level data from Rijkswaterstaat was used to calculate inundation frequency (floodings per day), inundation duration (hours per day) and the maximum length of the inundation free-periods (the maximum number of days for a subsection not to be submerged) in each measurement section. For the measurement sections along the coast of Groningen, 10-minute interval water levels were used from Schiermonnikoog water level station were used, which are available online (waterinfo.rws.nl). The inundation frequency, duration and inundation free-period were calculated during the growing season of *Z. noltii* between April 1 and August 31.

To calculate the inundation frequency for each year, first the maximum water level for each high tide was calculated during the growing season. Second, the number of tides for which the tidal height is higher than the sediment height of each subsection was determined and divided by the number of days in the growing season. The inundation duration in hours per day was calculated by the number of hours that the tidal height was higher than the sediment height and divided by the number of days in the growing season. The inundation free-period is the maximum period (in days) for a subsection to be not inundated in the growing season. For these calculations it is assumed that local morphology does not have depressions in which water remains.

5.2.4.4 Seagrass occurrence

For the Groningen salt-marsh works monitoring (Elschot et al. 2020), the occurrence of seagrass was originally noted down according to the Braun-Blanquet approach (Braun-Blanquet 1921, IN: Van der Maarel 1975). Because estimates of coverage may easily vary between observers, we converted these data into presence (1) or absence (0) of seagrass within each subsection, which was also done for the second dataset (the seagrass survey explained in section 5.2.5). The frequency of seagrass occurrence per sedimentation field was calculated by dividing the number of subsections where the presence of seagrass was observed by the total number of subsections which were monitored for the presence of seagrass.

5.2.4.5 Final datasets

The full data set for the Groningen saltmarsh works existed of 7058 unique rows. In this dataset, subsections with low vegetation cover (<5%) where only *Salicornia* sp., *Zostera* spp. and/or *Spartina anglica* are present are referred to as "pre-pioneer zone". In the Rijkswaterstaat seagrass surveys (2nd data set, see §5.2.5), seagrass also occurred in sub-sections that are listed in the Groningen salt-marsh monitoring as "unvegetated". To facilitate comparison between the two data sets, we have analysed the relationship between seagrass and environmental conditions in the Groningen salt-marsh works for the data set covering the "unvegetated" and the "pre-pioneer" zone combined.

Reduction of this data set to the "unvegetated" and "pre-pioneer" zone resulted in a data set of 2106 rows (with each row containing information on one subsection during one year), which was further reduced to 819 rows after selection of the study period (2009-2018) and excluding the sedimentation field closest to the dike (where no seagrass occurred; -10 rows). After removing the rows which did not contain information on seagrass presence or absence ("NA"), the remaining data set consisted of 1792 rows. The final data set for which only complete rows (data on seagrass and four environmental variables) were selected consisted of 1627 rows distributed over 198 locations and years, with seagrass present in 17 of the 198 locations for all years between 2009 and 2018 taken together.

5.2.5 Rijkswaterstaat seagrass surveys in the Wadden Sea

5.2.5.1 Dataset Rijkswaterstaat seagrass surveys 2006 – 2009

Surveys on the presence and density of seagrasses in the Wadden Sea are performed by the Rijkswaterstaat and available as maps online[15]. The methods used for these surveys differ between years and are carried out by several external parties. Between 2006 and 2009, all previous known seagrass areas were mapped annually. Seagrass areas with a continuous cover between 1 and 15 % were mapped by hand, areas with a cover above 15% were mapped by aerial photographs. Since new small seagrass patches are easily missed, additionally seagrass density was mapped at several random points along the Groningen coast. Only data that was collected inside the sedimentation fields were included in the statistical analysis, but we report on other data as well.

[15] https://www.rijkswaterstaat.nl/water/waterbeheer/waterkwaliteit/indicatoren-voor-waterkwaliteit/zeegras/meer-weten/rapporten-zeegraskartering.aspx

Unfortunately, the precise location of random points without seagrass is not documented precisely and can only be interpreted based on maps. Therefore, for this analysis we had to assume that when there were random points taken within one sedimentation field, all the measurement sections in that specific sedimentation field were monitored. This assumption will slightly increase the chance of including false negatives in the analysis. Additionally, not all sedimentation fields in all 13 measurement sections were monitored every year in this survey. To analyse the data (2006-2009), the seagrass area was converted to a raster with a cell size of 20 m x 20 m with seagrass presence or absence.

For data that was collected within a subsection of a measurement section, the sediment height, inundation and other variables from the Groningen saltmarsh works monitoring could be linked to the presence or absence of *Z. noltii* from the Rijkswaterstaat seagrass survey. After removing missing values for the explanatory variables, the final dataset had 13 rows.

5.2.5.2 Dataset Rijkswaterstaat seagrass surveys 2010 - 2017

In the period 2010 – 2018 the seagrass survey was only performed four times (in 2010, 2011, 2014 and 2017). In 2010, the seagrass survey at the Groningen saltmarsh works was mapped according the grid method, where the two local grids partially overlapped measurement sections 8 and 13. For each grid cell (20 m x 20 m), the presence and density of seagrasses was documented. From 2011 onwards transects were used crossing almost all measurement sections along the Groningen coast, except for measurement section 2.

For this dataset, the data on seagrass presence is more accurate and chances of false negatives are smaller than the Groningen salt-marsh works monitoring. However, data on environmental variables are only available in the Groningen salt-marsh monitoring and limited to the measurement sections. Similar to the data from 2006-2009, we linked the *Z. noltii* presence and absence to the explanatory variables from the monitoring of the Groningen saltmarsh works. After removing missing values for the explanatory variables, the final dataset had 35 rows.

5.2.6 Statistical analyses

For each dataset we tested which variable (environmental variable, see §5.2.2) could best explain the observations on seagrass presence (univariate model).

To compare models, we followed an Information Theoretic approach (Anderson & Burnham 2002) and calculated differences Δi between the Akaike Information Criterion (AIC) of each model and the minimum AIC. Anderson & Burnham (2002) state that the level of empirical support for model i is substantial if Δi is between 0 and 2 (these are models with similar AICs as the optimal model), considerably less if Δi is between 4 and 7, and essentially none if Δi is larger than 10.

We also calculated Akaike weights wi (Anderson & Burnham 2002), which have the convenient ability that they can be interpreted as probabilities that a given model is judged the best model on repeated sampling. If the weight for a particular model has a value of 0.75, for example, this implies that this model has a probability of 75% of being the best model within the series of models tested.

Statistical analysis was done using R 3.6.2 version (R Core Team 2013) in a R Studio environment (version 1.2.5033; RStudio Team 2020), with using the package mgcv (version 1.8-31; Wood 2017) for generalized additive mixed modelling and the package MuMIn (version 1.43.17; Barton 2020) for calculating the Akaike weights.

5.3 Results

5.3.1 Seagrass occurrence

5.3.1.1 Groningen salt-marsh works monitoring program (SMW 2009 – 2018)

The seagrass *Zostera noltii* was first observed in the Groningen salt-marsh works monitoring programme (that started in the 1960s) in 2011 (Figure 5.3). Over the years (2014 – 2019) there has been a gradual increase in its occurrence. The distribution of seagrass did not reveal an obvious geographical trend in occurrence from west to east. For measurement sections 3-8, however, occurrence appeared to be higher in the sedimentation field 3 (being closer to the mudflats than sedimentation fields 2). For the other sections (1-2, and 9-13), seagrass appeared to have a more or less similar occurrence in sedimentation fields 2 and 3.

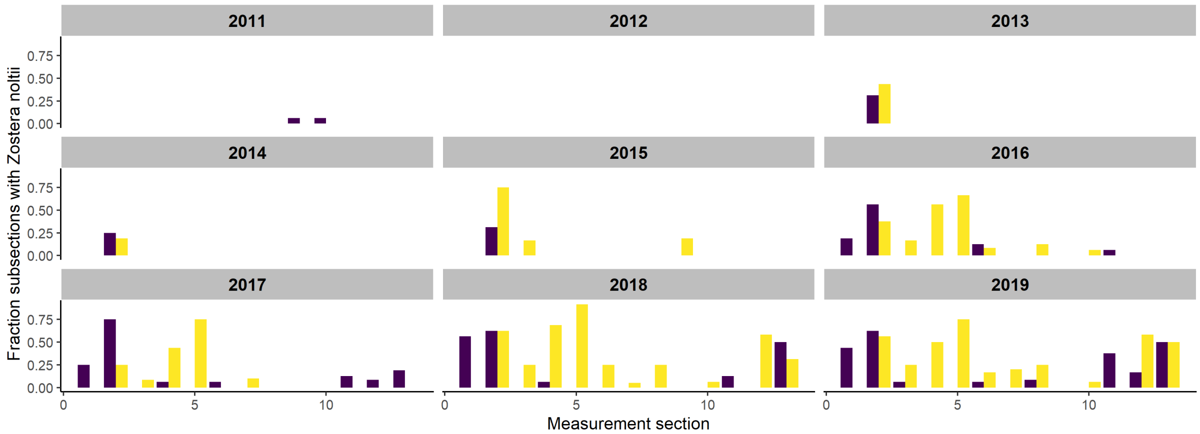


Figure 5.3. Groningen salt-marsh works (SMW) monitoring program: the fraction of subsections with seagrass (Zostera noltii) in each sedimentation field (2 & 3 are shown in yellow and purple, respectively) for each measurement section (1-13; see Figure 5.2) and for each year during the period that seagrass was found (2011-2019). No Z. noltii was found before 2011.

5.3.1.2 Rijkswaterstaat seagrass surveys (SGS 2006-2009 & SGS 2010-2017)

According to the Rijkswaterstaat surveys, highest abundance of *Z. noltii* occurred just east of the man-made salt-marsh works, with a cover of 90% in 2007. Note that, although there is no saltmarsh present at this location, brushwood groynes are present (see bottom panel of Figure 5.2). At the beginning of the study period (2006), measurement section 8 was also characterized by a higher cover of *Z. noltii*, but this decreased hereafter. Along the rest of the mainland coast of Groningen the cover remained low.

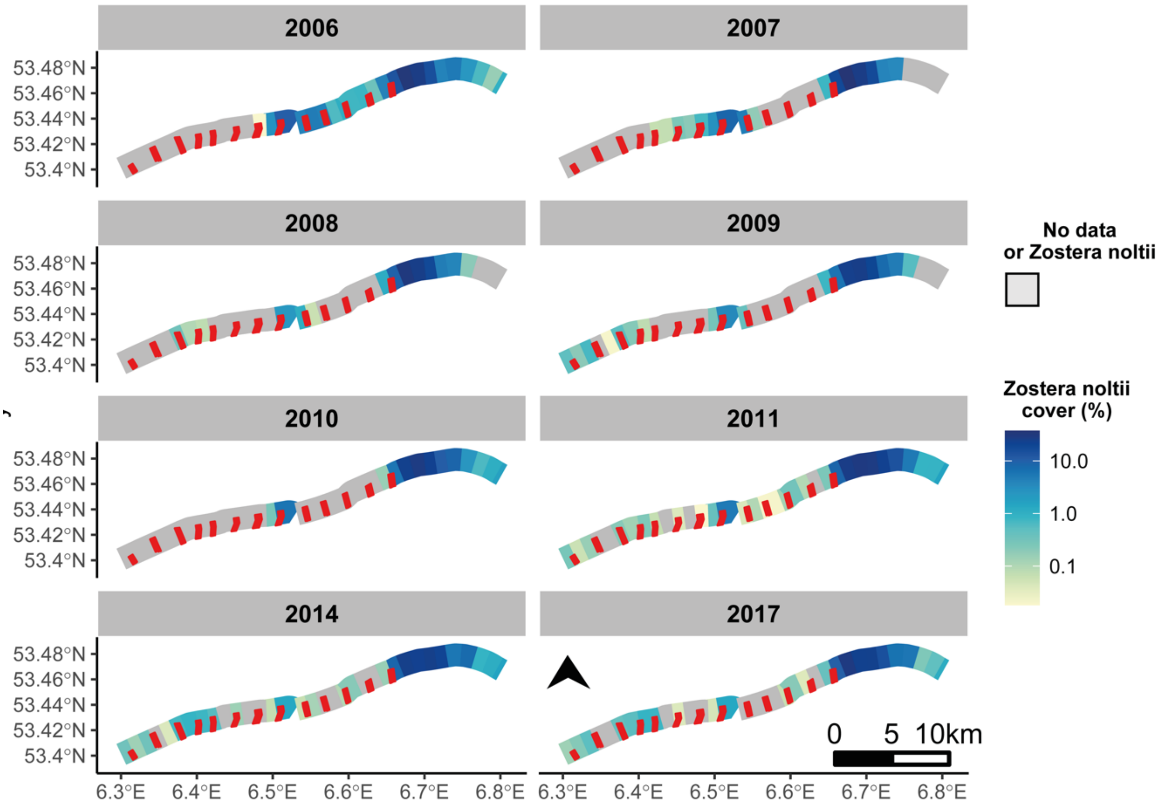


Figure 5.4. Rijkswaterstaat seagrass surveys: cover (%) of seagrass (Zostera noltii) along the coast of the mainland of Groningen. The mainland coast has been split in 35 blocks of approximately 1 km wide. Within these blocks, the percentage of the area of all the 20x20 m raster cells that contained Z. noltii is shown. From 2006 – 2009 areas of Z. noltii were mapped and random points were added to find small Z. noltii patches. From 2010 – 2017 a raster grid and transects were monitored for Z. noltii. The grey color indicates that either the location was not monitored for Z. noltii or that Z. noltii was not present in these blocks. The red squares are the locations of the measurement sections of the sedimentation fields. Sedimentation fields were present east from the most eastern measurement section, but maintenance stopped in 1990.

5.3.1.3 Comparison of surveys

The Rijkswaterstaat seagrass surveys revealed a different distribution of *Z. noltii* than the Groningen salt-marsh monitoring program. Seagrasses had a relatively high cover in 2006, and decreased thereafter. And in contrast to the Groningen saltmarsh monitoring, the results of the Rijkswaterstaat surveys do not indicate an increase in seagrass cover after 2015. When comparing the presence of seagrass as scored in the Groningen saltmarsh works monitoring (SMW) and the Rijkswaterstaat seagrass surveys (SGS), it can be seen that overlap in observations (with similar outcomes on presence or absence) was mostly less than 50%, with exception of the last year (2017) of observations. The differences were mainly due more observations on the presence of seagrass in the SGS than in the SMW data set (Table 5.1).

Table 5.1. A comparison of the two types of datasets used in this study, the seagrass surveys (SGS) as commissioned by Rijkswaterstaat and the monitoring within the saltmarsh works (SMW) as performed within the WOT framework for each measurement section (MS; see Figure 5.2) separately. No data is indicated by "nd", seagrass being absent by "0" and seagrass being present by "+". A green colour indicates that both the SGS and SMW had similar outcomes with respect to the presence or absence of seagrass (within a section for that particular year), a red colour indicates that observations were different.

		SGS 1st series				SGS 2nd series			
MS	Source	2006	2007	2008	2009	2010	2011	2014	2017
1	SGS	nd	nd	nd	+	nd	+	+	+
	SMW	0	0	0	0	0	0	0	+
2	SGS	nd	nd	nd	0	nd	nd	nd	nd
	SMW	0	0	0	0	0	-	+	+
3	SGS	nd	nd	+	+	nd	+	+	+
	SMW	0	0	0	0	0	0	0	+
4	SGS	nd	nd	0	nd	nd	0	+	+
	SMW	0	0	0	0	0	0	0	+
5	SGS	nd	nd	nd	nd	nd	+	+	+
	SMW	0	0	0	0	0	0	0	+
6	SGS	nd	+	nd	nd	nd	nd	nd	+
	SMW	0	0	0	0	0	0	0	+
7	SGS	nd	+	nd	nd	nd	0	0	0
	SMW	0	0	0	0	0	0	0	+
8	SGS	+	+	+	+	+	+	+	+
	SMW	0	0	0	0	0	0	0	0
9	SGS	+	+	+	+	nd	0	+	0
	SMW	0	0	0	0	0	+	0	0
10	SGS	+	nd	nd	nd	nd	+	0	0
	SMW	0	0	0	0	0	+	0	0
11	SGS	+	nd	nd	nd	nd	+	+	+
	SMW	0	0	0	0	0	0	0	+
12	SGS	+	nd	nd	nd	nd	+	0	+
	SMW	0	0	0	0	0	0	0	+
13	SGS	+	+	+	+	+	+	+	+
	SMW	0	0	0	0	0	0	0	+
Nr obs.		6	5	5	6	2	10	10	12
Similar obs.		0	0	1	1	0	3	3	11
Fraction similar		0%	0%	20%	17%	0%	33%	33%	83%

5.3.2 Environmental conditions

After aggregation of the original data set (by averaging the original data per subsection of 100x100m), the ranges (differences between maximum and minimum values) for environmental conditions remained more or less similar (Table 5.4). Due to the very low number of observations that contained values for changes in sediment height in combination with seagrass present (n=11), it was decided to exclude this explanatory variable from the statistical analyses in the aggregated dataset and only include it in the original dataset.

Within the aggregated data set, the environmental variables sediment height and inundation duration were strongly correlated ($r=-0.99$, $p < 0.001$). There was no significant correlation between sediment height and year ($r=0.03$, $p=0.37$), nor between sediment height and the measurement section within the east-west gradient ($r=-0.17$, $p=0.23$). Inundation frequency and maximum inundation-free period, however, were both correlated with the east-west gradient ($r=0.85/p=0.013$ and $r=-0.94/p=0.029$, respectively).

Table 5.4. Overview of range in values of explanatory variables in the Groningen saltmarsh works for the original (n = 1627) and aggregated data set (n = 198) of the unvegetated and pre-pioneer zones combined.

			Original		**Aggregated**	
Code	**Variable**	**Unit**	**Min**	**Max**	**Min**	**Max**
SH	Sediment height	mm	-13	1087	134	1020
SHC	Change in sediment height	mm y^{-1}	-60	90	not included	
IF	Inundation frequency	d^{-1}	0.61	1.93	0.86	1.93
ID	Inundation duration	h d^{-1}	1.08	13.26	1.73	12.06
IP	Maximum inundation-free period	d	0.32	12.88	0.36	7.78
SF	Sedimentation field	-	2	3	2	3
MS	Measurement section	-	1	13	1	13
YR	Year	-	2009	2018	2009	2018

5.3.3 Relationships between seagrass and environmental conditions

5.3.3.1 Groningen salt-marsh works monitoring program (2009 – 2018)

Based upon the original (non-aggregated) data, seagrass occurred at a sediment height of 515 ± 212 mm (relative to Dutch Ordnance level (NAP), a change in sediment height of -4 ± 12 mm per year, an inundation frequency of 1.83 ± 0.19 times per day, an inundation duration of 8.15 ± 2.57 hours per day, and an maximum inundation-free period of 1.48 ± 1.47 days (Figure 5.5). After selection of the (non-aggregated) data of the pre-pioneer only, it appears that seagrass preferred the lower sedimentation heights and the (associated) longer inundation periods, higher inundation frequencies and shorter maximum inundation-free periods (Appendix 3). Furthermore, seagrass appeared to occur more often in the Western part of the study area and in later years of the study period (Figure 5.5).

For the univariate model, the values of the Akaike weights wi indicated that the occurrence of seagrass was best explained by (a smoothed) sediment height (Table 5.6). This model suggested that seagrass was most likely to be found at locations that were located at a sediment height of approximately 350 mm above Dutch Ordnance Level (Figure 5.6), and submersed around 9.5 hours within one day (24 hours) (Figure 5.5). The univariate model had a probability of 99% of being the best model within the series tested (Table 5.6) and explained 26% of the variance within the data set.

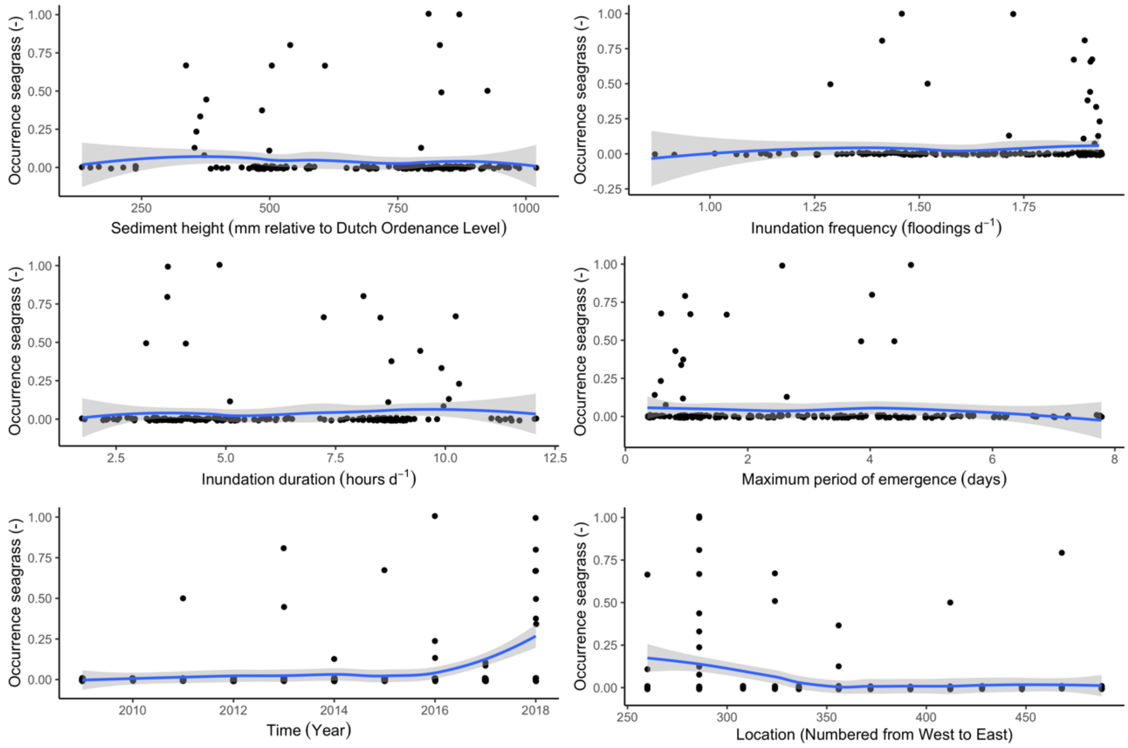


Figure 5.5. Groningen salt-marsh works monitoring program: occurrence of seagrass Zostera noltii (as fraction of subsections with seagrass present in the total number of sub-sections) in relation to several environmental conditions as averaged for each sedimentation field of the artificial salt marshes of Groningen between 2009 and 2018. The blue line is a loess smoother, the dark-grey area indicates the 95% confidence interval around the smoother. The data points are jittered to better illustrate the distribution of the data along the values of the environmental conditions.

Table 5.6 Groningen saltmarsh works monitoring program: results of statistical analyses for different models explaining the presence/absence of seagrass in relation to environmental variables (see Table 5.4) with results of best explanatory model printed in bold. SH= Sediment Height, IF= Inundation Frequency, ID= Inundation Duration, MEP= Maximum Emergence Period, SF = Sedimentation Field, EW= East-West location, YR = year, AIC=Akaike Information Criterion, delta= difference in value of AIC of a model compared with the best model, w=Akaike weight.

			SMW 2009-2018		
Code	**M**	**Model**	**AIC**	**delta**	**w**
SH	1l	Linear	576.5	33.01	0.000
	1s	Smoother	**543.5**	**0.00**	**0.992**
IF	3al	Linear	579.6	36.05	0.000
	3as	Smoother	579.2	35.63	0.000
ID	3bl	Linear	576.8	33.27	0.000
	3bs	Smoother	560.8	17.29	0.000
MEP	3cl	Linear	579.2	35.69	0.000
	3cs	Smoother	579.2	35.68	0.000
SF	4f	Factor	583.8	40.24	0.000
MS	5l	Linear	570.6	27.07	0.000
	5f	Factor	559.7	16.18	0.000
	5s	Smoother	553.3	9.72	0.008
YR	6l	Linear	574.7	31.20	0.000
	6f	Factor	570.7	27.14	0.000
	6s	Smoother	567.9	24.38	0.000

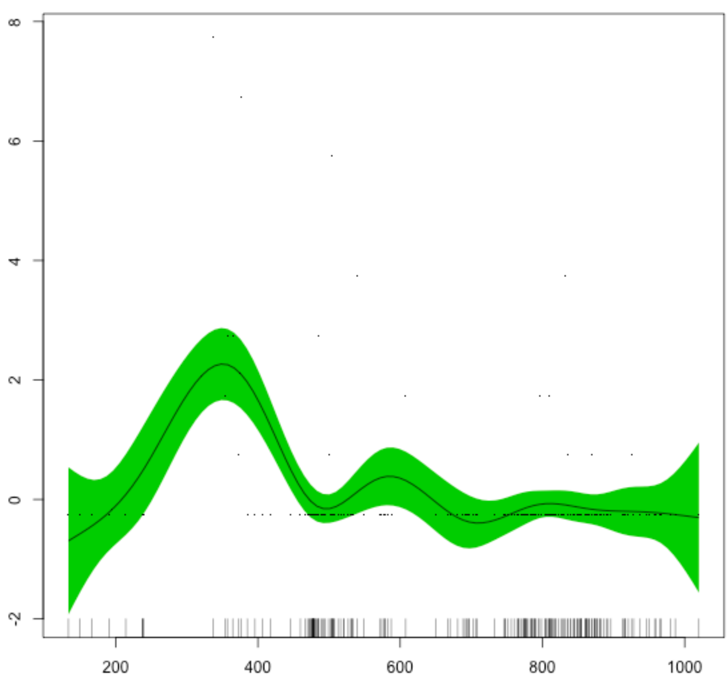


Figure 5.6. Groningen saltmarsh works monitoring program (SMW 2009-2018): Smoothers for best fits for univariate data model describing the relationship between a relative index for seagrass occurrence (y-axis) and sediment height (x-axis) in mm (see Table 5.6 for statistics).

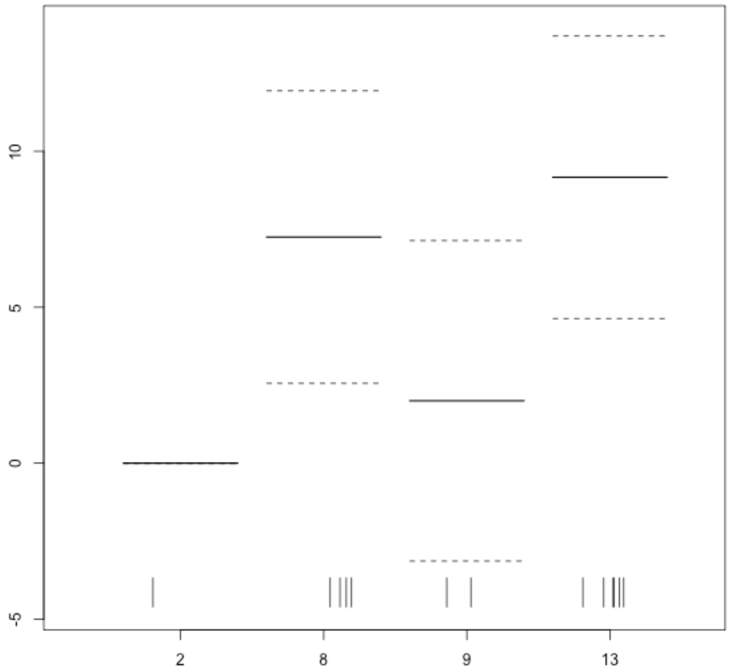
5.3.3.2 Rijkswaterstaat seagrass surveys (SGS 2006-2009 & SGS 2010-2017)

2006-2009: The variation in seagrass occurrence was best explained by three univariate models: the first model ("5f"), stating that seagrass presence is significantly different for the measurement sections (2, 8, 9 and 13), has the lowest AIC and a probability of 38% of being the best model (Table 5.7; Figure 5.7a). This is followed by the second model ("5l"), describing a linear relationship between seagrass and measurement sections, with a delta AIC of 0.53 and a probability of 29% of being the best model. The third model ("6l"), describing a linear relationship between seagrass and year, has a delta AIC of 1.50 and a probability of 18% of being the best model (Table 5.7).

2010-2017: The variation in seagrass occurrence after 2010 was best explained by two univariate models. The first model ("1s"), describing a non-linear relationship between seagrass and sediment height, has the lowest AIC and a probability of 57% of being the best model (Table 5.7; Figure 5.7b). The second model ("3bs"), describing a non-linear relationship between seagrass and inundation duration, has a delta AIC of 0.60 and a probability of 42% of being the best model (Table 5.7).

Table 5.7. Rijkswaterstaat seagrass surveys (SGS): results of statistical analyses for different models explaining the presence/absence of seagrass in relation to environmental variables (see Table 5.4) with results of best explanatory model printed in bold and models with substantial support underlined. SH= Sediment Height, IF= Inundation Frequency, ID= Inundation Duration, MEP= Maximum Emergence Period, SF = Sedimentation Field, EW= East-West location, YR = year, AIC=Akaike Information Criterion, delta= difference in value of AIC of a model compared with the best model, w=Akaike weight.

			SGS 2006-2009			SGS 2010-2017		
Code	**M**	**Model**	**AIC**	**delta**	**w**	**AIC**	**delta**	**w**
SH	1l	Linear	78.7	8.75	0.005	186.9	18.68	0.000
	1s	Smoother	73.0	3.07	0.082	**168.2**	**0.00**	**0.565**
IF	3al	Linear	78.6	8.71	0.005	186.8	18.52	0.000
	3as	Smoother	235.1	165.17	0.000	175.7	7.48	0.013
ID	3bl	Linear	78.7	8.74	0.005	186.9	18.61	0.000
	3bs	Smoother	77.0	7.02	0.011	<u>168.8</u>	<u>0.60</u>	<u>0.419</u>
MEP	3cl	Linear	78.7	8.75	0.005	186.9	18.65	0.000
	3cs	Smoother	93.3	23.36	0.000	179.6	11.34	0.002
SF	4f	Factor	77.3	7.33	0.010	186.9	18.70	0.000
MS	5l	Linear	<u>70.5</u>	<u>0.53</u>	<u>0.294</u>	186.4	18.12	0.000
	5f	Factor	**69.6**	**0.00**	**0.382**	190.9	22.62	0.000
	5s	Smoother	Not enough data for testing					
YR	6l	Linear	<u>71.4</u>	<u>1.50</u>	<u>0.180</u>	186.5	18.28	0.000
	6f	Factor	75.8	5.83	0.021	190.9	22.68	0.000
	6s	Smoother	Not enough data for testing					



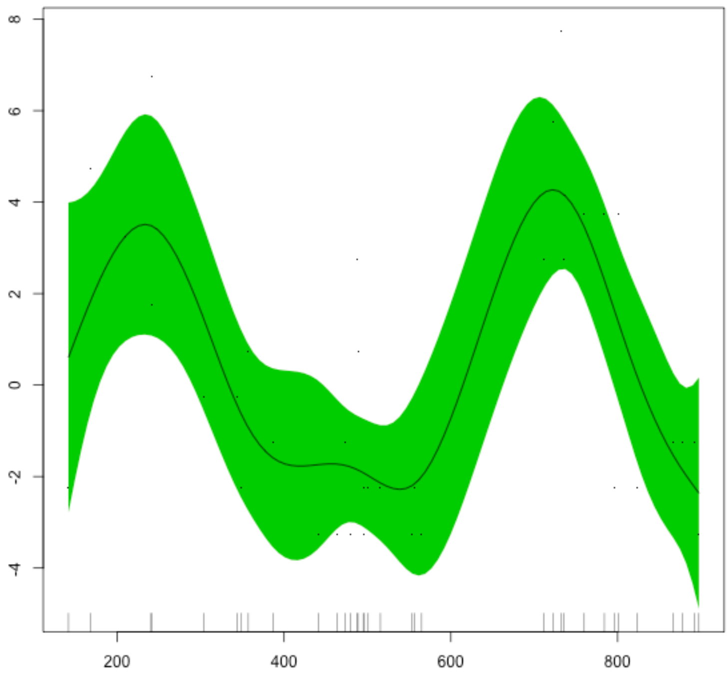


Figure 5.7. Rijkswaterstaat seagrass surveys (SGS). Left panel: factors for best fits for univariate data model describing the relationship between a relative index for seagrass occurrence (y-axis) and measurement section (x-axis) in mm for SGS 2006-2009. Right panel: smoother for best fit for univariate data model describing the relationship between a relative index for seagrass occurrence (y-axis) and sediment height (x-axis) in mm for SGS 2010-2017 (see Table 5.6 for statistics).

5.4 Discussion & conclusions

5.4.1 Relationships of seagrass with environmental conditions

The results from both datasets suggest that the occurrence of seagrass is mainly related to sediment height and/or inundation duration. Additionally, presence or absence of seagrasses depended on year and measurement section. Because sediment height in itself is not expected to impact on seagrass occurrence and because inundation duration was derived from data on sediment height and tidal amplitudes, we assume that inundation duration is the structuring variable determining the option for seagrass growth and survival. Low inundation duration can result in desiccation stress of *Zostera noltii*, whilst high inundation duration limits periods with sufficient light conditions required for photosynthesis (Leuschner et al. 1998; van Katwijk et al. 2000; de Jong et al. 2005; Shafer et al. 2007). If so, then changes in sediment height and/or tidal amplitudes will affect the potential for seagrass growth.

Sediment height can be influenced by maintenance of the saltmarsh works (see 5.4.4), whilst tidal amplitudes might be impacted by weather conditions. Eastern winds, for example, may result in extended periods of emergence combined with very low temperatures in winter resulting in ice-rafting of the top layer of the sediment (Rohjans et al. 1999) and very high temperatures in summer enhances desiccation stress (Vermaat et al. 1993). Such extreme conditions might be more influential on the survival of seagrass than average annual conditions.

The highest temporal resolution of the measurements in sediment height was once a year, whilst the variation in this value can be up to 8 cm per day during winter (Elschot et al. 2020). This implies that actual conditions with regard to sediment and erosion rates are most likely far more variable than the data suggest. Cabaço & Santos (2007), for example, found that survival of *Z. noltii* was reduced when buried under a 4 to 8 cm layer of sediment or when 2 cm of the top soil eroded during an event. Although our data suggest that sedimentation and erosion rates varied between -6 cm and +9 cm per year, it cannot be excluded that actual sedimentation and erosion rates (mm d^{-1}) during events were higher and subsequently limiting seagrass establishment and survival.

5.4.2 Changes in seagrass

The data sets appear to provide conflicting information on the changes in seagrass over the years. Whilst the Rijkswaterstaat survey data indicated a decline within the saltmarsh works between 2006 and 2017 (in particularly related to a decrease in the seagrass bed north-east of the study area), the Groningen salt-marsh works data suggest an increase of the presence of seagrass within the saltmarsh works between 2009 and 2018.

Due to the large variations in methods and efforts (see §5.4.1), it is difficult if not impossible to tell which data set best reflects the actual changes in seagrass cover within the man-made salt-marsh works near Groningen. The fact that the measurement section data are not suitable for monitoring seagrass recovery has not previously been observed, nor reported to the monitoring agencies, because no extensive analysis has been performed on the seagrass data before.

5.4.3 Management implications

Along the mainland coast of Friesland and Groningen brushwood groynes have been placed to increase sedimentation rate, reduce erosion rate and thereby stimulate saltmarsh development.

The objective of this study was to determine whether *Z. noltii* could establish more successfully in the sedimentation fields. We found that *Z. noltii* did establish in, but was not restricted to, the sedimentation fields and also occurred seaward of these fields. The brushwood groynes in the third and last sedimentation field are no longer maintained since 1990-2002 and will no longer provide any protection against high energy waves. However, presence of *Z. noltii* was not limited to the 2nd field that is still being maintained and seemed to occur in both the 2nd and 3rd sedimentation field. Therefore, based on our data we found no evidence that brushwood groynes have a positive effect on the establishment of *Z. noltii*.

Based on the Rijkswaterstaat survey data, we do know that there is a large seagrass bed outside the salt marsh works / within the no longer maintained salt marsh works on the east side. In addition, we see no distinction in seagrass cover in the well-maintained section 2 vs. section 3 that is no longer maintained. It is therefore very likely that restoration of seagrass does not depend on the salt marsh works.

If the area and cover of the seagrass bed north east of the man-made salt-marsh works is declining, then this may also result in a decline of supply of seagrass seeds and rhizomes to the salt-marsh works themselves. This would imply that management should not only focus on creating environmental conditions within the salt-marsh works for seagrass growth and establishment, but also focus on the conservation of the seagrass beds outside these areas that might be crucial for enabling the recovery.

5.4.4 Data limitations

In this study, we used two different datasets. The dataset of the Groningen saltmarsh works monitoring was designed to monitor saltmarsh development, where *Zostera noltii* is one of 30 plant species that was recorded annually. The second dataset is a seagrass survey by Rijkswaterstaat and is specifically designed to monitor seagrass cover and density. Both datasets had limitations that resulted in contrasting outcomes of the analyses made in this study.

According to the first dataset -the Groningen saltmarsh works monitoring- *Z. noltii* was only present after 2011. Additionally, in the most eastern measurement section (nr. 13) no seagrass was recorded between 2006 and 2016. In contrast, based on the second dataset – the Rijkswaterstaat seagrass survey- *Z. noltii* had the highest cover and area in 2006 and a large seagrass bed with high cover of *Z. noltii* intersects with the last measurement section (number 13) for the entire measurement period (2006-2017). This indicates that presence of *Z. noltii* in the Groningen salt-marsh works monitoring is often overlooked in earlier years (before 2015). This implies that the salt-marsh works monitoring program alone is not designed or suited to study seagrass recovery in the Wadden Sea before 2015.

In the Groningen salt-marsh works monitoring program small patches of seagrass on the bare intertidal flat are easily missed, especially further away from the salt-marsh edge. The observer(s) might not have seen *Z. noltii* in the furthest subsections, which look bare from a distance. Therefore, the increase in *Z. noltii* cover over the years is likely caused by changes in observer effort that may have increased once it became clear that seagrasses were present in a specific measurement section, implying that there is a high chance of false negatives in this dataset. In the seagrass survey only predefined transects and a number of random points were measured, missing many subsections of the salt-marsh monitoring program. Therefore, we could only include a small part of the survey data that was measured inside the measurement sections where the sediment height is measured as well.

One of the most important factors for the establishment of seagrasses appears to be sediment height and in the Groningen salt-marsh works monitoring this is measured every three to four years. Therefore, is it unknown whether strong sedimentation or erosion events occurred in between the years the bed level was measured and whether the change in height that was measured occurred fast -in just a short time period- or whether it is a gradual process stretching over the whole period. Furthermore, sediment height is not always measured in the furthest sediment fields where *Z. noltii* presence is most likely. This reduced the amount of data that could be used for the analyses and reduced the power of the results.

Searching for patches of seagrass in 400m x 400m bare spaces (where it is difficult to walk) as being done within the Groningen salt-marsh works monitoring program is similar to looking for a needle in a haystack. If a patch is accidentally encountered, and will most probably be more extensive being checked for the presence of seagrass hereafter. This creates a researcher bias, which in practical terms is almost unavoidable unless you first determine the locations with drone flights to identify the presence of seagrass, followed by a more detailed monitoring when walking through the area.

At present, the Rijkswaterstaat seagrass surveys are limited to transects, do not cover the full area of a sedimentation fields and do not include bottom height measurements. Overlap with the measurement sections (within which we do know the ground level height) is very limited. Due to the aforementioned aspects, both datasets are not entirely suitable for linking seagrass presence to environmental changes such as those in exposure time and sedimentation rates.

Overall, the data is far from optimal with most likely a high error in the results. Therefore, we should be careful to draw any conclusions due to the high uncertainty of the data. Based on the analyses presented here we can conclude that sediment height -linked to inundation duration- is very important for successful recovery of seagrasses. Additionally, based on the large seagrass beds outside the salt-marsh works as well as in the no longer maintained outer (third) sedimentation field, it seems highly unlikely that seagrasses depend on the protection provided by the wooden groynes surrounding the 2nd sedimentation field. To better study the processes controlling *Z. noltii* in the future, the sediment height should also be measured during the Rijkswaterstaat seagrass survey.

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6. SYNTHESIS

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6.1 Introduction

In general, seagrass meadows are declining globally (Duarte 2002; Orth et al. 2006; Waycott et al. 2009; van Katwijk et al. 2016), most likely due to an increase in turbidity and nutrient loadings (Erftemeijer and Lewis 2006). More recently, however, there appears to be a European-wide recovery (de los Santos et al. 2019). The Wadden Sea harbours two species of seagrass, specifically *Zostera noltii* and *Z. marina*, with intertidal *Z. noltii* more prevalent nowadays (Zipperle et al. 2009, Dolch et al. 2017). Within the trilateral Wadden Sea, seagrass has expanded in the northernmost parts of the Wadden Sea, but remained low in other areas including the large estuaries of the Weser, Ems and Elbe during the last decades (van Katwijk at al. 2000; Folmer et al. 2016; Dolch et al. 2017). These findings suggest that river discharges might be limiting (littoral) seagrass growth within areas in the central and southern Wadden Sea, that would otherwise (with respect to hydrodynamics and geomorphology) be suitable for seagrass growth. In the Dutch Wadden Sea, the intertidal beds of *Zostera noltii* and *Z. marina* declined during the 1970-80s, presumably due to anthropogenic eutrophication (den Hartog & Polderman 1975; de Jonge & de Jong 1992; Philippart 1994). Based upon seagrass mapping as performed by Rijkswaterstaat[16], the total surface area of three selected seagrass beds increased from ca. 1.5 km^2 in the early 2000s to around 2.5 km^2 in the late 2000s and early 2010s, with this development mainly due to changes in the largest seagrass bed near the coast of Groningen (Dolch et al. 2017).

In the early 1990s, the distribution of seagrass (*Z. noltii* and *Z. marina*) was found to be related to the period of emersion, sediment type, sediment stability and region (Philippart & Dijkema 1992). The models showed that no seagrass was expected in the proximity of main river estuaries, even under optimal conditions with respect to the other factors. This may point to low salinities limiting seagrass growth and survival, but possibly also to growth-restricting compounds being transported by rivers into the sea, including excess nutrients (Philippart & Dijkema 1992). Within the Dutch Wadden Sea, suitable habitats (ca. 60 km^2) were located at Balgzand, the tidal divide of Terschelling, the mudflats near Griend, and just offshore the mainland of Fryslan and Groningen (Philippart et al. 1992).

In the mid-2000s, the habitat suitability of seagrass (*Zostera noltii* and *Z. marina*) was assumed to be related to the tidal exposure, hydrodynamics (current velocity, wave action) and an interaction between salinity and ammonium flux (de Jonge et al. 2005). Based on the outcome of this compilation, presented as a so-called "opportunities map", it was concluded that the Dutch Wadden Sea comprised ca. 20 km^2 that was considered suitable habitats for seagrass. The best areas (ca. 2 km^2) were mainly located north of the mainland, south of the islands and at the mudflats between Lake Lauwers and the Ems estuary (de Jonge et al. 2005).

In the mid-2010s, consensus forecasting for seagrass occurrence in the trilateral Wadden Sea region (involving Denmark, Germany and the Netherlands), using hydrodynamic and geomorphological characteristics of the intertidal area as predictors, indicated that extensive areas (211 km^2) in the Dutch Wadden Sea should be suitable for seagrass, and that these areas are

[16] https://www.rijkswaterstaat.nl/water/waterbeheer/waterkwaliteit/indicatoren-voor-waterkwaliteit/zeegras/zeegraskartering.aspx

mainly located at the tidal divides and close to the mainland of Fryslan and Groningen (Folmer et al. 2016). Further detailed studies on seagrass distribution in the Dutch part of the Wadden Sea, additionally incorporating waves, sediment composition and benthic fauna as predictors, reduced the surface area of potential seagrass habitats to 130 km^2 (Folmer et al. 2019). This was mainly due to a decrease in the area of previously identified locations through a re-evaluation in this report.

The observed reversal of seagrass meadows in Europe is likely related to conservation and restoration efforts, including the reduction of nutrient loading, improving water quality, by direct habitat protection and transplant experiments (Dolch et al. 2017, de los Santos et al. 2019). So far, reestablishment of seagrass meadows in the last decades in the Wadden Sea had low success rates (Bouma et al. 2009, van Katwijk et al. 2016). In recent years (2018-2020), however, the transplant of *Z. marina* seeds near Griend resulted in a seagrass meadow of almost 2 km^2, but it is not yet clear if this bed is self-sustaining[17].

One of the most important sites within the Dutch Wadden Sea, where seagrass (mainly *Z. noltii*) appears to be slowly recovering, is offshore along the northern coast of Groningen[18] (Dolch et al. 2017, Elschot et al. 2020). Here former land-reclamation works are present, which are created by man-made groynes and drainage ditches. These have resulted in semi-natural saltmarshes (Dijkema et al. 1988, 2013). So far, it is not clear whether this increase is due to larger-scale changes underlying the European-wide recovery (Dolch et al. 2017, de los Santos et al. 2019) or due to management influencing local conditions, i.e. protection against high energy waves and storms by increased maintenance of brushwood dams (Dijkema et al. 1988, Elschot et al. 2020).

The low occurrence of seagrass meadows in presumably suitable habitats suggests that potential habitats are still subject to growth-limiting environmental conditions and/or that recolonisation is hampered by restricted dispersal from donor populations. Dispersal of *Zostera* seeds, for example, is limited (ca. 1 km), most probably due to their relatively heavy weight (Costa et al. 1988; Loques et al. 1988; Orth et al. 1994; Zipperle et al. 2009). Detached spathes (single floral units with female and male flowers grouped) and flowering shoots can be successfully transported over longer distances (Harwell and Orth 2002; Erftemeijer et al. 2008; Ferber et al. 2008; Zipperle et al. 2009), but most probably not cover lengths more than approximately 10 km (van Katwijk et al. 2016). Isolation by distance, however, occurs at distances of more than 100 km (Coyer et al. 2004).

Because present seagrass beds are not expanding and the success rates of the restoration efforts are low, the potential impact of growth-limiting environmental conditions cannot be excluded. If so, then reducing such environmental stressors will increase the probability of settlement, growth and survival of seagrass and, therefore, promote seagrass reversal in the Dutch Wadden Sea as was witnessed in other parts of the Wadden Sea and the rest of Europe. In this chapter, we explore which environmental conditions may hamper seagrass growth here. First, we supply an overview of stress factors resulting from human impacts. Second, we explore if we can identify thresholds in nutrient and pollutant concentrations for seagrass occurrence. Third, we examine which environmental factors may explain the successful recovery of seagrass along the coastline of Groningen.

[17] zeegrasherstelwaddenzee.com
[18] https://geoservices.rijkswaterstaat.nl/apps/pdokkaart/applicaties/zeegras/

6.2 Human impacts on seagrass

Seagrass is affected by any factor that changes water and sediment quality. Consequently, when environmental variables such as salinity, turbidity, light, current speed or temperature are altered due to human impact, both growth and survival of seagrass can be compromised (Chapter 2).

Coastal constructions such as harbours, docks, breakwaters and beach stabilization change sedimentary dynamics and consequently affect seagrass habitats, including the burial of adult plants and seeds (Cabaço et al. 2008). Artificial saltmarshes, mainly found along the coasts of Groningen and Friesland, have been embanked to provide coastal protection and new land for agricultural exploitation (Bakke et al. 2002). Seagrass beds (adult plants, rhizomes, and seedlings) may also suffer limitation of light availability due to increased turbidity during coastal constructions, and consequently, experience reduction of photosynthesis and growth (Duarte 2002).

Dredging and sediment extraction have been traditionally deployed for construction of dikes and roads, and it is, nowadays, mainly performed for the maintenance and deepening of shipping lanes, in particular within the estuaries of the Elbe, Weser, Jade and Ems (Schultze & Nehls 2017). In addition to removal, disturbance and burial of seagrass (Hootsmans et al. 1987, Jensen & Mogensen 2000, Schultze and Nehls 2017) dredging can result in high turbidity reducing photosynthesis (Yaakub et al. 2014). The critical seagrass thresholds for turbidity can be expressed by relative light availability (% of surface irradiance: SI), with minimum light requirements for adult plants of *Zostera noltii* being lower (2% SI) than those for *Z. marina* (11 - 36% SI) (Erftemeijer and Lewis 2006).

Bottom-dredging fisheries have a direct impact on the benthic zone and have been recently restricted in the Wadden Sea area (Baer et al. 2017). Shrimp trawl fishing damages the seafloor, eroding the sediment and reducing seagrass biomass (Collie et al. 2000; Baer et al. 2017). The impact of this erosion on seagrass is strongly size-dependent (Cabaço et al. 2008). The root length of seedlings, for example, determines the sensitivity to dislodgement (Balke et al. 2011), and adult plants with longer leaves experience larger losses of foliage at hydrodynamically exposed sites (Hermus 1995).

Climate change affects all habitats with major consequences for local temperatures, precipitation and sea-level (Oost et al. 2017). Increasing temperatures may enhance diseases and parasites. Rapid salinity changes may produce osmotic shocks affecting seagrass meadows (Duarte 2002), but may also affect germination rates of seeds and desiccation of adult plants (Hootsmans et al. 1987). Sea level rise may induce landward migration of seagrass meadows (Valle et al. 2014). Wind from other directions may change the dispersal of seeds, spathes and shoots and thereby changing the connectivity between seagrass habitats of the Wadden Sea (Coyer et al. 2004; van Katwijk et al. 2009).

Salinity changes due to river discharges can provoke osmotic shocks to seedling and adult seagrass plants (Duarte 2002), with *Zostera* spp. able to withstand fluctuations between 9 and 31 PSU (Pinnerup 1980; Wium-Andersen & Borum 1984; de Jong et al. 2005). Seagrass is rarely found in areas where yearly averages are below 18 PSU (Bos et al. 2005), and plant survival is higher at average salinity levels between 22 and 27 PSU than at 30 PSU (Kamermans et al. 1999); van Katwijk et al. 1999). Lower salinities (< 20 PSU) stimulates seed germination (Hootsmans et al. 1987; Xu et al. 2016), but reduces the seedling growth (Fernández-Torquemada and Sánchez-Lizaso 2011; Xu et al. 2016).

Nutrient over-enrichment, especially phosphorus and nitrogen compounds, can stimulate overgrowth of epiphytes which limit light conditions and gas exchange for intertidal seagrasses in the Wadden Sea (Philippart 1994; Burkholder et al. 2007). Negative effects of excess ammonium on several physiological and morphological response variables of seagrass have been observed, including a reduction in primary production and significantly decreased shoot, rhizome and root elongation rates, thus affecting plant survival (Brun et al. 2002 & 2008, van der Heide et al. 2008, van Katwijk et al. 1997). Direct toxicity of ammonium on seagrasses has been demonstrated at concentrations as low as 0.02 mmol (van Katwijk et al. 1997; Brun et al. 2002).

Pollutants such as antifouling compounds, fungicides, insecticides, and herbicides can impact seagrass growth and survival and have already been detected in roots and leaves of *Zostera* spp. (Scarlett et al. 1999; Haynes et al. 2000; Lewis and Devereux 2009; Fernandez and Gardinali 2016). Concentrations of several metals, including mercury and lead, pose a risk in the large parts of the Wadden Sea (OSPAR 2009, Bakker et al. 2009). Chemical toxicity leads to chronic effects on photosynthesis, reducing energy reserves at plant and population level, and consequently reducing the resilience of seagrass meadows (Diepens et al. 2017). Herbicides such as glyphosate, bentazone and MCPA reduce seagrass growth, length and introduces changes in photosynthetic pigments ratios (Nielsen and Dahllof 2007; Diepens et al. 2017). Furthermore, the antifouling compounds irgarol 1051 and diuron also provoke significant reduction in *Zostera* spp. growth (Lamoree et al. 2002).

6.3 Threshold concentrations in nutrients and pollutants

To identify concentration thresholds in potentially growth-hampering or growth-required compounds in the Dutch Wadden Sea, observational data from Rijkswaterstaat[19] was combined with known information about seagrass occurrence (Folmer et al. 2016, Folmer 2019). Compounds with potential negative effects on seagrass survival include the herbicides glyphosate, bentazone and MCPA, as well as antifouling compounds irgarol 1051, diuron and tributyltin (TBT) (Chapter 2). The latter occur in boat paints, with irgarol and diuron replacing TBT after its use was officially banned within the EU in 2003 due to negative effects on shellfish reproduction (Waldock et al. 1986, Champ 2003). For this initial study, only surface water values are considered.

At present, the concentrations of ammonium are higher (> 0.02 mmol) than those when direct toxicity of this nutrient on seagrasses has been demonstrated (van Katwijk et al. 1997; Brun et al. 2002). Concentrations of the metals cadmium and mercury, both identified as hazardous substance for non-inland surface waters, were also higher than the respective environmental quality standards of an annual average concentration (AAC) of 0.2 µg l^{-1} and 0.05 µg l^{-1} (Bakker et al. 2009). Both metals are considered to be harmful to seagrass growth, and the ability of seagrass to accumulate mercury might facilitate the transfer of this toxic metal from abiotic elements of the marine environment to higher levels of the trophic chain (Beldowska et al. 2015). Based on the average concentrations of suspended particulate matter (SPM), the range in proportions of the remaining light conditions at a depth of 0.5m ($PAR_{-0.5m}$) would be from 1% near the Eemshaven to 60% at Balgzand. In addition, growth might not only be hampered when the seagrass is submerged but possibly also during low tide if high turbidity of the water results in covering the seagrass leaves with a layer of fine sediment.

These observations suggest that seagrass growth may, therefore, be locally hampered by high concentrations of ammonia, cadmium, mercury and SPM. Because sensitivity and toxicity of seagrass to these compounds appears to be related to its phenology (e.g. occurrence of various life stages during the year), further (experimental) research should focus on impacts during various life stages and their possible cumulative effects. The potential of harmful effects of high nutrient and metal concentrations in the sediments should also be investigated. The findings should then be extrapolated to high-resolution data on field conditions within and outside seagrass beds, which requires an upgrade of the monitoring network, and in particular for ammonia, cadmium, mercury and SPM.

[19] Waterinfo.nl

6.4 Seagrass dynamics

Seagrass interacts with the flow of water and, in the case of *Z. noltii*, with air during exposure time at low tide. Seagrass beds and the communities they form are well known for their ability to alter their local hydrodynamic environment, reducing current velocities and altering turbulent structure in and around the canopy (Fonseca and Koehl 2006). Also, by interacting with suspended sediment and its erosion and deposition, seagrass provides shelter for sediments to settle and therefore alters the morphology. Accordingly, seagrass beds typically have a positive effect on the stability of shorelines. The geomorphological role of seagrass beds (and aquatic vegetation in general) is particularly important for the stability of (artificial) saltmarshes. Here, in fact, seagrass:

- decreases the near-bed shear stresses, thus reducing the sediment flux to the salt marsh platform;
- dissipates the wave energy acting on the salt marsh scarp (Brampton 1992; Moller et al. 1999, Suzuki & Klaassen 2011), thus reducing boundary erosion;
- increases sediment deposition (especially during summer) via complex ecosystem engineering (Jones et al. 1997; Bouma et al. 2005).

However, the very same physical processes from which seagrass offers protection, can also contribute to the demise of seagrass beds. Seagrasses are extremely sensitive to hydrodynamics (currents and waves), desiccation, as well as to extreme changes in temperature and salinity (Dolch & Reise 2009, Folmer et al. 2016). Also, seagrass beds require sediment stability, i.e. low rates of erosion, transport and deposition. The latter is also an important factor that can limit seagrass recovery (Philippart 1994; Schanz & Asmus 2003; Dolch & Reise 2009, Suykerbuyk et al. 2016). In the Wadden Sea, most of the current seagrass beds are found in the mid to upper tidal zone along the leeside of islands and high sand bars, as well as along the parts of the mainland coast that are sheltered from prevailing storms. This suggest that low hydrodynamical regimes (and the associated sediment dynamics) are preferred by seagrass. It is important, therefore, to consider the relationship between seagrass and the flow of the surrounding water, air and sediments.

It was suggested that seagrass predominantly occurs in places with a low sedimentation rate and therefore does not grow at the Frisian coast where sedimentation rates are very high (van der Graaf & Wanink 2007). Along the coast of Groningen, where the largest seagrass beds of the Dutch Wadden Sea are found, seagrass growth might be facilitated by solid peat and clay underlaying surface sediments which prevent bioturbation by lugworms (Philippart 1994) and supply the seagrass rhizomes and roots with a fair hold (Reise & Kohlus 2008). If so, then net sedimentation in these areas might deprive the seagrass beds of this local protection resulting in their decline. The spatial pattern and a recent decrease in storminess both suggest that sediment stability is the key factor for seagrass dynamics in this tidal area. On exposed sand, high sediment mobility may be limiting and along the sheltered mainland shore, land reclaim activities with high accretion rates may cause a scarcity of seagrass (Reise & Kohlus 2008).

Most studies so far assumed the vegetation is rigid, i.e. they did not include nor consider the motion of vegetation. However, most aquatic vegetation is flexible and moves with and in response to the flow. This adaptation to the hydrodynamic forcing affects the effective plant height and the drag that is exerted on vegetation. Therefore, the flow-induced movement of the vegetation eventually affects the water flow itself and has implications for sediment stability and transport. By means of flume experiments, Paul et al. (2012) showed that wave attenuation is positively correlated with blade stiffness and, for a given wave in shallow water, this attenuation is dependent on a combination of shoot density and leaf length, which can be described by the leaf area index.

Furthermore, the presence of a tidal current strongly reduced the wave-attenuating capacity of seagrass mimics, and this reduction was most pronounced at high shoot densities. Thus, most studies that have been carried out considering only waves will structurally overestimate wave attenuation for tidal environments. This emphasises that tidal currents need to be taken into account in future studies on wave attenuation by vegetation. Since the seminal work of Dijkstra (2008), however, the flexibility of aquatic plants has been formally implemented into larger-scale hydrodynamic and morphodynamical models (Dijkstra & Uittenbogaard 2010).

With higher water levels above seagrass beds, storm surges will have stronger effects on sediment stability and seagrass meadows. Extrapolating winter storm surge levels observed at tide gauges over the last four decades (Weisse & Pi 2006) into the next 40 years indicates that storm surge levels could rise by about half a meter, irrespective of any acceleration in global sea level rise. For the Wadden Sea, the effects of wind on sea level are considerable (Gerkema & Duran-Matute 2017). In 1996, for example, the stronger easterly winds caused an anomalously low annual mean sea level (Kobayashi et al. 2015, Vermeersen et al. 2018). Due to year-to-year annual variations in annual average energy from Eastern and Western winds, annual mean sea levels may vary by up to 2 dm (Vermeersen et al. 2018).

With regard to sea level rise and possibly increasing storm frequencies due to climate change (Wolf et al. 2020), higher waves and long period waves can be expected to occur near cliffs of natural and artificial saltmarshes. This could have profound effects on salt marsh ecosystem stability and the potential for recovery worldwide (Reise & Kohlus 2008). It can be expected that habitats which are just marginally sheltered and suitable, such as in the more open Southwestern Wadden Sea, will be affected most.

In order to get more grip on present and future options for the Wadden Sea as a hydrodynamically suitable habitat for seagrass (including a further improvement of the seagrass probability maps), more information is needed on the characteristics of seagrass meadows (blade stiffness, shoot density, leaf length) to allow for modelling of complex plants (with leaves and buoyancy structures) in complex flows and waves, on seagrass (seed) dispersal, and on wind, waves, local relative sea level and sediment dynamics as base-line information for impacts on seagrass dispersal, settlement, growth and survival.

Such information can be gathered through two subsequent efforts. Firstly, fine-scale modelling studies of individual seagrass plants for the species native to the Wadden Sea. This is important for the development and validation of accurate parameterisations of their behaviour relative to local hydrodynamic conditions. The above can then be gathered by means of more detailed regional models (possibly with higher resolution at areas where seagrass is already present and is most likely to occur) which are fed with high-resolution data on seagrass and the main structuring environmental factors. Secondly, once calibrated and validated, such models can be used to identify potential hotspots (which can then be protected), for estimating the impacts of various climate scenarios, and for exploring the potential of various seagrass restoration efforts.

6.5 Seagrass in saltmarsh works

6.5.1 Artificial saltmarsh works

Along the Dutch coast, salt-marsh works are present that consist of artificial sedimentation fields constructed in the first half of the 20th century to stimulate the settlement and prevent erosion of sediment (by damping wave action) followed by the colonization of salt-marsh vegetation (Dijkema et al. 1988, Bakker et al. 2002). Brushwood groynes that surround each sedimentation field are designed following the Schleswig-Holstein method (Dijkema et al. 1988, 1990).

Within the sedimentation fields, ground dams and drainage channels were constructed according to a fixed pattern (Figure 6.6, Dijkema et al. 1988). Main drainage channels were located every 200 m perpendicular to the dike, primary ditches were constructed every 100 m parallel to the dike and secondary (smaller) ditches every 10 m (draining into the primary ditch). Along the coast of Groningen, all maintenance of the brushwood groynes surrounding the third and outer sedimentation field stopped between 1990 and 2005 (Elschot et al. 2020).

6.5.2 Seagrass occurrence

To explore the presence of seagrass in relation to environmental conditions, we also analysed two different datasets on the presence of seagrass (*Zostera noltii*). The first (1) using the Groningen saltmarsh works dataset (Figure 6.6) with monitoring of subsections of sedimentation fields (2009 – 2018) by Wageningen Marine Research (WMR). The second (2) using the Rijkswaterstaat seagrass survey dataset within subsections of sedimentation fields, divided into two periods, being (2a) between 2006 and 2009, and (2b) between 2010 and 2017. Occurrence was not restricted to the 2nd maintained sedimentation fields, but was also present in the no-longer maintained 3rd sedimentation fields as well as outside the salt-marsh works.

Based upon the Groningen salt-marsh monitoring programme, the seagrass *Zostera noltii* was first found with the Groningen saltmarsh works monitoring programme (that started in the 1960s) in 2011 (Figure 6.8a). Over the years (2014 – 2019) there has been a gradual increase in its occurrence. The distribution of seagrass did not reveal an obvious geographical trend in occurrence from west to east. For measurements in the measurement sections 3-8, however, occurrence appeared to be higher in the 3rd sedimentation, being the closest to the mudflats (Figure 6.6).

The Rijkswaterstaat seagrass surveys revealed, however, a different distribution and trend of *Zostera noltii*. Here, this seagrass species had the highest cover in 2006, and decreased thereafter (Figure 6.8b). Highest abundance of *Z. noltii* occurred just east of the man-made saltmarsh works, with a cover of 90% in 2007. Note that, although there is no saltmarsh present at this location, brushwood groynes are present (see bottom panel of Figure 6.6). At the beginning of the study period (2006), measurement section 8 was also characterized by a higher cover of *Z. noltii*, but this decreased hereafter. Along the rest of the mainland coast of Groningen the cover remained low.

The WMR monitoring programme was designed to monitor saltmarsh development and small patches of seagrasses on the bare intertidal flat are easily missed, especially further away from the salt-marsh edge. The observer might not have seen *Zostera noltii* in the furthest subsections, which look bare from a distance. Therefore, it cannot be excluded that the increase in *Z. noltii* cover between 2014 and 2019 is due to changes in observer effort that may have increased once it became clear that seagrasses were present in a specific measurement section. Although for the Rijkswaterstaat seagrass survey only transects and a number of random points were measured (and many subsections were missing), the observed decrease in seagrass since 2006 may be the most realistic.

The observed increase in the WMR data set would be in line with the large-scale reversal of seagrass occurrences since the 2000s (de los Santos et al. 2019). The observed decline in the Rijkswaterstaat data set is similar to Dolch et al. (2017), who stated to have observed a marginal decrease in surface area *Zostera noltii* in the Dutch Wadden Sea between 2010-2011 and 2014 (based upon the same data set). Due to the large variations in methods and efforts, it is difficult, if not impossible, to tell which data set best reflects the actual changes in seagrass cover within the artificial saltmarsh works near Groningen.

6.5.3 Relationships between seagrass and environmental conditions

Within a selection of the unvegetated and pre-pioneer zones of the Groningen salt-marsh data, seagrass occurred on average at:

- a sediment height of 515 ± 212 mm with respect to Dutch Ordnance Level (within a full range of -13 to 1087 mm);
- a change of sediment height of -4 ± 12 mm y^{-1} (within a full range of -60 to 90 mm y^{-1});
- an inundation frequency of 1.83 ± 0.19 times d^{-1} (within a full range of 0.61 to 1.93 times d^{-1});
- an inundation duration of 8.15 ± 2.57 hours d^{-1} (within a full range of 1.08 to 13.26 hours d^{-1});
- a maximum emergence period of 1.48 ± 1.47 hours (within a full range of 0.32 to 12.88 hours).

Statistical analyses of aggregated data sets (where values were averaged for sub-sections) revealed that seagrass occurrence was best explained by sediment height or inundation duration (Table 6.1). The optimum sediment height for seagrass occurrence was approximately 0.35 m above Dutch Ordnance Level. Since sediment heights cannot directly influence seagrass growth, inundation duration (which was calculated from sediment height and measured sea levels from a nearby tidal gauge) was the most likely environmental factor determining the occurrence of seagrass in the Groningen saltmarsh works. Based upon model results (for the pre-pioneer zone only), the optimum inundation for seagrass was being submerged for approximately 9 hours per day (ca. 4.9 hours per tide), while seagrass was not found where tidal flats were submerged for less than 7 hours per day (ca. 3.8 hours per tide).

Part of this study was to determine the effect of man-made sedimentation fields on the occurrence of the seagrass *Zostera noltii*. We used two long-term datasets that both monitor seagrass occurrence along the Groningen coast. However, both datasets had limitations, partially due to observer bias or lack of data. Overall, we can conclude that *Z. noltii* mainly occurred on lower elevations with higher inundation duration and with limited sediment dynamics. We did not find clear evidence that maintenance of the salt-marsh works promoted seagrass establishment. Recovery within the saltmarsh works might be the result of improved environmental conditions that resulted in larger scale recoveries in the entire Wadden Sea area. The decline of the seagrass bed just northeast of the study site, however, calls for further attention in particular due to its potential role in supplying seeds and rhizomes to the nearby saltmarsh works.

Table 6.1 Summary of statistical analyses of occurrence of seagrass in relation to environmental factors within aggregated data sets, with "+" indicating the main explanatory variable in the univariate model (U) and "+" the second explanatory variable in the bivariate model (B). Note that there were multiple models (m) for the Rijkswaterstaat data that had substantial support for explaining such relationships. For each model, the deviance explained (DE; %) is given.

		n	s	DE	Sediment height	Inundation duration	Year	Section
SMW	2009-2018	142		66%		++		
SGS	2006-2009	13	a	76%				++
		13	b	47%				++
		13	c	43%			++	
	2010-2017	35	a	66%	++			
		35	b	66%		++		

6.6 Conclusions & recommendations

Seagrass

In this study, we observed that the monitoring of the remaining seagrass beds is not yet complete, e.g. missing crucial information on seagrass and habitat characteristics and observed trends sometimes even conflicting. Far and foremost, therefore, we advise to more closely and more consistently monitor existing seagrass beds when mapping seagrass in the Wadden Sea including winter survival (by means of seeds or rhizomes) and the characteristic of the seagrass (e.g. density, shoot lengths) (Figure 6.1a). Furthermore, we strongly advise to make an inventory of the seasonality in environmental conditions of the present and former habitats of seagrass beds (e.g. the hydrodynamics, sediment dynamics and thickness of the sandy sediment top layer) (Figure 6.1a).

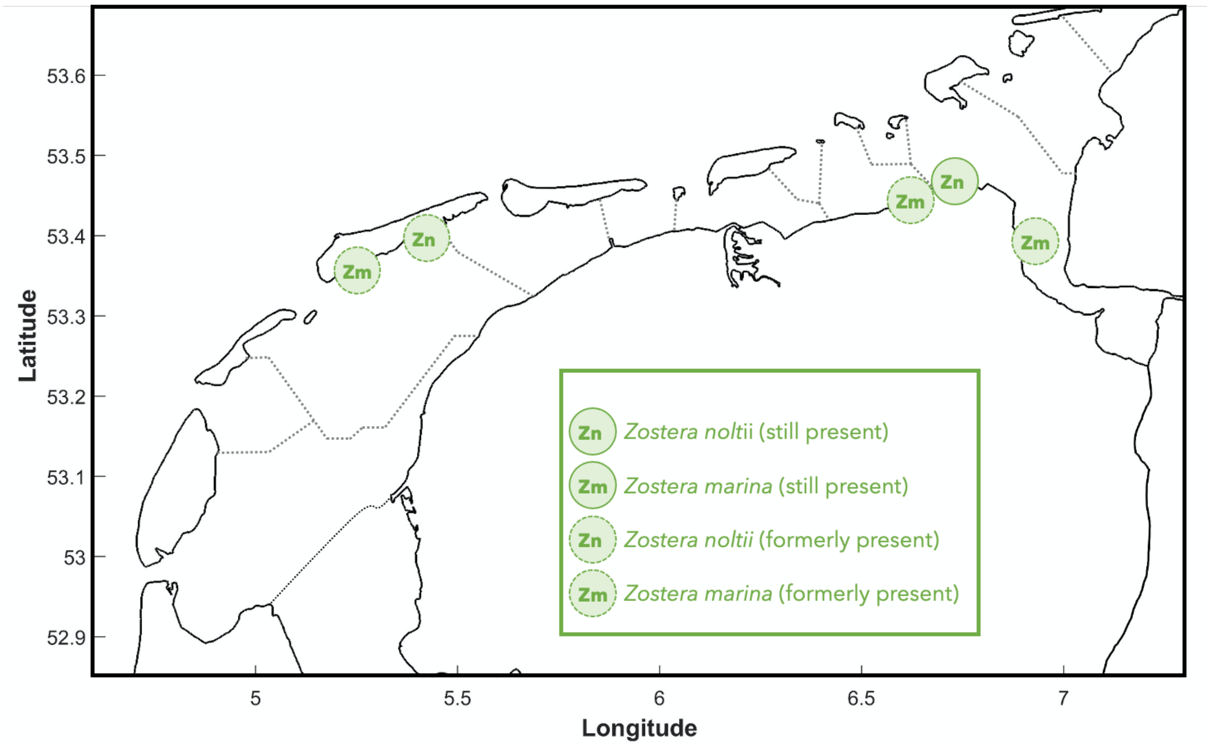


Figure 6.1. Locations where seagrass beds with a relatively high (5% or more) coverage were present in 2017 or were observed between 2000 and 2016 (Folmer 2019). The dotted lines indicate the tidal divides between the tidal basins.

Water quality

With respect to potentially toxic compound, we confirmed and (further) quantified previous findings and assumptions on the importance of ammonia for seagrass occurrence in the Dutch Wadden Sea (Table 6.2; Figure 6.2). Furthermore, we found circumstantial evidence on the additional role of cadmium, mercury and suspended particulate matter restricting seagrass growth in several parts of the Wadden Sea. We advise to gather more information (e.g., by means of experiments) on the dose-effect relationships to underline management actions to reduce the concentrations of these compounds (Figure 6.2) and to take sediment-based concentrations into account.

Table 6.2. Overview of environmental factors that are assumed (de Jong et al. 2005) or were observed (all others) to be correlated with the occurrence of seagrass in the Dutch Wadden Sea.

Factor	Philippart ea 1994	de Jong ea 2005	Folmer ea 2016	Folmer 2019	This study
Exposure time	x	x	x	x	x
Sediment type	x		x	x	
Sediment stability	x				x
Region	x				x
Current velocity		x			
Wave action		x	x		
Salinity		x			
Ammonium		x			x
Bottom shear stress			x	x	
Slope			x	x	
Lugworms				x	
Cadmium					x
Mercury					x
SPM					x

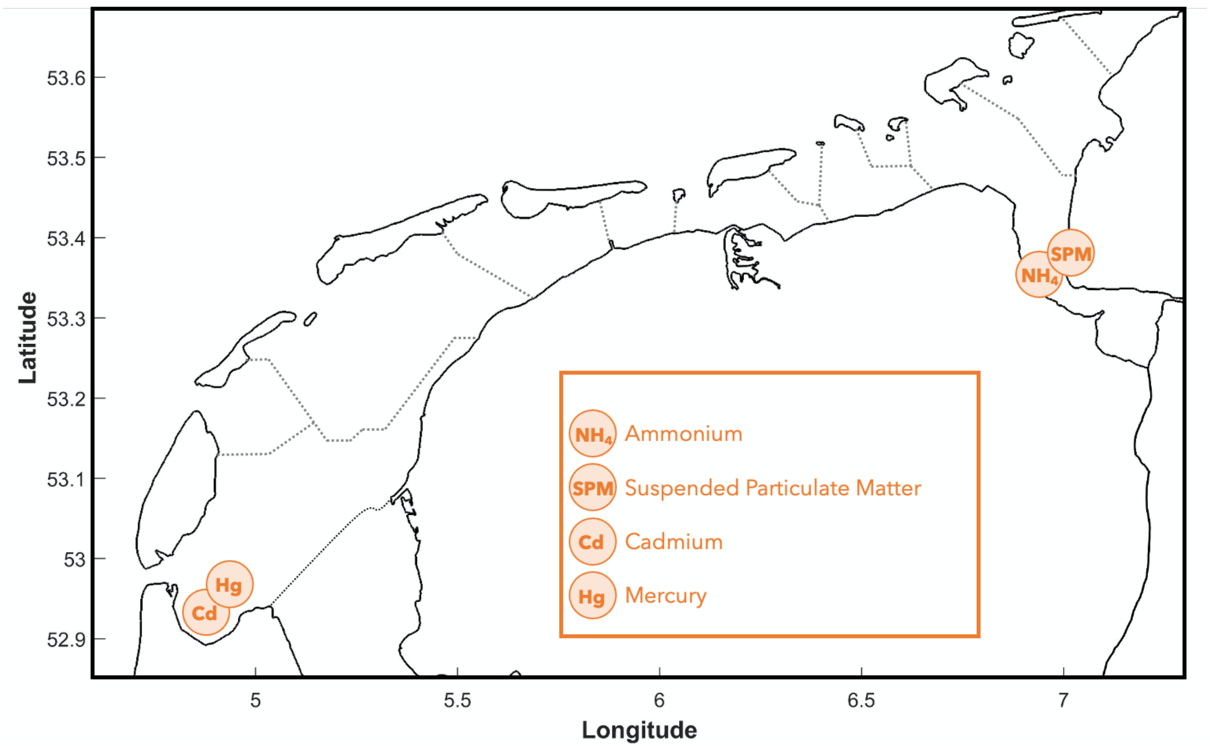
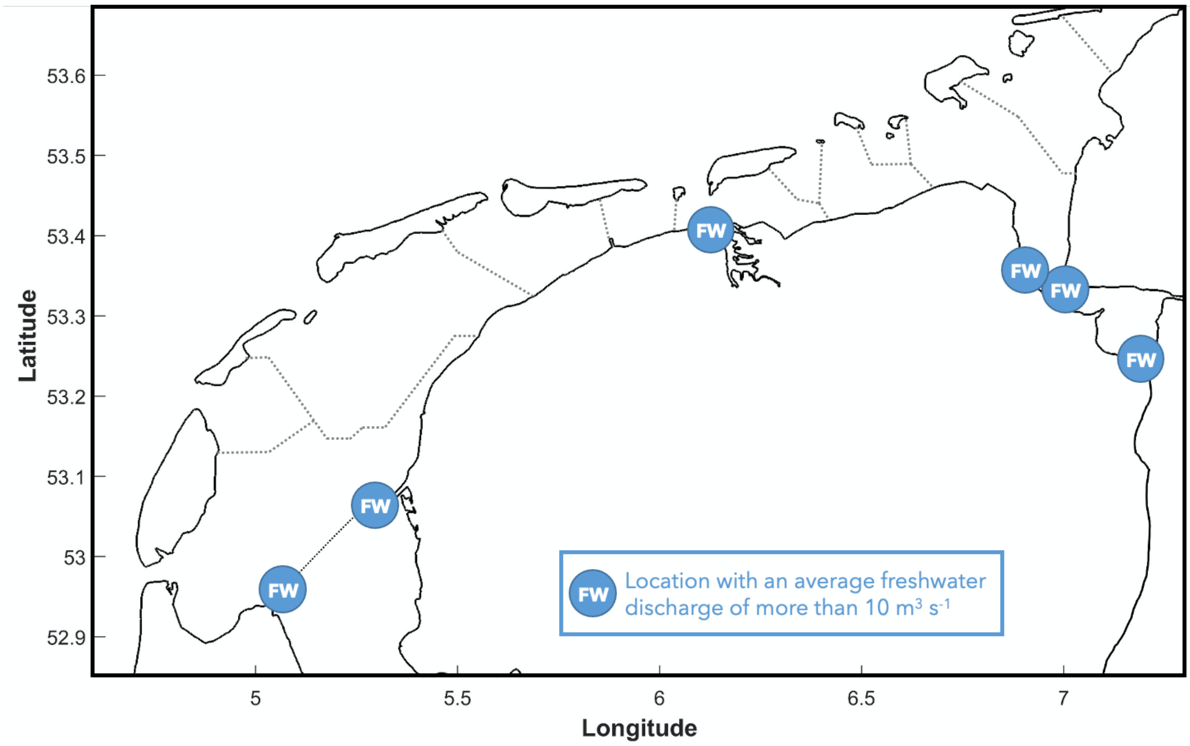


Figure 6.2. Locations with high concentrations of pollutants potentially restricting seagrass growth and survival (this report).

With respect to sensitivity of seagrass to mean values and variations in salinity, we advise explore the present and future impacts of mean and variations in salinity on seagrass germination and survival at those locations and tidal basins which are under the influence freshwater discharges (Figure 6.3). In addition, we advise to use this information to discuss the options for Wadden Sea friendly discharge regimes with national and local freshwater authorities.



6.3. Locations of major freshwater discharges in the Dutch Wadden Sea (Philippart & Baptist 2016).

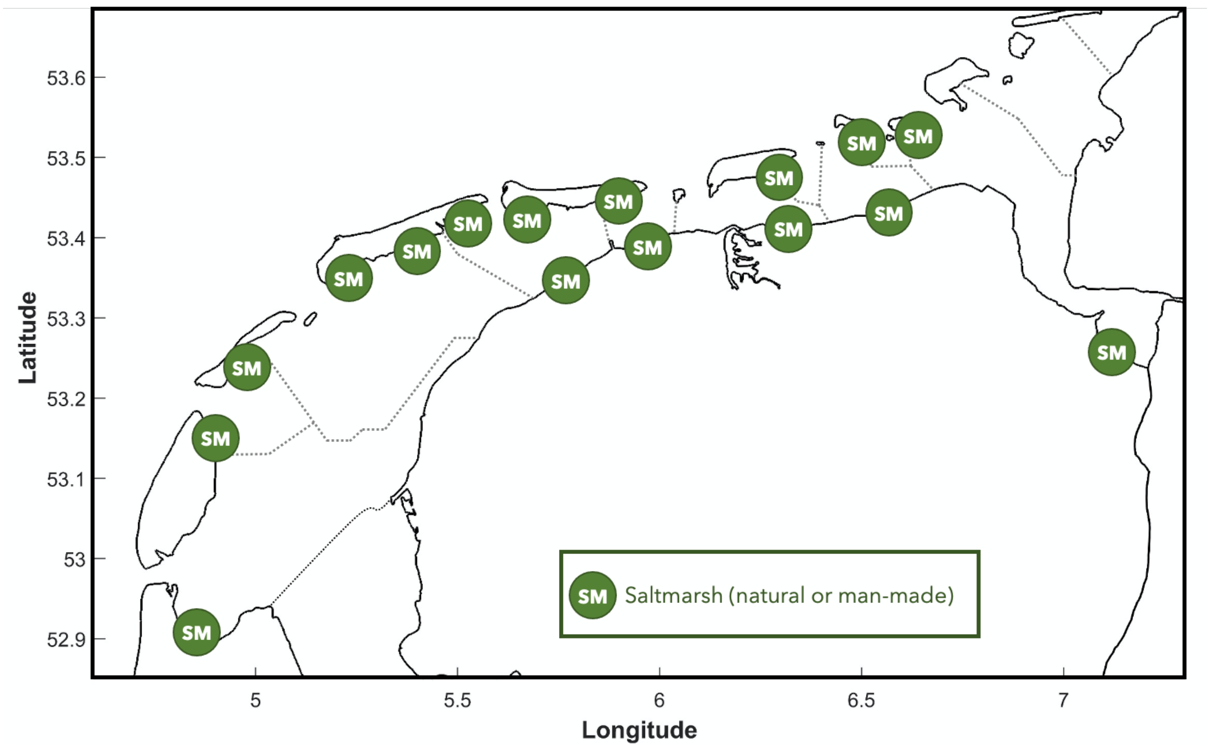
Saltmarshes

We found no evidence that (changes in the) maintenance of the saltmarsh works had an impact on the changes in seagrass occurrence at the coast of Groningen, implying that changes in maintenance are not likely to stimulate seagrass growth. Given the observed decline of the largest seagrass meadow in the Dutch Wadden Sea (Figure 6.1), we advise to study potential underlying causes (as single and cumulative effects) in more detail in order to be able to better understand, quantify and ultimately halt this development).

Even if net sedimentation occurs with a slow pace, it might still be detrimental if the seagrass beds are locally protected by solid peat and clay underlying surface sediments because an increase in the thickness of the sandy layer might reduce the possibility of seagrass to root into the stable underground. We, therefore, advise to map and monitor the areas adjacent to saltmarshes for hydrodynamic conditions, sediment dynamics, the (variation in the) thickness of the sandy top layer of the sediment and the (occasional or structural) presence and characteristics of seagrass (Figure 6.4).

Sediment dynamics

In the Wadden Sea, sediment dynamics are not only determined by currents and waves, but also by a suite of human activities including dredging, land reclamation, coastal infrastructures, bottom-trawling and recreational activities. Relatively small activities such as mud walking may have relatively large impacts when structurally crossing existing or potential seagrass beds at a higher frequency than the recovery rate of these plants. If this occurs, then such activities should be reduced or restructured (e.g. changing routes or avoiding sensitive areas by means of shipping).



6.4. Locations of saltmarshes in the Dutch Wadden Sea (van Loon-Steensma 2015).

In addition, sediment dynamics are likely to change resulting from changes in bathymetry (o.a. due to sea level rise) and in weather conditions (o.a. due to climate change). If so, then future protection and restoration efforts should consider the option that probability maps can change in time.

Towards dynamic probability maps

In order to get more grip on present and future options for the Wadden Sea as a hydrodynamically suitable habitat for seagrass (including a further improvement of the seagrass probability maps), more information is needed on

- the characteristics of seagrass meadows (blade stiffness, shoot density, leaf length) to allow for modelling of complex plants (with leaves and buoyancy structures) in complex flows and waves,
- on seagrass (seed) dispersal, and
- on wind, waves, local relative sea level, sediment dynamics and water quality as base-line information for impacts on seagrass dispersal, settlement, growth and survival.

With respect to seagrass behaviour relative to local hydrodynamic conditions, fine-scale modelling studies of individual seagrass plants is important for the development and validation of accurate parameterisations. The above can then be gathered by means of more detailed regional models (possibly with higher resolution in areas where seagrass is already present and is most likely to occur) which are fed with high-resolution data on seagrass and the main structuring environmental factors. Once calibrated and validated, such models can be used to identify potential hotspots (which can then be protected), for estimating the impacts of various climate scenarios, and for exploring the potential of various seagrass restoration efforts.

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