The colonization by seaweed and fauna of different revetment types at Sint-Annaland, Tholen

RAAK-PRO BUILDING FOR NATURE

FINAL REPORT

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Cover photo: the experimental dike at Sint-Annaland, 4 November 2015. Sections from left to right: hydroblocks with lavastone ecotop (covered in gutweed); standard hydroblocks; hydroblocks with BfN design. This sequence repeats three times. Photo: B. Schollema.

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Summary

Dikes are primarily designed to protect the hinterland against storm surges. The aim of the RAAK Building for Nature (BfN) project is to innovate the design and construction of dikes to give them an added value to nature and facilitate their multifunctional use for recreational diving, fishing and aquaculture. As part of this project the development of biodiversity on different types of revetments was monitored for one-and-a-half years at Sint-Annaland (Tholen, Zeeland). In May 2015 triplicate sections of 10 m width of different types of hydroblocks were placed on a sheltered NE facing dike: standard blocks, blocks with a lavastone ecotop and BfN blocks with a varying number of diamond-shaped pits. In addition, duplicate 5m-sections of standard and porous Hillblocks were placed. Based on pictures that were taken every 6 to 8 weeks, the coverage rate of the top surface of the blocks by three main seaweed species groups; gutweed (consisting of different elongated *Ulva* species, including *Ulva intestinalis*, and *Blidingia* sp.), *Fucus* sp. and *Porphyra umbilicalis*– was estimated at two different inundation times; 37% and 60%.

There were strong differences in the initital development of seaweed coverage at both levels between the different revetment types. Five months after the placement of the revetments, at the high inundation time the % cover was highest (>80%) on the BfN blocks and the Hill blocks, followed by the hydroblocks with ecotop (65%). The standard hydroblocks had the lowest coverage (35%). At the low inundation time the blocks with ecotop had the highest coverage (>80%), followed by the BfN blocks (65%), the Hill blocks (25%) and the standard hydroblocks (<10%). The coverage rate with gutweed was high on hydroblocks with ecotop. In the next seven months *Fucus* sp. growth increased strongly. Its % cover increased most on the BfN blocks, followed by the Hillblocks and the standard hydroblocks. The colonization by *Fucus* sp. was delayed on the hydroblocks with a lavastone ecotop. After seven months at the low inundation time, the BfN blocks were 100% covered by *Fucus* sp. whereas this was 50% for the blocks with an ecotop. This relatively low cover was confirmed by GIS-analysis of aerial pictures taken over the full vertical height range in spring 2016, 10 months after placement. Faunal colonization, especially by amphipods, correlated with *Fucus* sp. cover.

In autumn 2016, differences in relative seaweed cover were minor, now all block types were almost entirely covered with *Fucus* sp.. Species composition and biomass analysis revealed that at relatively low inundation times (<30%) the BfN blocks specifically stimulated the growth of *Fucus vesiculosus*. At these inundation times it contributed up to 50% of the *Fucus* biomass whereas it was virtually absent on the other block types. There were minor differences between the four BfN-block types as well as between the two Hill block types.

It can be concluded that in the first year all revetments tested perform better than the standard hydroblocks in terms of seaweed cover. Since this report only covers the first fifteen months after placement no statements can be made on the differences of the species composition of the climax community at each of the revetment types studied. The climax state of the seaweed population may take a minimum of four years to develop and includes the brown seaweeds *Fucus serratus* and *Ascophyllum nodosum* and a variety of smaller red and green algae at the inundation times studied. We also emphasize that given the sheltered location of the test dike section this research cannot be extrapolated to exposed dikes. We recommend to continue the monitoring of the dike sections over the coming years. Finally, we suggest to do additional research on the seaweed development on innovative revetments under exposed conditions, which may also be achieved by mimicking extreme disturbance events at a sheltered dike.

Table of contents

1. Introduction

1.1. Background

Over the past centuries dikes were constructed along long stretches of the Dutch coast. Dikes were and are primarily designed from a civil engineering perspective: the main focus is on flood protection and water management (Firth et al., 2014). The Building for Nature (BfN) approach aims at innovating the design of coastal protection structures in order to increase their ecological value. Dikes with this type of design are called rich dikes, or rich revetments (Fig. 1). These revetments can support the multifunctional use of dikes, e.g. for diving, fishing or aquaculture (Baptist et al., 2007). Where the nature on dikes has special protection, such as in the Natura2000 area the Eastern Scheldt, bringing back the nature value that existed in the past (Meijer and Van Beek, 1988; Meijer & Waardenburg, 1994). may be a requirement during the reinforcement of dikes. In past years at several locations in the Netherlands, including a few dike sections in Zeeland and the pier of IJmuiden first experiments were carried out to promote nature on dikes (eg. Borsje et al., 2010; Paalvast, 2011)

Fig. 1. An artist impression of a 'rich revetment' with a high biodiversity on the revetment, the riprap at the toe and in the foreshore (illustrator: Ruth Hengeveld).

In the context of the above-mentioned overarching goals, the RAAK-project Building for Nature has initiated several experiments to test different designs and materials that can be applied to increase biodiversity on different parts of the dike, including the foreshore, the riprap layer at the toe and the revetment on the slope of the dike. This report focuses on the revetments, the research on the other parts of the dike is presented in several other project reports. Information on the Building for Nature project can be found on de the DeltaExpertise site (www.deltaexpertise.nl).

1.2 Approach

Structural complexity strongly influences biodiversity on rocky shores (Little et al., 2009). By adding complexity to artificial shores it is possible to enhance marine biodiversity (Martins et al., 2016). On dikes this can be achieved by adding structure to the surface of revetment blocks. For this project, in Spring 2015, a dike section of 100m was built at Sint-Annaland where replicate sections of different types of revetments were placed to test their potential to contribute to a ‘rich revetment’ in the intertidal zone (Fig. 2). The blocks studied include different types of hydroblocks: standard blocks; blocks with a lavastone ecotop and BfN blocks with a varying number of pits. In addition standard Hillblocks and porous eco-Hillblocks were placed. The Hillblock sections were not part of the original design of the experiment but were added by Rijkswaterstaat/PBZ to gain more insight into the added value of the eco-Hillblocks to nature. The comparison of the influence of the surface characeristics of the Hillblocks with the other types is comprised by the fact the Hillblocks have a different shape. This report will focus on the different types of hydroblocks but will also report the development of seaweed on the Hillblocks.

One of the aims of the pits in the BfN blocks was to increase the microfauna on the dike by creating a heterogeneous surface with hiding places for different sized organisms. However, the pits also increase moisture retention capacity and the edges may provide good attachment possibilities for algae holdfasts, thereby potentially facilitating various seaweed species. Consequently, the different block types may strongly differ in the seaweed population development.

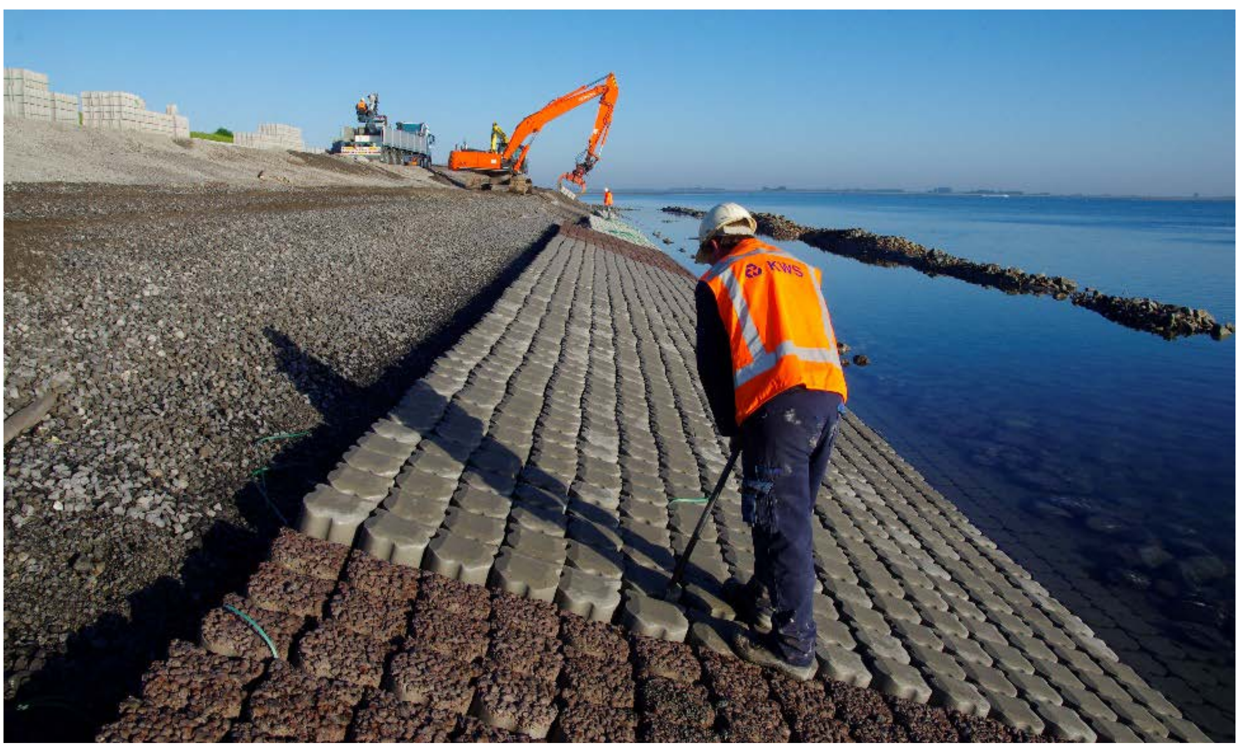


Fig. 2. The placement of the revetment at Sint-Annaland during spring 2015. Photo: T. van Heuvel.

1.3 Research questions and hypothesis

Main question:

What is the difference in seaweed and fauna abundance and community composition between standard hydroblocks, hydroblocks with a lava stone ecotop, hydroblocks with BfN designs, and standard and porous Hillblocks in the intertidal zone, in the first 15 months after placement?

Subquestions:

- What are the differences in the development of the seaweed coverage and composition between each of the tested block types?
- What are the differences in seaweed coverage and composition between the four BfN-designs (with 1, 2 4 or 9 diamond-shaped pits)?
- What are the differences in seaweed coverage and composition between the standard and porous Hillblock?
- What is the effect of inundation time on the seaweed coverage and composition on the different types of revetments?
- What are the differences in the development of the fauna abundance and community composition between each of the tested block types?

Hypothesis

Since the dike section at Sint-Annaland is located at a NE-faced sheltered place, wave impact is expected to be limited. Settlement of seaweed is expected to be relatively easy, with a low chance of disruption of the growing individuals. Moisture retention rather than attachment possibilities is therefore expected to be a key factor determining which seaweed species groups will develop and how fast they will grow. Specifically, gutweed might profit from the moisture retention capacity of the lavastone ecotop, porous Hillblocks and BfN blocks – the latter retain water in the pits. For the same reason these blocks are hypothesized to facilitate faster growth of the seaweed species present at lower inundation times that the standard blocks. Since this research is covering the first fifteen months only, the seaweed vegetation is expected to first be dominated by pioneer species, i.e. gutweed species, followed by *Fucus* sp. (hereafter referred to as *Fucus*). Concerning the fauna present, an early colonization of all block types is expected by crustaceans including barnacles and amphipods (Meijer & Van Beek, 1988). The latter group is dependent on the first development of seaweeds which are an important food source including *Fucus* species (Martins et al., 2013). Sessile molluscs like the Pacific Oyster (*Crassostrea gigas*) are expected to be especially abundant on the blocks with pits, since these pits have shown to facilitate their settlement and growth in a pilot experiment at Yerseke (see Appendix 6 and Van Oijen, 2017).

Limits and preconditions

Given the sheltered location of the test dike section, this research only studies the effect of the revetments in sheltered conditions. Another limitation of the study is that the upper part of the intertidal zone and the splash zone could not be studied because hydroblocks with basalt split were placed in this zone to facilitate the growth of chanelled wrack. Furthermore, this report only covers the first fifteen months after placement. No statements can be made on the differences of the species composition of the climax community. This is the seaweed community after ecological succession reached a steady state. This community includes species like the brown seaweed *Fucus serratus*, *Ascophyllum nodosum*, several smaller red and green algae species, hydrozoa and anemones and may take over minimal four years to develop (Meijer & Van Beek 1988; Meijer & Didderen, 2014).

2. Theoretical background

In this chapter we review the international literature on the existing knowledge on the relation between the physical (and chemical) characteristics of revetments and their species richness. Paragraph 2.1 provides a general introduction on the ecology of revetments. In 2.2 the effect of surface characteristics of revetments and other artificial structures on species richness is discussed. 2.3 provides a conceptual framework for the optimization of revetments surfaces in relation to species richness. Then we synthesize the outcomes of field experiments with (new types of) revetments in The Netherlands (2.4). In 2.5, we discuss our findings and their implications for the present study as well as for future research and the implementation of new designs.

2.1 Ecological functions of revetments

Revetments can fulfil some of the ecological functions provided by natural rocky coasts. These functions include: 1) hiding places, both for predator and prey species, 2) shelter against currents, 3) substrate for attachment, 4) food acquisition by foraging (see eg. Fig. 3) or, in the case of plants by photosynthesis and 5) reproduction/nursery/surface to attach eggs (Little et al., 2009).

Fig. 3. Revetments are an important foraging area for ruddy turnstones. Photo: G. Schechter.

Some organisms such as mussels, oysters and seaweeds are ecosystem engineers. Through their presence and their own physical structure, these organisms influence and often improve the ecological functions provided by the substrate they live on. Fucoids, mussels, oysters and sabellariid worms provide hiding places, refuges from currents, and foraging grounds for small mobile invertebrates (Thompson et al., 1996).

2.2 Physical properties of revetments and their relation to their ecological functions

Different revetments harbor different physio-chemical properties. The focus of our study is on the physical characteristics. Some are general, like the color of the material used, but most other characteristics can be subdivided into several size scales. On a mm-cm scale, examples of physical properties are water retention capacity, surface roughness, small pools and pits. On a larger scale (cm-m), examples are: the size of substrates such as tiles, boulders or columns, their sorting (one or multiple sizes), their spatial orientation, the size of stone clusters and the distance between them. Since in the present study we look at the alteration of the surface of revetment blocks, we focus on the influence of surface structure on a mm-cm scale. Our study does not include the space in between elements and therefore the suitability of revetment designs for larger animals will not be considered. Moreover many of these larger species like the European lobster live in the sublittoral zone.

Aside from the substrate characteristics, the ecological functions of revetments are dependent on several other abiotic factors. Abiotic factors are non-living conditions, such as water, air temperature, and salinity that influence the survival of species, and hence the species community. Other key factors that influence the species community on a revetment are the local inundation time, exposure to waves and currents, and wave run-up. The sediment concentration in the water is also an important abiotic factor because it determines the amount of scouring and hence the development of the fouling community. Between and along revetments abiotic factors vary naturally over both small and large spatial scales such as sunny and shady areas, but also physical and chemical differences in the water quality between different water bodies. Abiotic factors also vary on temporal scales like seasonality. However, it is possible to steer abiotic factors such as inundation time by changing the exposure or slope of the dike and thereby influencing the success of species colonizing the revetments.

A carefully designed revetment which takes into account the local abiotic conditions may facilitate several ecological functions. For sessile species or species with a sessile life stage, it is important that the substrate surface is suitable for attachment. For organisms that use revetments as hiding place or shelter, it is important that the dike surface contains pools, pits, cavities and crevices. The attachment and growth of seaweed, bivalves or other ecosystem engineers in turn creates a habitat for other marine benthic species including other shellfish, anemones and small crustaceans (Fig. 4). This may lead, as shown by the loop in the center of figure 4, to a positive feedback of more ecological functions, such as food supply for larger species of fish, crustaceans and birds like ruddy turnstones (*Arenaria interpres*). Ultimately, the revetment will also provide several ecosystem services, which may include the conservation of biodiversity or, on the other end, the exploitation of edible species.

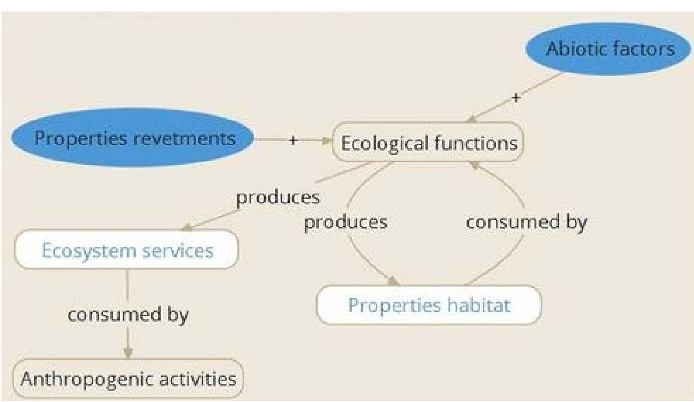


Fig. 4. Schematic overview of the relationship between the properties of revetments, (other) abiotic factors and the ecological functions ecosystem services they provide. This scheme is available as a clickable conceptmap: https://www.deltaexpertise.nl/wiki/index.php/Bfn_Natural_values_of_solid_dikes_VN

2.3 The optimization of the small scale surface structure of revetments

Nowadays, most revetments are monotonous constructions that show lower habitat complexity and heterogeneity than natural rocky shores (Moschella et al., 2005; Chapman and Bulleri, 2003). Complexity encompasses the abundance of the same structures in a habitat, per unit area or per unit volume, and heterogeneity encompasses the relative abundance of different structures in a habitat. Together they provide variation in structural habitats (McCoy and Bell, 1991). Habitat complexity and heterogeneity determine the species richness and ecological functioning, together with other local abiotic factors. In addition, existing revetments are often also characterized by higher levels of natural (e.g. storms, sediment scour) and anthropogenic (e.g. harvesting, trampling, maintenance works) disturbances than natural habitats. Habitat quality is therefore often lower than on natural substrates, with high dominance of opportunistic and invasive species (Airoldi et al., 2005; Bulleri and Airoldi, 2005; Bulleri et al. 2006).

Species richness on coastal defenses can be promoted by changing local abiotic conditions by increasing surface roughness and the number of and structural variation in pools, pits and crevices. Several international studies provide evidence that surface roughness on a cm-m scale leads to enhanced colonization and species richness (Martins et al., 2016 and references therein). In particular, algae, ascidians, barnacles, bivalves, hydroids, anemones, shrimps, annelids, crabs, ctenophores, sponges and gastropods, benefit from the presence of small pools, holes and crevices (Firth et al., 2014). Larger holes, pools and ditches (cm-m scale) may also create a suitable habitat for anemones, tunicates and sponges.

On a small scale, a set of abiotic conditions that is distinctive from surrounding areas, can create a microhabitat for species to live. By optimization of the physical properties of revetments a diverse species community can be sustained thereby strengthening the ecological functions provided by revetments. Theoretically, the distribution of structures could mimic the size distribution of natural species assemblages. These generally consists of relatively low numbers of large species. The numbers of intertidal animals increase with decreasing body size, following a power law (Marquet et al., 1990; Kostylev et al., 2005). It can therefore be hypothesized that heterogeneity in refuge spaces and in surface texture are important factors for the biodiversity on hard substrates.

The following example illustrates the challenge of designing a revetment surface that takes into account the complex relations between a species and biotic and abiotic factors. In order for a hard substrate to be a suitable habitat for a small invertebrate, it must provide refuge spaces in which the organism can shelter to avoid the threats of predation, desiccation and wave action. These refuge spaces should be large enough for the organism to fit inside, but small enough to prevent larger predators from reaching the organism, prevent excessive evaporation during low tide, and to protect the organism from being swept away by wave action (Menge et al., 1983). The suitability of a hard substrate for a particular species therefore depends, in part, on the size of the refuge spaces available (Menge et al., 1983). Furthermore, compared with smooth surfaces, rough surfaces provide a much more suitable attachment substrate for algae (Borsje et al. 2010), which in turn provide refuge habitats for the small invertebrate.

2.4 Effects of revetment structure on the intertidal species community in the Eastern Scheldt

In this paragraph we integrate the current knowledge on the effect of physical characteristics of revetments on the biodiversity on hard coastal defense structures in The Netherlands. A number of studies have been conducted in the Eastern Scheldt and other locations in the Netherlands to study the effect of adapting the surface structure of revetments on the colonization by seaweeds and other species groups (Table 1). Summaries of the outcomes of these experiments are presented in Appendix 5. In addition, several monitoring studies that have been carried out in the Eastern and Western Scheldt provide information on the effect of revetment type on biodiversity (eg. Meijer et al. 2011; Meijer and Didderen, 2014).

Table 1. Overview of a selection of experiments on the effect of revetment type on the ecology on dikes in the intertidal zone in the Netherlands relevant to this study.

Location	Name	Studies ecological development on	Key references
Neeltje Jans	Dijktuin I	several revetment types	Van Berchum and Kater (1997)
Tholen	Dijktuin II	several revetment types	Van den Burg and Everaars (1999), Meijer (2004)
Oosterschelde/Petten	-	Elastocoast with different treatments	Bijlsma (2008), Lock et al. (2009)
Hondsbossche en Pettemer Zeewering	-	Elastocoast	Dekker et al. (2014)
Ellewoutsdijk	-	C-star blocks with different structure and/or topping	De Kluijver and Vanagt (2009)
IJmuiden	-	Concrete cubic-shaped boulders with different surface structures	Rijkswaterstaat West Nederland-Noord (2014).
IJmuiden	-	Eco-concrete and C-fix plates with different structures	Paalvast (2011)
IJmuiden	-	Eco-concrete X-blocks with different structures	Paalvast (2011)
Burghsluis	-	Eco-Hillblocks and reference blocks at other locations	Didderen and Meijer (2015)

The experiments reveal that surface roughness influences local species richness in the colonization phase. Roughening of concrete surfaces on a mm-scale increases colonization rates of seaweed, mussels and other sessile organisms (eg. Paalvast, 2011). This includes the blue mussel, *Mytilus edulis* and bladderwrack, *Fucus vesiculosus*, which are important species for supporting biodiversity in Dutch waters. Their presence and structure provides food and shelter for prey species such as amphipods and other associated small macrofauna that are a food source for fish and shorebirds (Little et al., 2010). Yet, under most circumstances, surface roughness on a mm-scale does not seem to determine the climax state of the seaweed community or the macrofauna community. After a certain period of time (months or years) cover and density of most organisms on both rough and smooth surfaces are similar (eg. De Kluijver and Vanagt, 2009). For example, green seaweeds and barnacles prefer to settle on rough surfaces, but eventually settle on all concrete structures.

On a cm-m scale, small pools, holes and crevices improve the survival of bladderwrack, periwinkles (*Littorinidae*) , the settlement and survival of mussels and overall species richness. Bladderwrack grows best in sheltered areas in the mid-intertidal. Bladderwrack also benefits from a lavastone ecotop possibly because of the rough surface and its high water retention capacity during low tide. Mussels grow best in horizontal crevices low in the intertidal and can form mats on the porous surface of Elastocoast (Bijlsma, 2008). Laboratory experiments suggest that the smooth surface of Elastocoast does not hinder colonization by seaweed (Lock, 2009). More recent field experiments indicate however that seaweed growth is limited on Elastocoast (Vergouwen et al., 2017).

2.5. Synthesis

We conclude that changing coastal defense surface roughness on a mm-cm scale can increase species richness and biodiversity. Roughened surfaces, pools, pits and crevices, as well as epibiota, increase species richness and may support target species. Inundation time and wave exposure greatly influence the climax community on coastal defenses. However, we do not fully understand their effect on the relationship between microhabitat availability and species richness, or the influence of other physical factors such as dehydration and scouring by suspended sediment.

As a result, more research is necessary to adapt and optimize the surface roughness of coastal defenses based on local physical factors. From our literature analysis it also became clear that most new revetment types were monitored after deployment but in many cases only for a period of a few years after placement while a full recovery of the biological community might take as long as ten years. Furthermore test sites for new revetment types were designed without replicate sections of the different types and there was no georeferencing of the transect data i.e. dGPS.

This is especially true for the Eastern Scheldt. To get the full picture of seaweed and faunal colonization, growth and survival, further and more complete monitoring is necessary.

3. Material and methods

3.1 Description of the research location

The research was carried out in the Eastern Scheldt at Sint-Annaland, Tholen, province of Zeeland, the Netherlands. The location of the test dike section is indicated in Fig. 5. The section is facing NE direction which is a sheltered location since the dominant wind direction is SW (www.knmi.nl).

Fig 5. The location of Sint-Annaland (left) and the location of the test dike section (right).

3.2 Design of the experimental dike

In May 2015 triplicate sections of 10 meters width of different types of hydroblocks were placed on the dike section: standard hydroblocks; hydroblocks with a lavastone ecotop and BfN blocks (hydroblocks specially made with a varying number of pits) (Fig. 6). Please note that a fourth section with lavastone ecotop, section nr 2 on Fig. 6, was not part of the set-up and not included in the analysis. The BfN blocks are designed in a way that the number of pits varies, but the total surface area of the block is constant. For a description of the design and production process of the hydroblocks with pits, we refer to Boersema et al. (2017). In addition to the different hydroblocks, duplicate 4,5/5m-sections of standard Hillblocks and porous eco-Hillblocks were placed. Figure 7 shows the order of the sections. The sections are six meters from top to bottom and cover a height range between -0.92m NAP and +0,95m NAP as measured with a dGPS. The top of the section had to be set at +95cm m NAP since higher up the dike hydroblocks with a basaltsplit ecotop were placed. This was done to facilitate the growth of transplanted chanelled wrack, *Pelvetia canaliculata*, a rare species for Dutch coastal waters wich was present at the site before the dike was replaced.

Of each section, the top five meters (lower limit: -0,62m NAP) were included in analyses since on part of the sections the lowest meter was covered with the stone-chippings used to stabilize the blocks of a revetment. Also, this part of the dike was under strong influence of breaking waves on the large stones in the crumble zone, which was not the focus of our research.

Fig. 6. Specimens of: the four different types of BfN blocks; a standard hydroblock; and a hydroblock with lavastone ecotop, a few weeks after placement at Sint-Annaland.

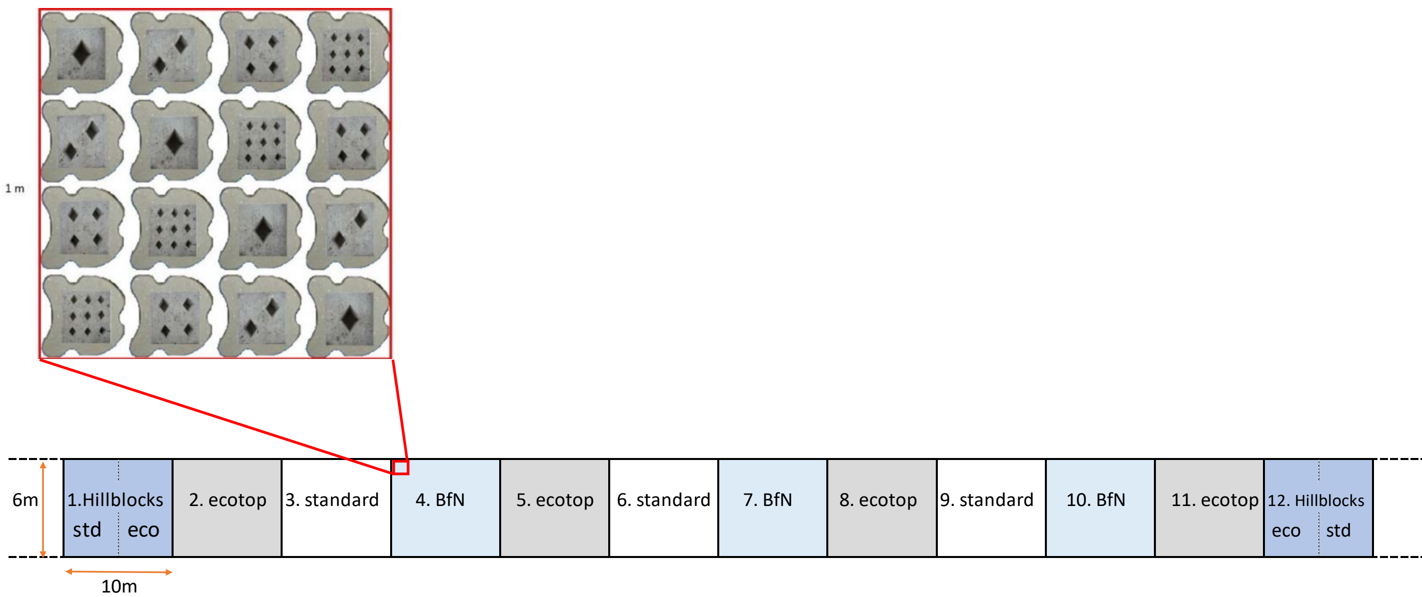
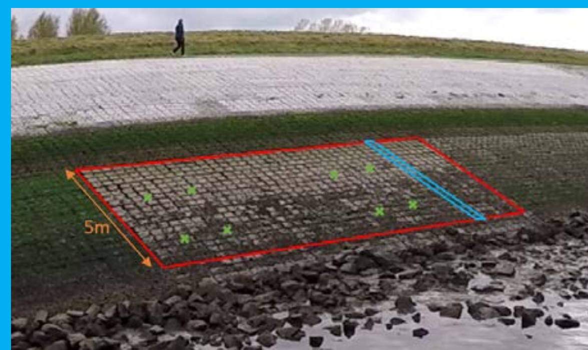


Fig. 7. The order and dimensions of the sections with the different block types as seen facing the dike (bottom). The different types of BfN-blocks were placed in an alternating way (see top left).

3.3 Data collection

The location was visited once every six to eight weeks from June 2015 through December 2016 (Table 2). Samples were taken for four types of analyses: picture analysis of seaweed cover on individual blocks at two height levels (3.3.1); picture analysis of seaweed cover on whole dike sections (3.3.2); seaweed biomass (3.3.3); seaweed and faunal species composition (3.3.4).

Table 2. Overview of the field sampling. The colour of the text for each sample type corresponds to the picture in the top right. This shows an example section with the surface that was included in GIS-analysis (red outline) and species composition and biomass analysis (blue outline). Also, the location of the blocks that were photographed to study the initial seaweed development at two levels are indicated (green crosses).



Sampling date	Sample type
2 June 2015	Pictures of individual blocks, two heights
15 July 2015	Pictures of individual blocks, two heights
9 September 2015	Pictures of individual blocks, two heights
21 October 2015	Pictures of individual blocks, two heights
16 December 2015	Pictures of individual blocks, two heights
17 February 2016	Pictures of individual blocks, two heights
11 April 2016	Pictures of individual blocks, two heights; Pictures whole dike sections
7&8 June 2016	Pictures of individual blocks, two heights; Species composition on vertical transects
7 September 2016	Pictures whole dike sections
18 October 2016	Seaweed biomass sampling on vertical transects
17 November 2016	Seaweed biomass sampling on vertical transects (extra sampling to study differences between the different BfN block types)

3.3.1 Seaweed coverage development at two different height levels

Pictures of individual blocks were taken with a Panasonic GH1 camera at two different height levels: -0,57 m NAP and +0.34 m NAP which correspond to an inundation time of 60% and 37%. On each of the sections pictures were taken of four replicate blocks on each height level, at least 1m apart from each other and 1m from the edge of the section (see green crosses in picture in table 2). On the sections with the BfN blocks, four replicate sets of the four different block types () were photographed at each height level. Since there are three replicate sections, a total of 12 replicate blocks was analyzed for each block type at each level.

Based on the pictures, for each of the seaweed species groups present the % cover on the square top part of the block was estimated in ArcGis. For a more accurate estimate a mask layer was added to the picture dividing the block surface into four different parts and analysis of the %cover on each of these parts. Cover estimates were made by one and the same person for all sampling dates.

The seaweed species found on the blocks could be grouped into five different species groups: gutweeds (including all *Ulva* species and *Blidingia minima*); *Fucus* sp. (hereafter referred to as *Fucus*); *Porphyra* sp. (hereafter referred to as *Porphyra*); *Gracilaria gracilis* and *Ectocarpales*. A few individuals of *Sargassum muticum* were observed on the Hillblocks. Since these do not normally occur at the inundation times studied, they are likely loose individuals that got stuck behind the blocks. They were excluded from the analysis, but influenced the %cover estimate of the other species on a few occasions. The gutweeds were grouped as they could not be distinguished from each other from pictures without additional sampling for microscopic identification. Young *Fucus* species were also difficult to identify at species level based on pictures.

NOTE: Since the pictures do not reveal what is underneath a species the %cover estimates have to be interpreted with caution: they do not include undergrowth and therefore underestimate the abundance of some species. This is especially a problem when large *Fucus* individuals are present as well as in the case of the epiphytes *Ectocarpales* which cover *Fucus* leaves. This also applies to the pictures taken over the full height range (see 3.3.2).

3.3.2 Seaweed coverage development over the full height range

In order to measure the coverage of seaweeds on each section of the dike pictures were taken using a Fujifilm x-e1 camera with Samyang 12mm lens that was mounted on a 4m long stick (fig. 8a). Pictures were taken in April and September 2016, 10 and 15 months after the revetment was placed. The photos were taken above the dike, perpendicular to its surface and with significant overlap between pictures (approx. 60%). The overlap between pictures prevented any issues regarding perspective that could cause problems when stitching the individual pictures together. The pictures were stitched together in Photoshop to create one picture per dike section (fig. 8b). Since a small part at the side of some sections was used for a disturbance experiment (not part of this report), for these sections not the whole section but the undisturbed subpart of 8m wide was analyzed.

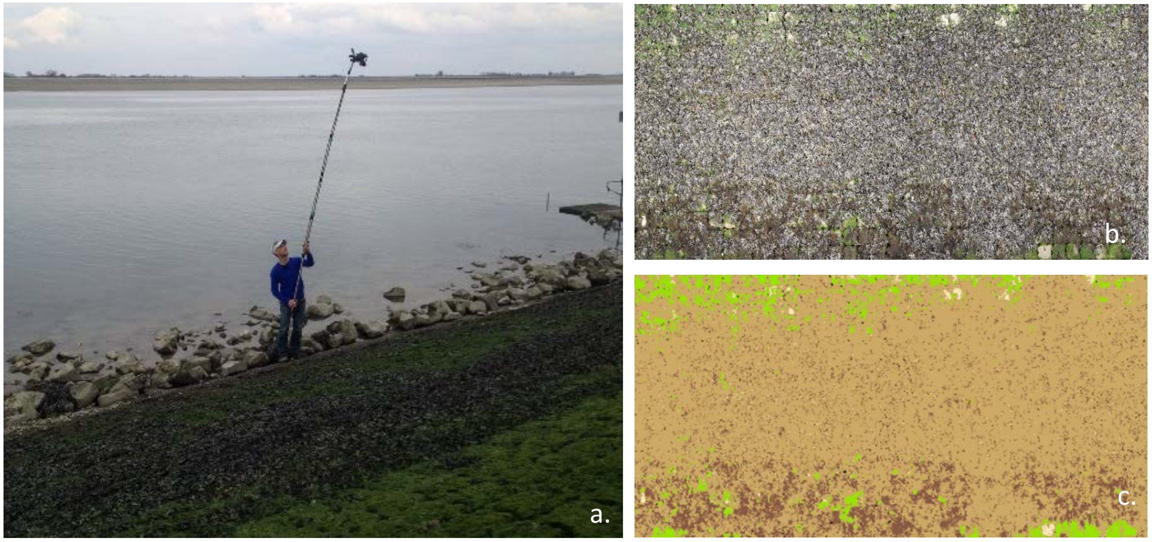


Figure 8.a. Taking pictures for the whole section analysis. b. Example of a picture composite of a dike section; c. GIS-analysis of a dike section where each color is a different species group/bare area: light green= gutweed; light brown=*Fucus*; dark brown=ectocarpales. Photos: T. van Oijen/E. Paree.

These pictures were analyzed with an Object-Based Image Analysis in ArcGIS. The pictures had lower resolution than the pictures taken at the two height levels, but were sufficient to identify the main species groups (see Fig. 9 and Appendix 2). The colors on the pictures were classified into five classes: gutweed; *Fucus*; ectocarpales; bare; and interstitial space (see fig. 8c for an example). Between ten and twenty sets of color ranges were created for a specific species group. After reclassifying, the data were georeferenced with dGPS (Leica GS08 plus) measurements. Subsequently a grid was created with a resolution of 10 cm. For each 10x10cm grid the coverage percentage of each species group was estimated. Subsequently data was integrated for each horizontal 10cm row. The areas of the classes 'bare' and 'interstitial space' were combined.

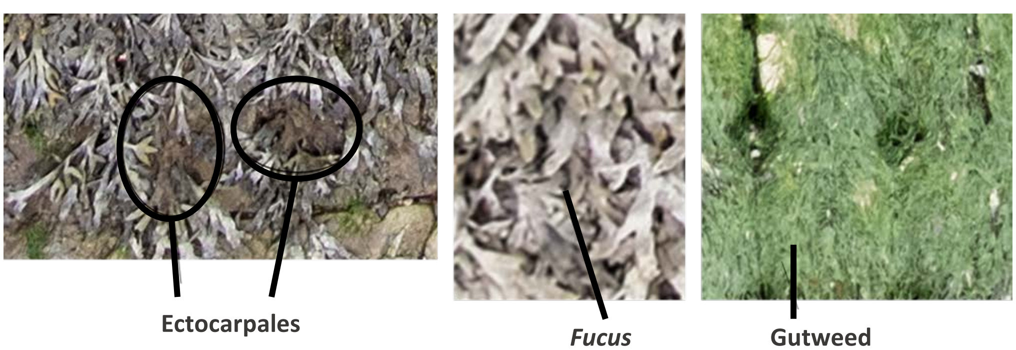


Figure 9. Details of images showing the three main species groups that could be identified.

The epiphytic brown seaweed species group ectocarpales was mostly present on the surface of *Fucus* in the lower intertidal zone. Note that it was present in low numbers at the two heights that were analyzed as described in 3.3.1 and only at the end of the observation period. In contrast, while a few individuals of *Gracilaria gracilis* were identified on the pictures of blocks at the two height levels, but were not visible/distinguishable on the pole pictures.

The differences that were observed in the mean seaweed coverage of the different revetment types in April and September 2016 were statistically analyzed by non-parametric one-way ANOVA's using AQB (Barnard et al., 2011). The difference in seaweed species composition between the different types of hydroblocks in April 2016 was tested with a two-way Chi-squared test, again using AQB.

3.3.3 Transect sampling for determination of brown seaweed biomass

At the end of the monitoring period, in October 2016, brown seaweeds were sampled along transects from top to bottom of each dike section. Therefore, for each block type triplicate transects were sampled. For the sections with BfN-blocks one extra transect was sampled to have a sample of each of the different block types at each height. Furthermore, on the second field day in November 2016 three extra block rows were sampled to have replicate samples of each of the four BfN block types at each level. These blocks were used to compare the biomasss on the different BfN blocks as presented in Appendix 4. A transect was a vertical row of 20 adjoining blocks which was located at least 1m from the edge of a dike section. All brown seaweeds growing on the top of a block were sampled by cutting their stems with a pair of scissors, leaving approx. 1cm of the stem behind. This gives a small underestimation of the wet weight present on the blocks which needs to be taken into account when comparing the results with other studies. All seaweeds were collected per block in numbered plastic bags and were stored in a cool dark place for max. 48h. before they were analyzed.

Figure 10. Transect sampling of brown seaweed for biomass analysis. Photo: E. Paree. On the right, clockwise: *F. spiralis*, *F. vesiculosus*, *F. serratus*.

In the lab, the brown seaweeds in a sample were first identified to species level using the identification guide in Zeeboek (edition 2014). The three species that were found are *Fucus spiralis, Fucus vesiculosus* and *Fucus serratus* (fig. 10). Key characteristics for distinguishing *F. spiralis* and *F. vesiculosus* from each other were the presence and location of air vesicles. The air vesicles of *F. vesiculosus* occur in pairs and are located all over the leaf. *F. spiralis* only has air vesicles at the tip of the leaves. Other characteristics that were inspected for species confirmation were the dichotomous branching and the infertile edge on the reproductive organs, both typical of *F. spiralis*. The leafs of *F. serratus* have serrated edges and can therefore it can easily be distinguished from the other two species. Seaweeds without air vesicles or serrated leaves could not be determined and were included as 'unknown' in the analysis. After sorting a sample the wet weight of each species was determined using a Vibra CG scale with an accuracy of 0.1g.

3.3.4 Transect surveys for species abundance and composition analysis

Flora and fauna transect surveys were carried out to be able to compare the species distribution per section over the full height range. Along transects on each dike section as described in 3.3.3, the top surface of each block was examined manually and inspected for all organisms present. All species occurring on the top surface of a block were identified to species group, recorded, and given a cover category based on the cover of the species of the top surface (Table 3). Cover, as defined for this purpose, is the fraction of the total top surface area that is obscured by a particular species when viewed from directly above. To translate the assigned cover interval into an estimated % cover, the mean value of the cover interval was taken. For the lowest (<0,5%) and the highest (>75%) cover interval, an estimated percentage of respectively 0,25% (the mean of 0 and 0,5%) and 87,5% (the mean of 75 and 100%) was used. As individuals of seaweed species could cover other species growing underneath it, the total % cover could be over 100%.

Table 3. The cover ranges and means of the cover categoriers used to estimate the presence and abundance of flora and fauna on the blocks.

Category	Category range (c=cover)	Category mean (used for data processing)
1	c<0,5	0,25%
2	0,5<c≤1,5%	1%
3	1,5<c≤3%	2,25%
4	3<c≤5%	4%
5	5<c≤12,5%	8,75%
6	12,5<c≤25%	18,75%
7	25<c≤50%	37,5%
8	50<c≤75%	62,5%
9	c>75%	87,5%

4. Results

In paragraph 4.1 the development in the seaweed coverage on the different sections at two different heights is described, followed by the analysis of seaweed coverage of the full height range at t=10 and t=15 months (4.2). Paragraph 4.3 describes the differences in *Fucus* biomass between the different sections at t=17/18 months. Finally the differences in seaweed and fauna composition at t=12 months are described (4.4)

Note: the west section of the Hillblocks (section 12) was excluded from the analysis. This section showed a seaweed development that strongly deviated from the other Hillblock section (section 1), especially on the most western side. For an illustration of this difference, see Appendix 2. This difference might be explained by the fact that the abiotic conditions at the location of this section are different. Specifically, there is a shallower sandy foreshore which might have caused more scouring.

4.1 Development in seaweed coverage at two heights

Figure 11 shows the development in % cover of the different seaweeds groups in the first year after placement at -0,57 and +0,34 m NAP, referred to as "low" and "high" in the text below. Not shown on these figures is the development of ectocarpales on the *Fucus* leaves, which were present in low numbers from April 2016 on the low level.

The top surfaces of all block types were colonized by gutweed in the first month after placement. There is a large difference in the amount of gutweed that develops on the blocks. Gutweed cover is highest on the lavastone ecotop at both heights (up to 100%) and the BfN designs at the low level (100%). There were also changes over time in the thickness of the gutweed vegetation i.e. the individual plants were much longer on highly covered blocks on later sampling dates compared with earlier dates (data not shown).

In October 2015, four months after the start of the experiment, *Porphyra* was present on all block types but % cover remained low (<10%). The cover rate for *Porphyra* was lowest on the standard hydroblocks (Fig. 11a,b). For this observation date there was a significant effect of revetment type on *Porphyra* coverage (two-way non-parametric ANOVA, $H = 10.41$, $df = 3$, $p = 0.02$). *Porphyra* coverage was not significantly dependent on the inundation time (two-way non-parametric ANOVA, $H = 2.24$, $df = 1$, $p = 0.13$). Later in the first year after placement *Porphyra* was no longer observed on the blocks.

In September/October 2015 *Fucus* plants started to develop on most block types. *Fucus* growth was particulary fast on both Hillblock types in at the low level (Fig. 11g,i). *Fucus* cover remained markedly low at the lavastone ecotop through February 2016, especially at the low level (<10%, Fig. 11c). By this time *Fucus* vegetation was already very dense on the BfN hydroblocks and both Hillblock types (70-100%). *Fucus* %cover also increased on the standard hydroblocks, but at a lower rate than on the BfN hydroblocks in the levels higher on the dike (see Fig.11b,f).

The influence of the different pit sizes on the BfN designs on the % cover of the different species groups was also investigated, but no significant differences were observed between these designs (see Appendix 1).

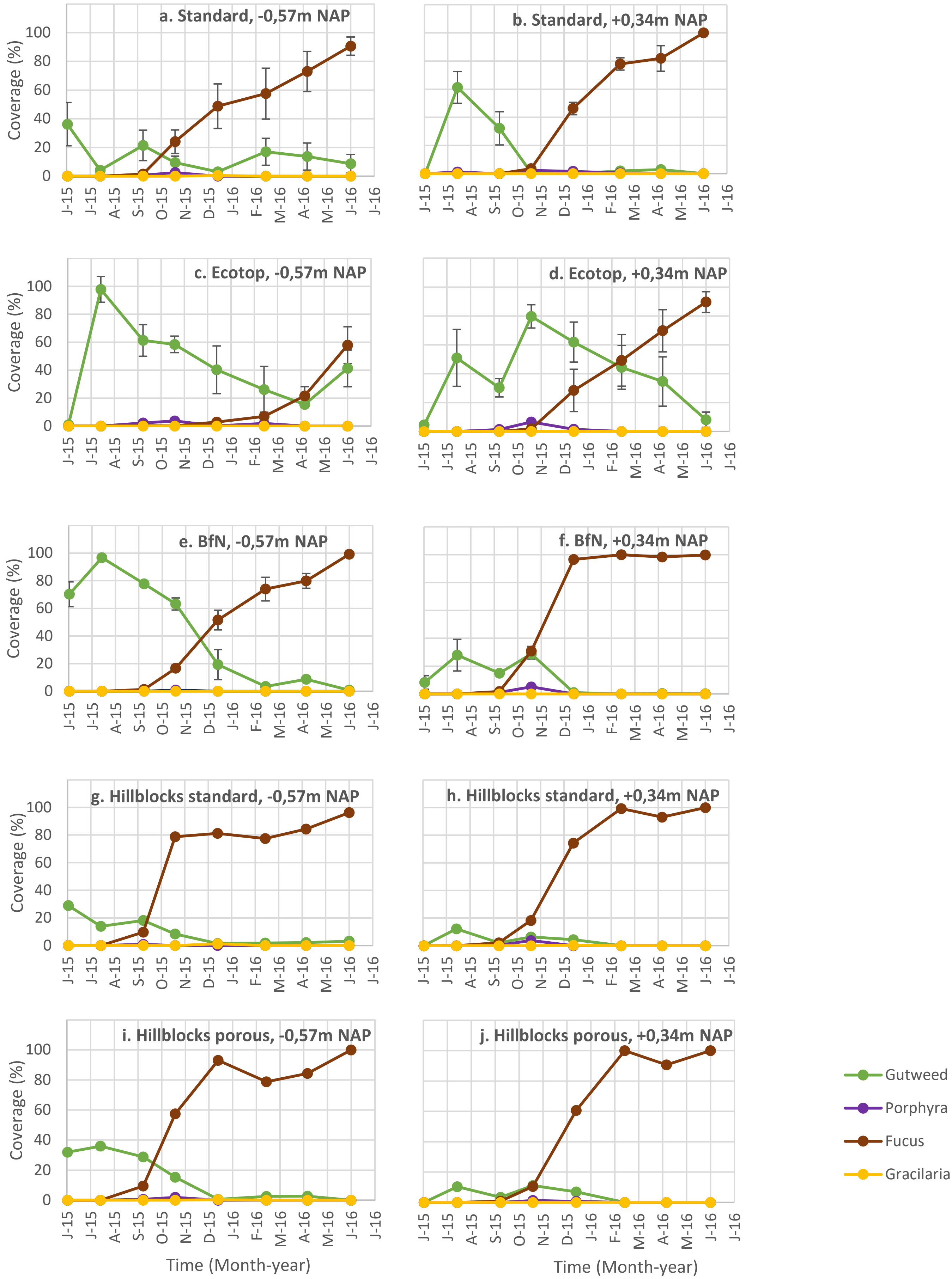


Figure 11. The development in seaweed cover for the different species groups on the five different revetment types in the first 12 months after placement. The error bars show the standard error of the replicate sections (n=3). Note: Ectocarpales growth on *Fucus* leaves is not shown.

4.2 Seaweed coverage development over the full height range

Pictures with full coverage of each section were taken in April and September 2016. An impression of the early development on the dike sections in November 2015 can be viewed in this video: https://www.youtube.com/watch?v=Rxv_OEpy-sE.

4.2.1 Vertically integrated coverage

In April 2016, there were strong differences in the seaweed composition on the different hydroblocks (Fig. 12a; Table 4). The Hydroblocks with a BfN-structure are 95% covered with brown seaweeds, whereas Hydroblocks with an ecotop layer are covered for 65% with brown seaweeds and 25% gutweed. The standard hydroblocks had an intermediate composition (Fig. 12a). BfN-hydroblocks had significantly higher *Fucus* cover than hydroblocks with an ecotop layer (one-way non-parametric ANOVA; H=4,5 ; df=1 ; p=0,0339). The brown seaweed cover of the standard and eco-Hillblocks was comparable to BfN hydroblocks but they had a relatively high contribution of ectocarpales. In September 2016 the sections were almost entirely covered with *Fucus* (Fig. 12b; Table 4). The coverage rate was not significantly different between the different types of hydroblock (one-way non-parametric ANOVA; H=2,00 ; df=4 ; p=0,7358).

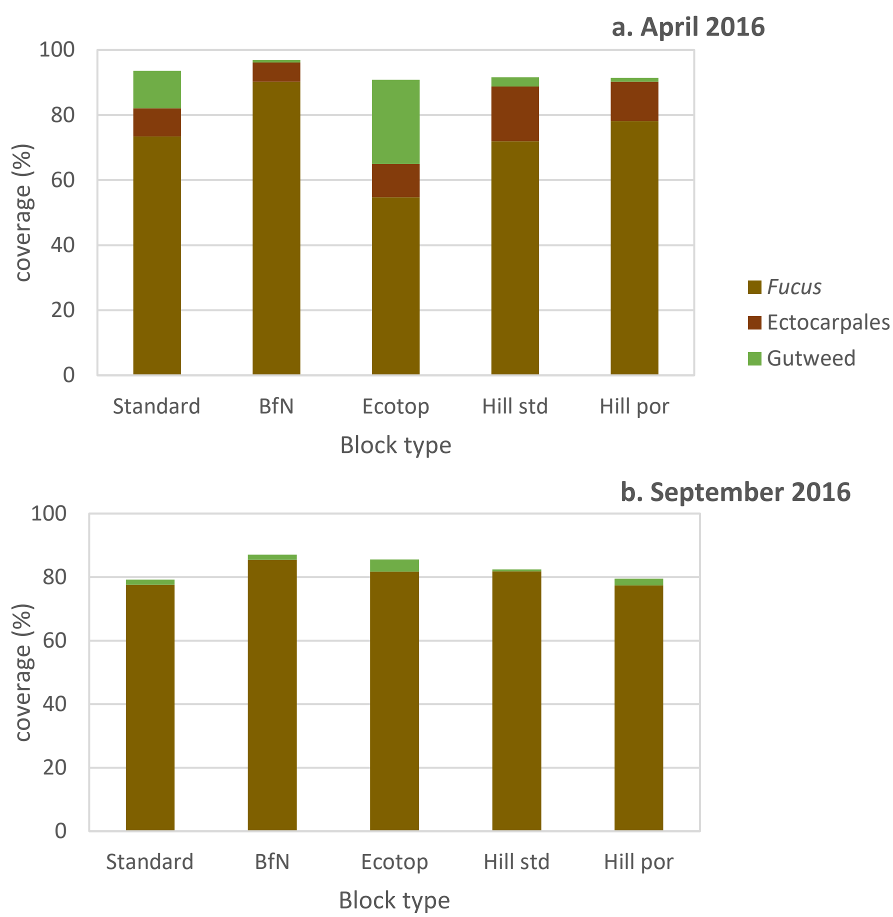


Figure 12. The average seaweed coverage for the different species groups integrated over the full height range of the experimental dike (-0,60 - +0,92 mNAP) on the different block types. Standard BfN and ecotop hydroblocks: n=3; standard (std) and porous (por) Hillblocks: n=1. a. April 2016; b. September 2016.

Table 4. Examples of the seaweed development on the different block types. The photos show parts of 4m width over the full height of a section. For full 5-10m width photos of all replicate sections, see Appendix 2.

Section	April (t= 10 months)	September (t=15 months)
Hydroblocks standard		
Hydroblocks BfN		
Hydroblocks lavastone ecotop		
Hillblocks standard		
Eco-Hillblocks (porous)		

4.2.2 Vertical distribution

Here we show the results for April 2016. In September 2016 differences in the vertical distribution between the different revetment types were minor. This figure is included in Appendix 3. The vertical distributions of seaweeds in April 2016 are presented as vertical kite graphs (Fig. 13).

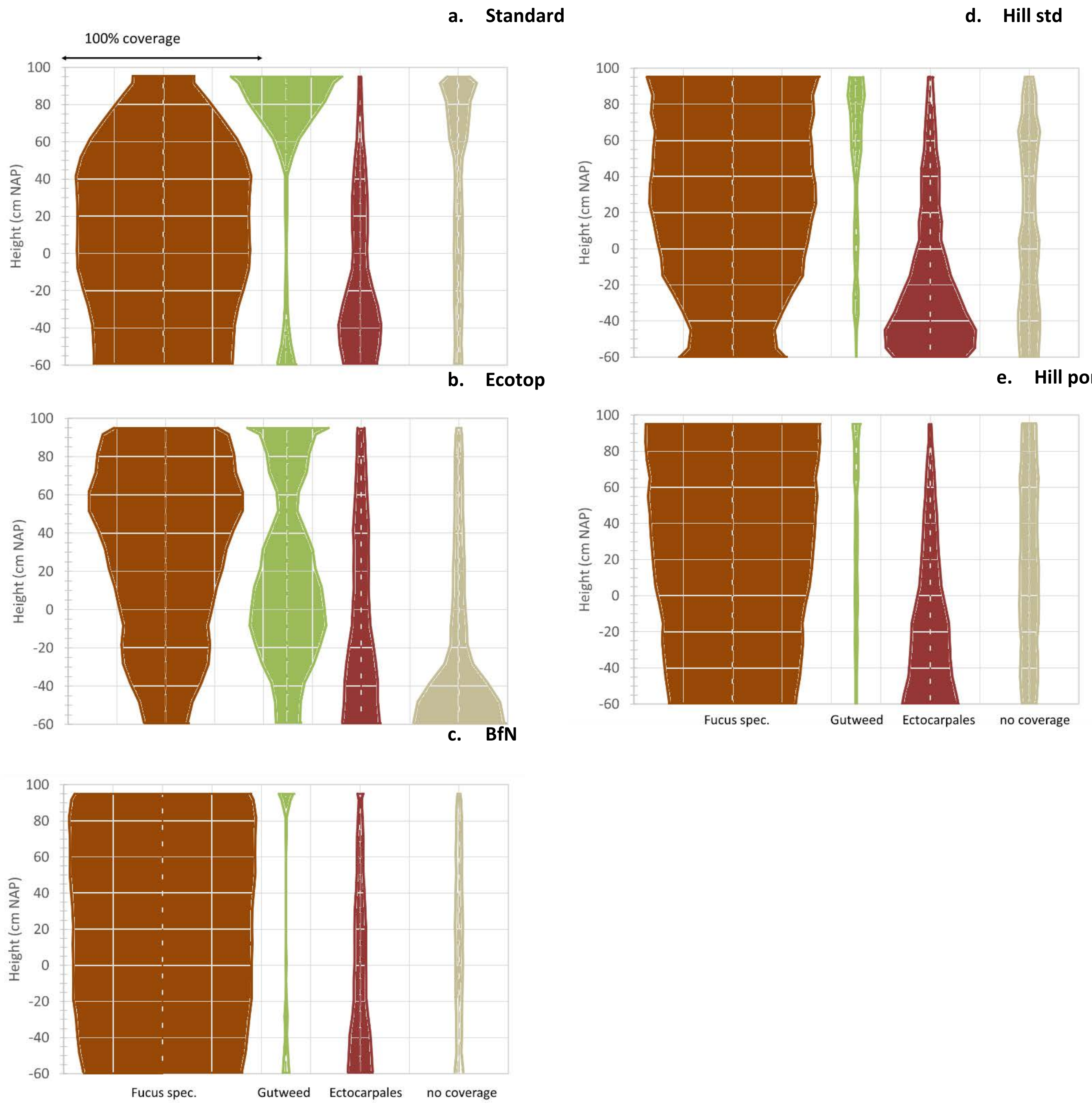


Figure 13. Vertical kite graphs of the distribution of the seaweed species groups on the different revetment types. a: standard hydroblocks; b: hydroblocks with an ecotop layer; c: hydroblocks with a BfN-structure; d: standard Hillblocks; e: porous Hillblocks

The standard hydroblocks (Fig. 13a) were largely covered with *Fucus* on most parts of the full vertical range. Gutweed was still present higher on the dike, above +0,50 mNAP. Here, also part of the surface is still bare. Ectocarpales are mostly present below NAP which is the case on all revetment types. The hydroblocks with an ecotop layer (Fig. 13b) were covered for a large part with gutweed in the middle and top part of the vertical range. *Fucus* cover seemed to increase when the gutweed decreases and vice versa. The lowest parts of the section were partly bare (up to 50%). The hydroblocks with a BfN-structure were nearly completely covered with *Fucus* over the entire vertical range (Fig. 13c). Gutweed was only present at the top and bottom of the section, covering a few percent of the block surface. The standard and porous Hillblocks (Fig 13d,e) are also mostly covered with *Fucus* but below NAP its percentage cover was markedly lower than on the BfN hydroblocks. Gutweed was present at the top of the sections but in low percentage cover. The highest percentage of Ectocarpales (up to 50% in low intertidal) was observed on the Hillblocks.

In September 2016, all revetment types were almost entirely covered with *Fucus* over the whole vertical range. The exceptions were the sections with hydroblocks with ecotop. On this revetment type gutweed contributed up to 20% to the seaweed cover at lowest part of the section (see Appendix 3).

4.3 Biomass of *Fucus* species

4.3.1 Total *Fucus* biomass

In October 2016 (t=16 months) the total biomass of all *Fucus* species was highest on the sections with porous Eco-Hillblocks followed by the BfN-hydroblocks and the standard Hillblocks (Fig. 14). The biomass of *Fucus vesiculosus* was highest on the BfN-hydroblocks and lowest on the hydroblocks with ecotop. On the hydroblocks with ecotop and on both Hillblock types *Fucus spiralis* was most abundant. The differences in biomass on the different BfN-types were minor (see Appendix 4).

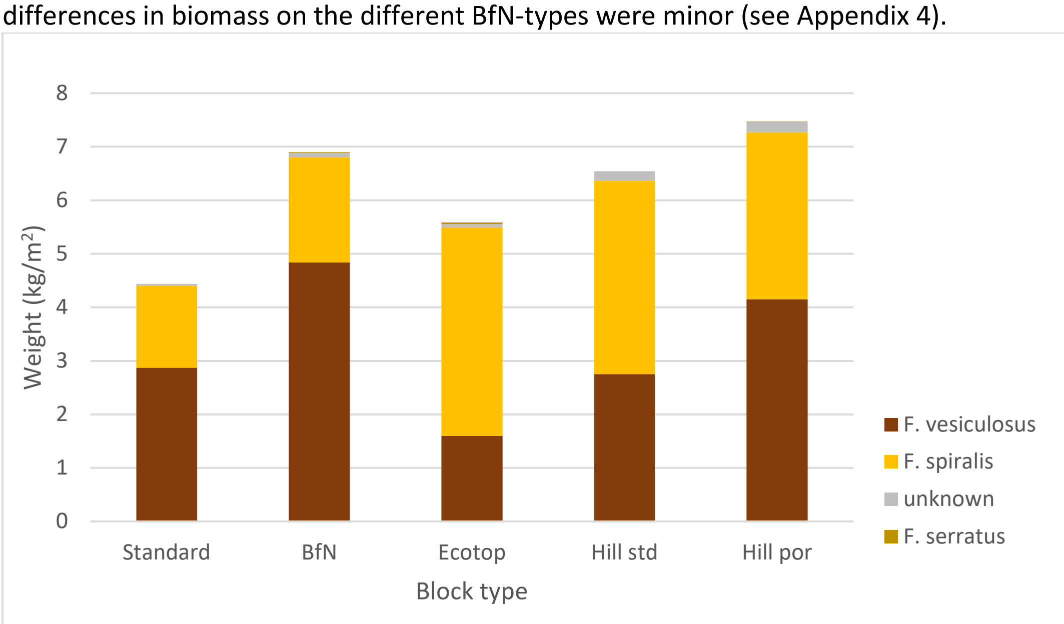


Figure 14. The average biomass at t=16 months for the different *Fucus* species integrated over the full height range of the experimental dike (-0,60 - +0,92 mNAP) on the different block types.

4.3.2 Vertical distribution of *Fucus* species

As shown by Fig. 14, the relative proportion in biomass of *Fucus vesiculosus* and *Fucus spiralis* differed between the different revetment types.
Above 0.5 m NAP, *F. vesiculosus* had a relatively high biomass on BfN-hydroblocks, whereas it was hardly present on the other revetment types (Fig. 15). On the lower parts of the sections, *F. vesiculosus* biomass was markedly low on hydroblocks with ecotop. The different BfN types did not differ from each other much in terms of vertical distribution of the different *Fucus* species (see Appendix 4). Of F. serratus a few individuals were spotted on hydroblocks with a lavastone ecotop at the and of the observation period.

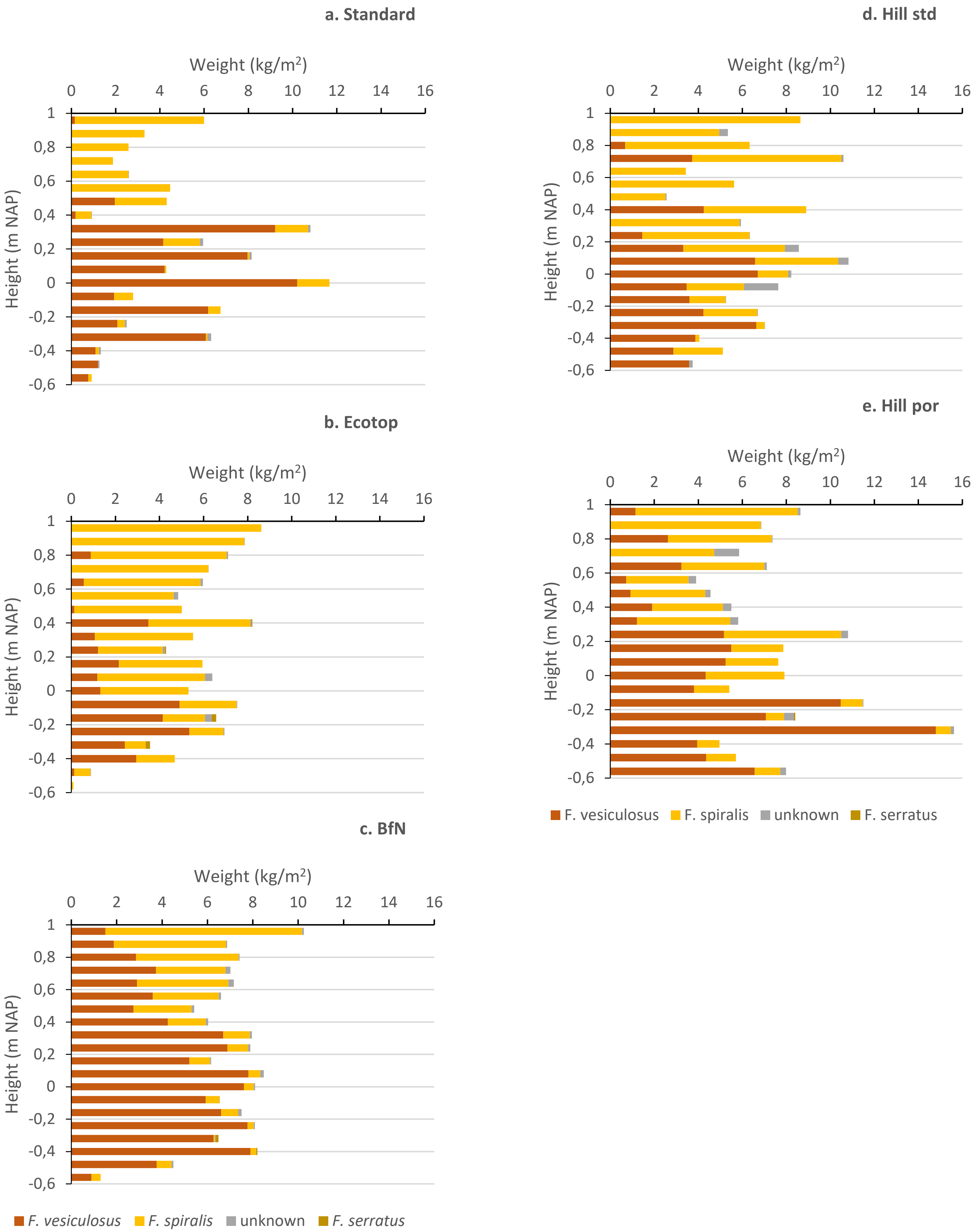


Figure 15. The vertical distribution of the biomass of the different *Fucus* species on the different revetment types at t=16 months. a: standard hydroblocks; b: hydroblocks with an ecotop layer; c: hydroblocks with a BfN-structure; d: standard Hillblocks; e: porous Hillblocks

4.4 Species composition analysis

4.4.1 Seaweed composition

In situ seaweed composition analysis was carried out one year after the start of the experiment. In contrast to the monitoring using pictures, this approach allowed the undergrowth to be studied. Figure 16 shows the vertical distribution of the dominant seaweed species. Distinguishing between the different gutweed species in the field was difficult. Specifically, *Blidingia minima* and *Ulva linza* and *Ulva intestinalis* were grouped to 'gutweed'. The *Fucus* species composition on the blocks was similar to that observed in the analysis of the biomass at t=16 months (see 4.3). Ectocarpales were also relatively abundant on the Hillblocks compared with the other revetment types. On the hydroblocks with ecotop, gutweed was far more abundant than on the other block types.

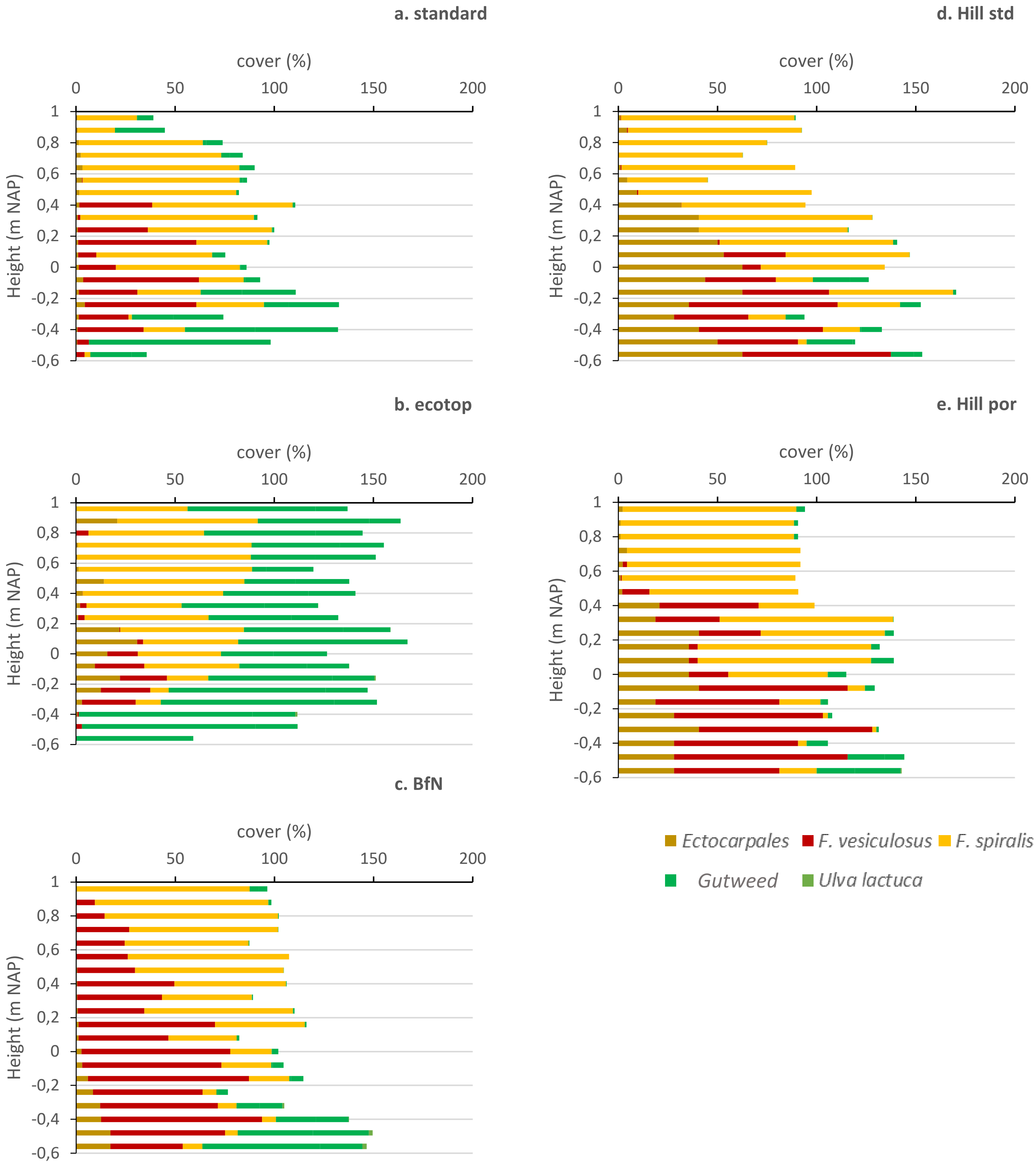


Figure 16. The vertical distribution of the dominant seaweed species on the different revetment types, at t=12 months. a: standard hydroblocks; b: hydroblocks with an ecotop layer; c: hydroblocks with a BfN-structure; d: standard Hillblocks; e: porous Hillblocks

4.4.2 Fauna

After one year all revetments types were colonized by a variety of invertebrates The species (groups) most often observed were springtails (*Anurida maritima*), the common crab (*Carcinus maenas*), barnacles (cirripedia), amphipods and isopods. Periwinkles were encountered incidentally. There were obvious differences in the abundance of main fauna species groups on the different revetment types (Figure 17). Relatively high abundances of amphipods were found on the BfN-hydroblocks and on both types of Hillblocks, while abundances were low on the hydroblocks with ecotop. The abundance data on the common crab are not reliable since a larger surface would need to be sampled to get an accurate estimate.

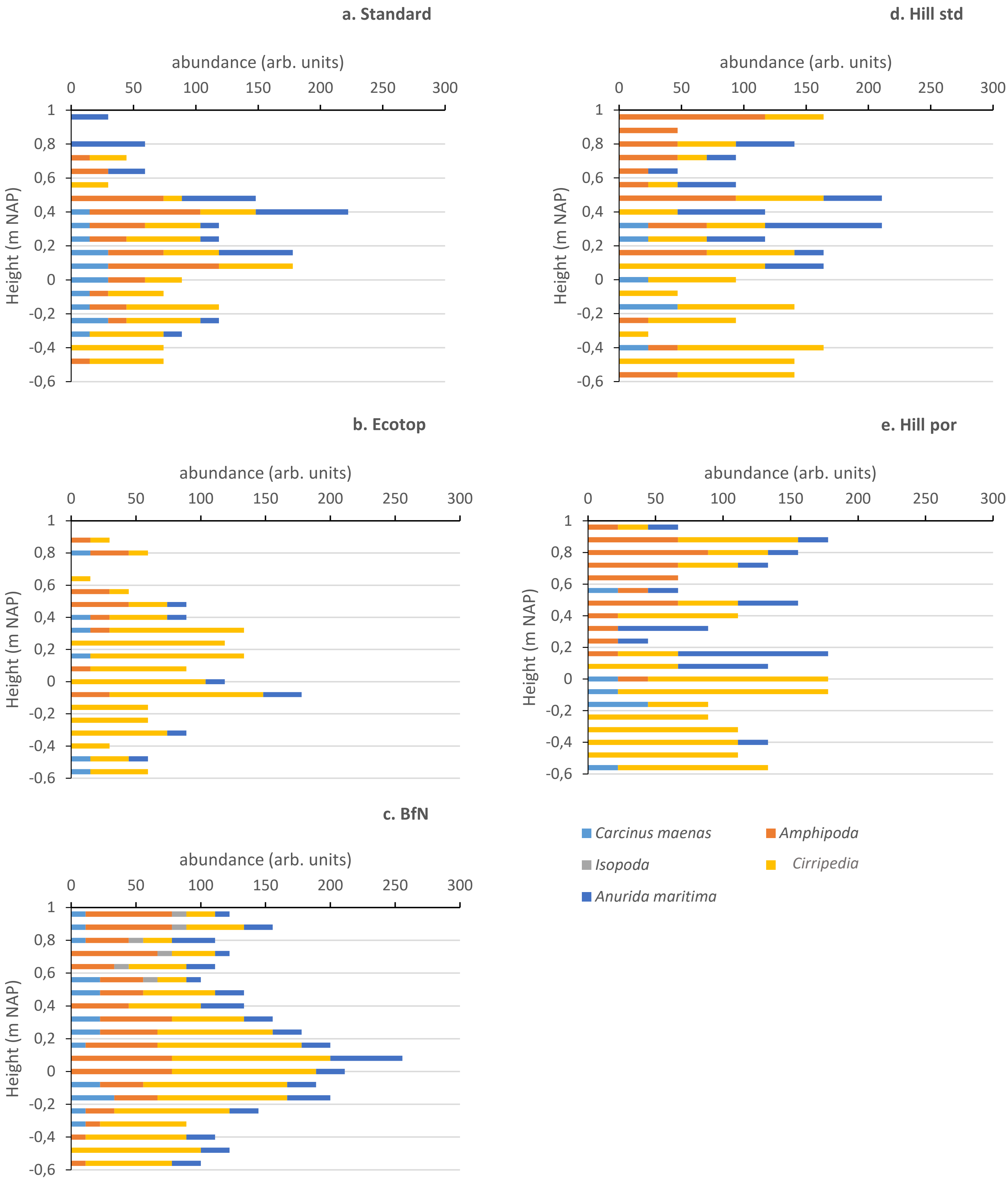


Figure 17. The vertical distribution of the dominant seaweed species on the different revetment types, at t=12 months. a: standard hydroblocks; b: hydroblocks with an ecotop layer; c: hydroblocks with a BfN-structure; d: standard Hillblocks; e: porous Hillblocks

5. Discussion and conclusion

There is a major challenge to civil engineers in the coming decades to find new ways for the execution of dike reinforcements that conserve the ecological value (Airoldi et al., 2005). In the intertidal zone seaweed coverage is key to the restoration of the ecosystem because it provides a habitat for many other species groups present including amphipods, isopods and littorinids. In the present study the recolonization by seaweed of several innovative revetment types was investigated and compared with the standard hydroblocks.

There were large differences in the development of seaweed coverage in the first 1.5 years after laying the blocks. The development of *Fucus vesiculosus* was particularly fast on BfN-hydroblocks and Hillblocks. The fact that *F. vesiculosus* was developing faster on BfN-blocks as compared to standard hydroblocks can likely be explained by water retention by the blocks. Since all blocks were produced by the same standard procedure at the same factory, it is unlikely that there are differences between the blocks other than the pits. The coverage rate of gutweed remained remarkably high throughout the first year on hydroblocks with ecotop. There may have been a competition for space between the pioneer species of gutweed and the *Fucus* species. Gutweed are known as pioneering species that develop on bare substratum. Gutweed are strong interference competitors, but only under conditions that are stable, as they are relatively sensitive to grazing and desiccation (Hurd, 2014). The ecotop seemed to stimulate gutweed growth the most, possibly by their relatively high moisture retention capacity. This might have resulted in reduced space available for brown seaweeds to settle. In the experiments with C-star blocks with lavastone ecotop, these were found to stimulate *Fucus* development more than on bare C-star blocks (De Kluijver and Vanagt, 2009). This contradicts our results, which may be caused by a difference in wave exposure (see also below).

In a study on the BfN-hydroblock designs on another site (NIOZ-Yerseke, Appendix 6) the pits clearly influenced seaweed growth on the blocks. Growth of *Ulva lactuca* in particular, was only observed on the edges of the pits while more red seaweed species developed at high inundation times. In this study we see an obvious stimulating effect of the pits on the total coverage rate of the whole block compared with standard blocks. However, the stimulation of red seaweeds was not observed. There were minor differences between the four BfN-block designs, which coincides with the results of the experiment at NIOZ-Yerseke. The porous eco-Hillblock design stimulated seaweed growth in a study on a test site near Burghsluis, Schouwen-Duiveland (Didderen & Meijer, 2015). Here, we did not observe such pronounced effects of the porous structure.

That the presence of amphipods correlated with *Fucus* biomass is logical as the algae is an important food source for amphipods (Martins et al., 2013; Ingolfsson and Agnarsson, 2003). Crustaceans like these are a food source to bird species like ruddy turnstones, which are known to use dikes as foraging habitat (Boudewijn and Meijer, 2007). The rapid colonization and biomass development on several of the block types tested may therefore benefit these species.

Yearly variation in abiotic factors like temperature and storminess/wave impact might significantly impact species settlement and growth. Therefore, the results of the experiment might in part be the result of the abiotic conditions during the experimental period. Another factor that might in part determine the outcome of the study is the timing of the construction of the dike. A dike that is constructed in early summer might have a considerable different evolution in seaweed coverage in the first years than one that is placed at the end of summer when most settlement has already taken place.

Based on the experiment, it is still hard to predict how much the revetment type influences the final seaweed community composition at the climax state. The climax community of the seaweed population on dikes is dominated by brown seaweeds (*Fucus vesiculosis*, *Fucus spiralis, Fucus serratus*, and *Ascophyllum nodosum*) and a variety of smaller red and green algae. *Ascophyllum nodosum* was a dominant species on the previous dike at Sint-Annaland before it was renovated (personal observation). This species is know to have a preference for sheltered location like the study site. It has a very slow growth rate, beginning at only 0.2 cm per year, and has not been observed on the dike since the blocks were placed in June 2015 (Sundene, 1973). It may take several years before *A. nodosum* is fully visible alongside the other seaweeds present. Therefore we have no idea yet what the impact of the different revetment types will be on this species. There is competition for space with other brown seaweeds on the revetments, so the community structure at t=1.5 years may influence its development (Keser and Larson, 1984).

The observations made at the sheltered dike at Sint-Annaland cannot be extrapolated to exposed shores. One approach to compare the results to an exposed condition is by introduction an atrificial disturbance on part of each of the sections. We performed a pilot study, where we treated the dike with a 100 bar power washer (Fig. 18). From this treatment it became clear that once *Fucus* has reached a certain threshold size, the plants were not sensitive to hydro-mechanical disturbance anymore. This suggests that, as *Fucus* development is fast on BfN-hydroblocks and on Hillblocks, growth of *Fucus* on these revetment types could be successful at exposed sites provided enough time is given to grow before the start of the stormy winter season. It was also observed that gutweed was easily removed with the treatment. As gutweed competes for space with brown seaweeds, the latter might dominate the hydroblocks with ecotop sooner on dikes in more dynamic environments but this requires further study.

Figure 18. Treatment of dike sections with a power washer. Photo: E. Paree.

Conclusion

In conclusion, at the sheltered dike at Sint-Annaland, all revetments tested performed better than the standard hydroblocks in terms of seaweed cover over the first ten months. However, after fifteen months differences in seaweed cover were minor. The results show that modifications of concrete block revetments can lead to significant changes in seaweed species abundance and recolonisation in the short-term. Alternative block designs could increase the pace at which a climax-state is reached and the invertebrate species that are present which could be of pivotal importance to bird species which are dependent on this habitat for foraging.

In terms of coastal defense, relatively simple adaptations to revetment surfaces like the pits may be cost-effective measures to manage local biodiversity on coastal defenses without compromising on safety. Habitat complexity and heterogeneity are crucial to species richness, implying that at a single location, the habitat needs to be complex and heterogeneous. Rich revetments must match local physical conditions which vary within and between water bodies. Furthermore, to ensure habitat heterogeneity at the scale of the water body, management authorities could aim to use various rich revetments in locations with similar physical conditions thereby maximizing species richness at a large scale. A better understanding of the relationship between rich revetments and species richness, and how this relationship is affected by physical factors, is needed to put these concepts into practice.

Outlook

Ongoing research at HZ includes a simulation of a disturbance event where all seaweeds on a part of each section will be completely removed using a bush trimmer (Fig. 19). The aim of this research is to gain insight into the ability of the seaweed community to recolonize the substrate after e.g. winter storms. This research will be part of the educational program of the Bachelor study Watermanagement: Aquatic Ecotechnology at the Delta Academy.

Fig. 19. The dike at Sint-Annaland after treatment with a bush trimmer (February 2017). Photo: T. van Oijen.

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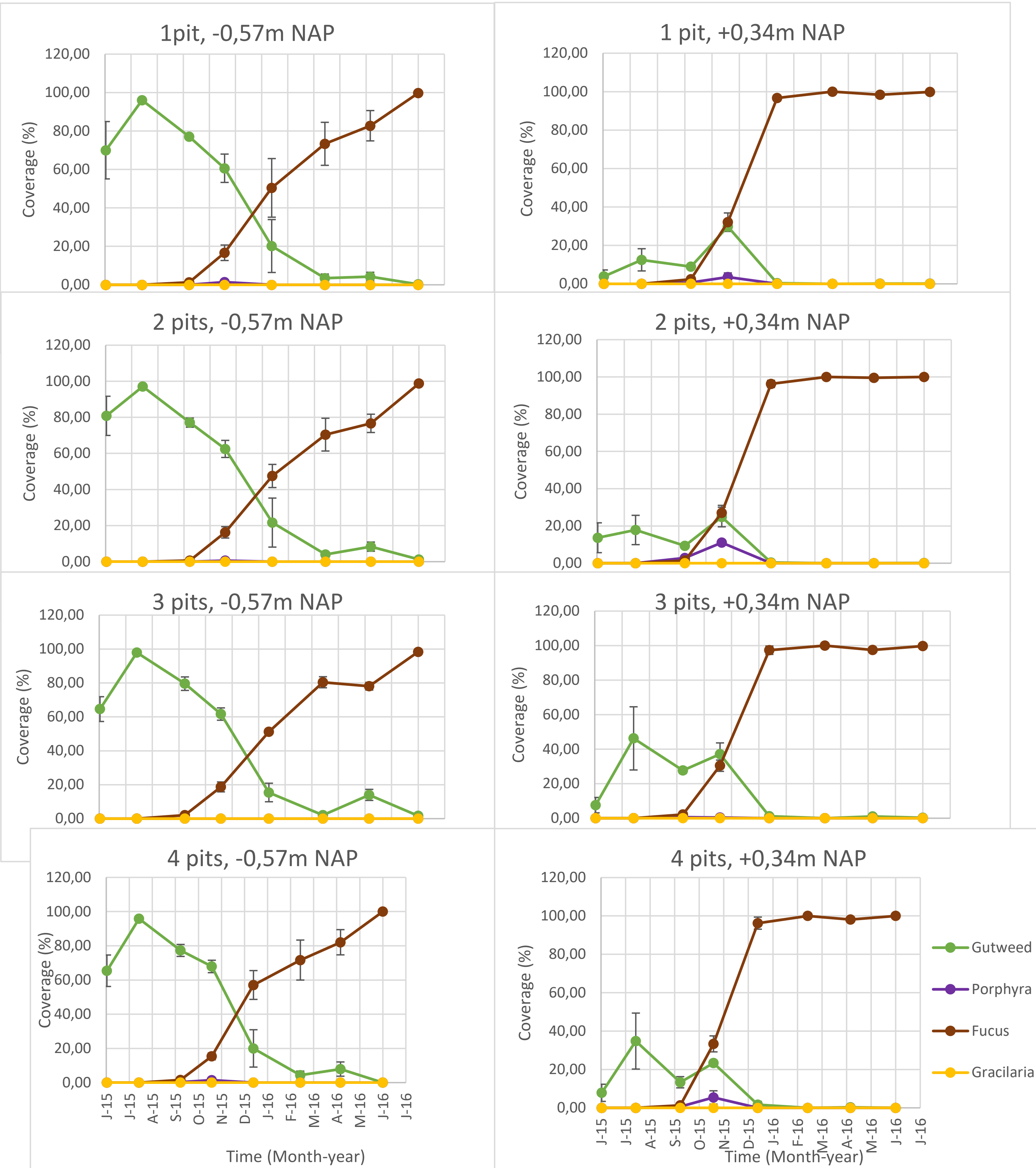
Appendix 1. The development in seaweed cover for the different species groups on the four different BfN designs in the first 12 months after placement at two different heights. The error bars show the standard error of the replicate sections (n=3). Ectocarpaceae are not shown – data to be processed.



Appendix 2. Photos of the different dike sections. Please note that the part of the pictures include less block rows. This is because for part of the sections some rows were used for a disturbance treatment (see Fig. 18) and are excluded from these pictures and from the picture analysis.

April 2016

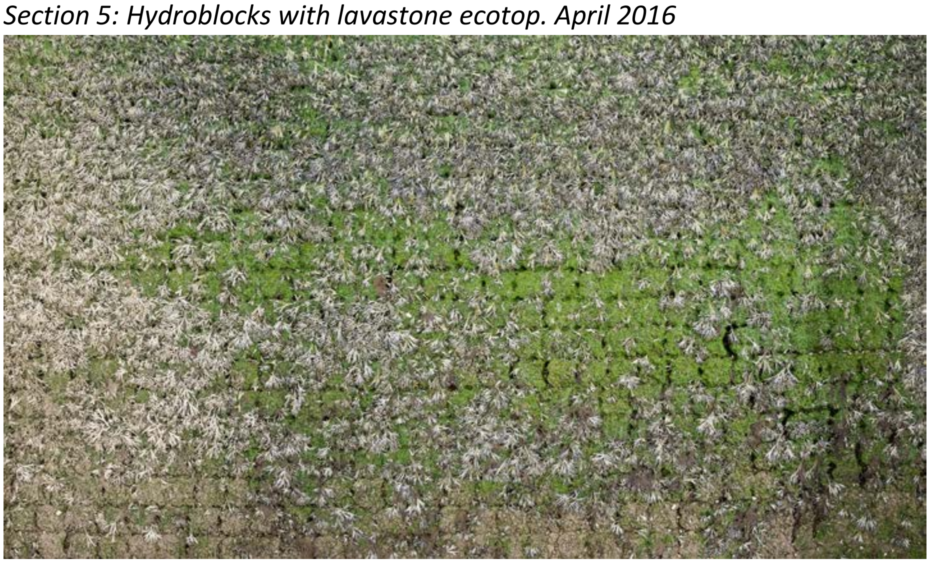
Section 1: Hillblocks. Left part: standard; right part: porous. April 2016

Section 2: Hydroblocks with lavastone ecotop. April 2016

Section 3: Standard hydroblocks. April 2016

Section 4: Hydroblocks with BfN-design. April 2016

Section 5: Hydroblocks with lavastone ecotop. April 2016



Section 6: Standard hydroblocks. April 2016

Section 7: Hydroblocks with BfN-design. April 2016

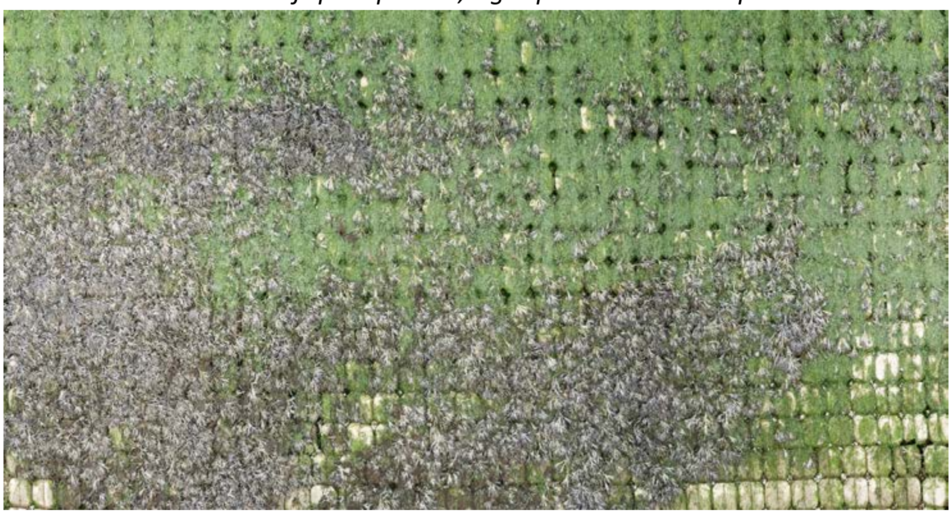
Section 8: Hydroblocks with lavastone ecotop. April 2016

Section 9: Standard hydroblocks. April 2016

Section 10: Hydroblocks with BfN-design. April 2016

Section 11: Hydroblocks with lavastone ecotop. April 2016

Section 12: Hillblocks. Left part:porous; right part: standard. April 2016



September 2016

Section 1: Hillblocks. Left part:standard; right part: porous. September 2016

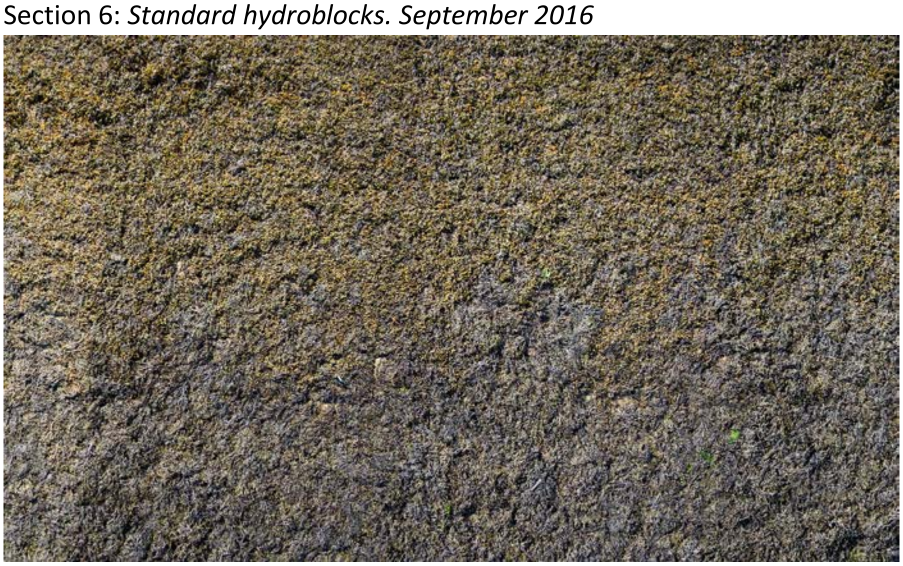
Section 2: *Hydroblocks with lavastone ecotop. September 2016*

Section 3: *Standard hydroblocks. September 2016*

Section 4: *Hydroblocks with BfN-design. September 2016*

Section 5: *Hydroblocks with lavastone ecotop. September 2016*

Section 6: *Standard hydroblocks. September 2016*



Section 7: *Hydroblocks with BfN-design. September 2016*

Section 8: *Hydroblocks with lavastone ecotop. September 2016*

Section 9: *Standard hydroblocks. September 2016*

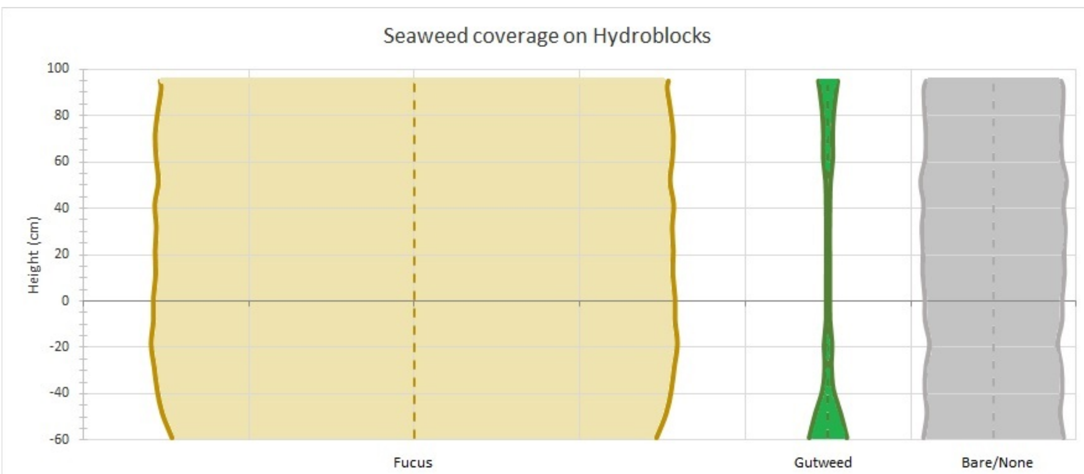
Section 10: *Hydroblocks with BfN-design. September 2016*

Section 11: *Hydroblocks with lavastone ecotop. September 2016*

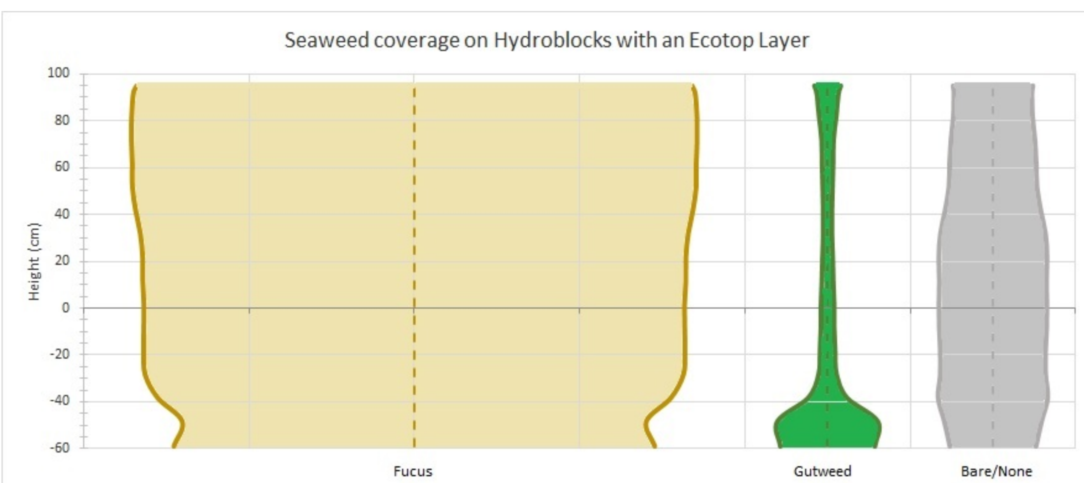
Section 12: *Hillblocks. Left part:porous; right part: standard. September 2016*

Appendix 3. Vertical kite graphs of seaweed coverage in September 2016 in percentages. a. standard hydroblocks; b. hydroblocks with ecotop layer; c. hydroblocks with the BfN structure; d.standard Hillblocks; e. porous Hillblocks. (BfN&Hydroblocks: n=3, Ecotop: n=4, Standard&Porous Hillblocks: n=1). Please note that here the extra section of hydroblocks with an ecotop layer (section nr 2 on Fig. 6) was included in the analysis.

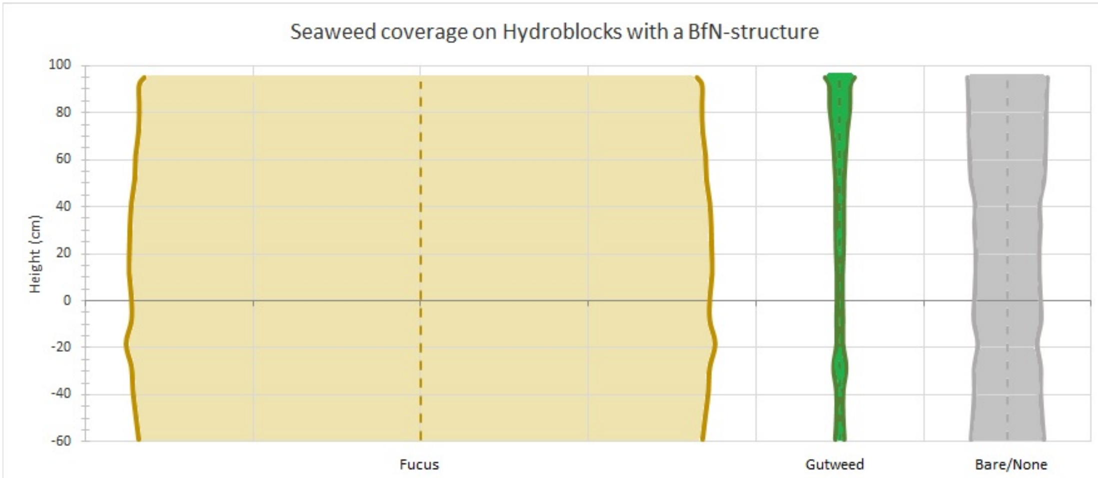
a.



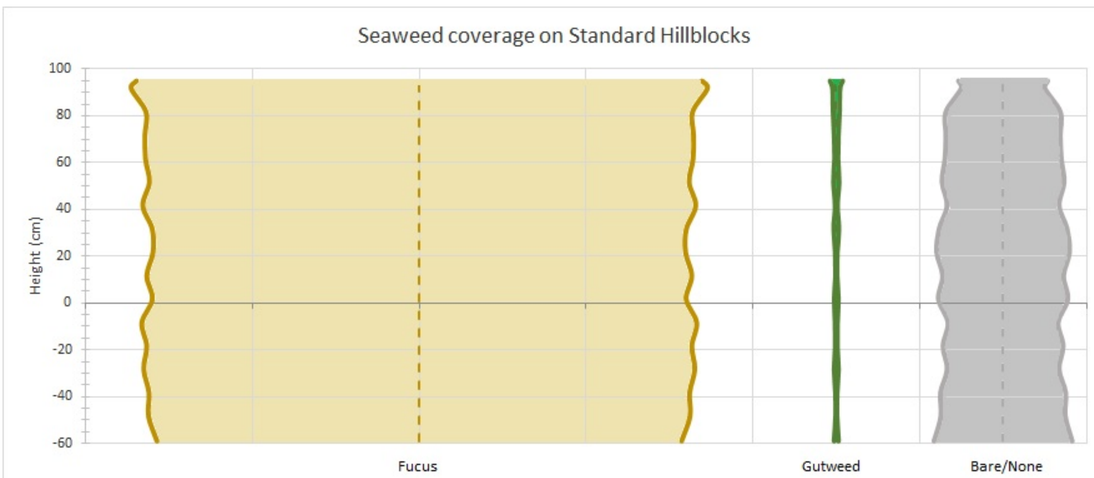
b.



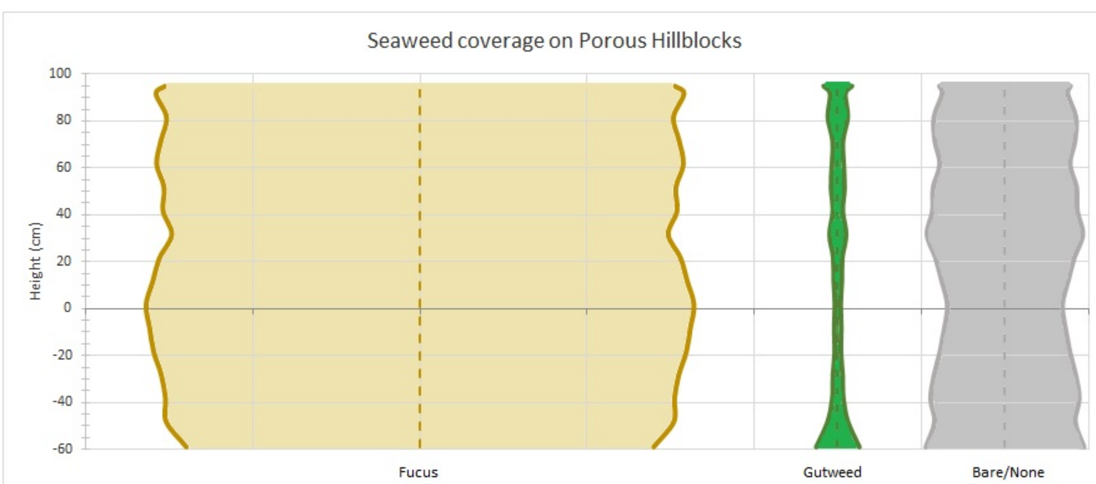
c.


Seaweed coverage on Hydroblocks with a BfN-structure
100
80
60
40
20
0
-20
-40
-60
Height (cm)
Fucus
Gutweed
Bare/None

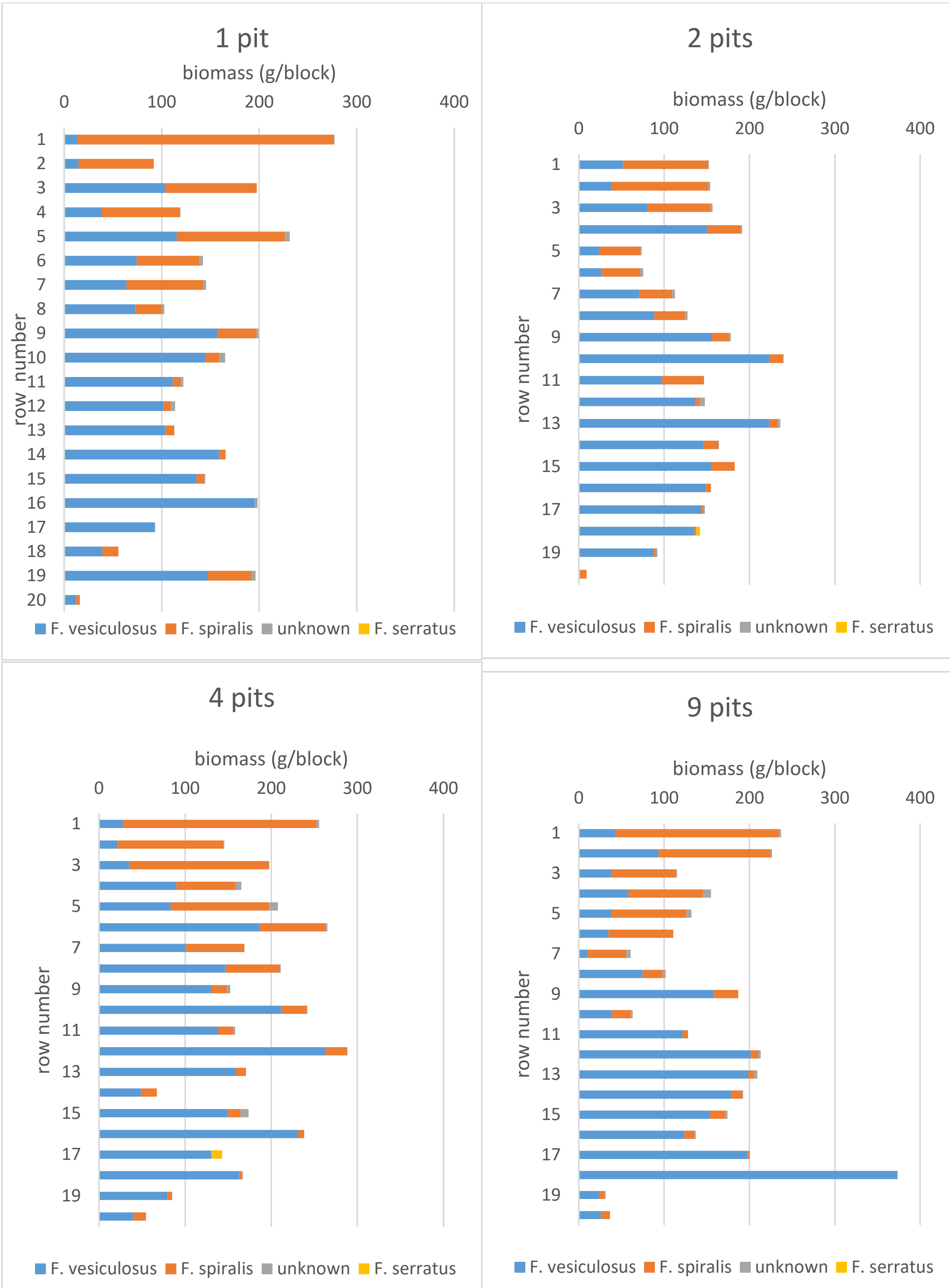
d.


Seaweed coverage on Standard Hillblocks
100
80
60
40
20
0
-20
-40
-60
Height (cm)
Fucus
Gutweed
Bare/None

e.


Seaweed coverage on Porous Hillblocks
100
80
60
40
20
0
-20
-40
-60
Height (cm)
Fucus
Gutweed
Bare/None

Appendix 4. Biomass of the different *Fucus* species on the different BfN designs at t= 16/17 months (n=3).



Appendix 5. Description of Dutch experimental case studies with new designs of revetment blocks

In the Netherlands, several experiments have been carried out to investigate the colonization of new 2D-structures of revetments by biota. The results of these experiments are summarized below. We focused on the relationship between the material used and inundation time and wave exposure. Many of the new types of revetments have not been experimentally tested nor has their effectiveness been monitored in the field. In A5.6, knowledge on these revetments is synthesized.

A5.1 Eco-concrete andsulfur-concrete (IJmuiden)

Key source: Paalvast (2011)

Experimental setup

The effect of surface structure on the colonization of seaweeds and macrofauna was studied by placing concrete plates with six different surface structures on a breakwater near IJmuiden (Havenhoofd IJmuiden). Horizontal and vertical plates were applied, each with their own structural pattern (Figure A5-1). To study effects of inundation time and exposure, the plates are installed high and low in the intertidal and at a sheltered and an exposed location. At the exposed location, it was impossible to install plates at the low intertidal due to waves and currents. At this location, the lowest plates are placed at the mid intertidal. Figure A5-2 is a schematic overview of the experimental setup. The experiment used two materials to create the plates: Eco-concrete and sulfur concrete. As material had no significant effect on colonization rates of seaweeds and mussels, the material is not further considered in this summary.

Figure A5-1. Left: a concrete plate for horizontal installation. Right: a concrete plate for vertical installation. The horizontal plates have one smooth surface, one surface is roughened at a mm scale and four surfaces are roughened at a cm - dm scale. The vertical plates have one smooth surface, two surfaces roughened at a mm scale and three surfaces roughened at a cm - dm scale. Both horizontal and vertical plates have one surface with pits with varying widths and two surfaces with crevices of varying widths. Crevices at the vertical plates are horizontally and vertically orientated.

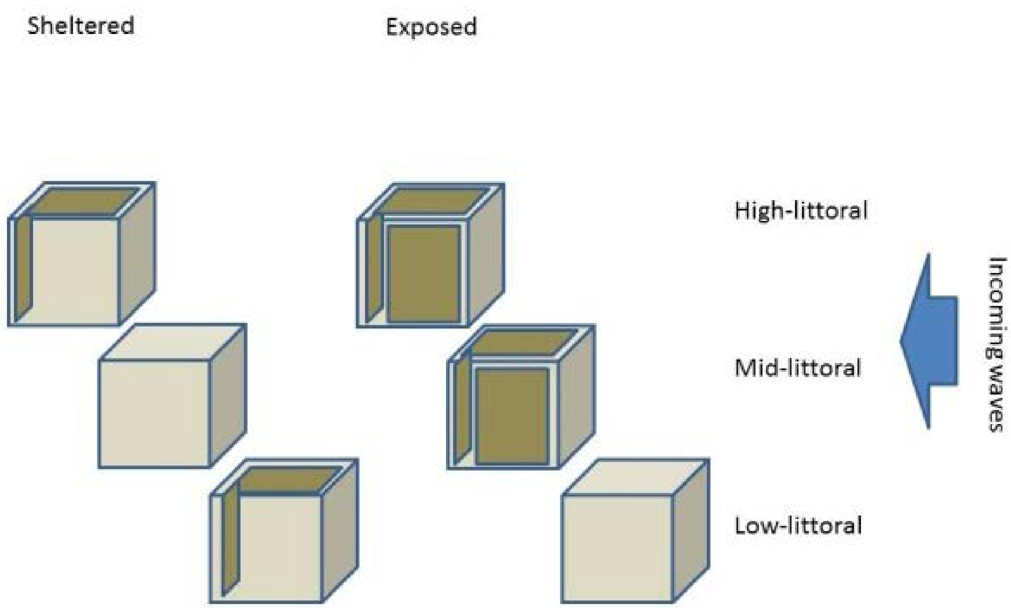


Figure A5-2. Schematic overview of the experimental setup at a breakwater near Ijmuiden.

<u>Colonization by Seaweeds</u>

Generally, the shorter the inundation time the less seaweed.

<u>Sheltered location</u>

Colonization by fast growing gutweeds is enhanced by the roughened surfaces on the concrete plates. However, this head start in comparison to smooth surfaces, disappears within months. Structure also has a positive effect on colonization by Bladderwrack (NL Blaaswier, Latin *Fucus vesiculosus*), but after three years, there is no difference between seaweed densities on smooth and structured surfaces. High in the intertidal, horizontal and vertical plates have equal seaweed coverage. At this position, the inundation time and wave exposure are probably more important than the slope of the substrate. Low in the intertidal, Bladderwrack grows best, especially on sheltered locations and on a horizontal substrate with structure. The settlement of mussel seed can hamper seaweed growth in the lower intertidal.

<u>Exposed location</u>

No seaweed was found on the exposed location between the mid intertidal and the low intertidal. This is probably due to the high wave exposure and strong currents in combination with a high coverage of barnacles (zeepokken). The seaweeds were removed or kept short by scraping over numerous barnacles. High in the intertidal, seaweed coverage highly fluctuates through the year. Surface structure improves the colonization of fast growing green sea weeds. After several months the difference in seaweed coverage between structured and smooth surfaces had disappeared. Bladderwrack only occurs here in very small quantities. No difference in seaweed coverage can be found between horizontal and vertical plates.

Colonization by mussels

<u>Sheltered location</u>

At the sheltered location mussel seed settled on the roughened surfaces of the concrete plates. Highest densities were found within horizontal crevices. Part of the settled mussel seed remained there and grew to large mussels over the years. High in the intertidal the vertical plates had a significantly higher density of mussels than horizontal ones. This is probably due to heat stress caused by direct sunlight, not inundation time. Low in the intertidal mussel densities on horizontal and vertical plates were equal.

Exposed location

At the exposed location mussel seed also settled on the roughened surfaces of the concrete plates. Furthermore, highest densities were found within horizontal crevices. However, due to waves and currents the mussel seed remained small and disappeared over the year. Plates were recolonized every year. After the second year, this re-colonization also occured in between barnacles growing on the finer structures on the concrete plates. Similar to the sheltered location, vertical plates high in the intertidal had significant higher mussel densities than horizontal plates, while no difference was found low in the intertidal.

Colonization by other macrofauna

Barnacles (Zeepokken (*Elminius modestus*))

Barnacles developed on all plates and all structures. However, at first higher densities were observed around roughened surfaces. Vertical plates showed higher densities, probably due to sunlight and dehydration. Barnacle density decreased where mussels seed had settled.

Periwinkles (Ruwe alikruik (*Littorina saxatilis*) and Kleine alikruik (*Littorina neritoides*))

Periwinkles mainly occured on vertical plates at both sheltered and exposed locations. At low tide, they used holes, crevices and barnacles for shelter. At sheltered locations, large individuals of *Littorina saxatilis* were dominant. At exposed locations, small individuals of the Periwinkle (*Littorina neritoides*) were dominant.

Pacific oyster (Japanse oester (*Magallana gigas)*)

Pacific oysters only settled on the smooth surface of one plate. The location of this plate was the low intertidal of the sheltered location.

Amphipoda and mosquito larvae

At both sheltered and exposed locations Amphipoda (vlokreeftjes) and mosquito larvae (dansmug) were found between the seaweed. Amphipoda are an important bulk food for fish and mosquito larvae are important food for Sandpipers and Turnstones (strand- en steenlopers) (Boudewijn en Meijer, 2007).

A5.2 C-fix-plates (IJmuiden)

- after Paalvast 2011

Experimental setup

Only one type of C-fix plates was used in these experiments (Figure A5-3). These plates were covered with a layer of fine gravel. Four plates (two horizontal and two vertical) were installed at a sheltered site high in the intertidal on the breakwater near IJmuiden (Havenhoofd IJmuiden). On C-fix plate horizontal high in the intertidal disappeared during the monitoring period.

Figure A5-3. A C-fix plate just installed at the breakwater near Ijmuiden.

Results

Seaweeds

In Table A5-1 shows the simplified picture of the succession of seaweeds on all C-fix plates combined. *Gayralia oxysperma* soon covered the C-fix plates after installation and remained dominant over the whole monitoring period. Bladderwrack appeared for the first time in the winter of 2009 and 2010 and continued to grow during the summer of 2010. The only difference between the horizontal and vertical C-fix plates is that in winter the sum of the abundances of green-, red- and brown seaweed was significantly lower on the horizontal plate.

Macrofauna

Periwinkle abundance was too low to draw conclusions. In September 2009 mussel seed covered the horizontal C-fix plate for 60%, but it disappeared quickly. C-fix plates were overgrown by barnacles, horizontal and vertical plates showed equal densities..

Table A5-1. Seaweed species on C-fix plates during the monitoring period. Each letter represents one act of taking inventory. - = absent, R = rare, P = present, S = subdominant, D = dominant.

	Dutch name	Summer 2008	Winter 2008-2009	Summer 2009	Winter 2009-2010	Summer 2010
Blidingia minima	-	--	-PPR	-DDS	S	SD-S
Ulva intestinalis	Zeesla	--	DSS-	----	-	-D--
Gayralia oxysperma	-	DD	DDDD	DDDD	D	DDDD
Porphyra umbilicalis	Navelwier	--	PPSP	SSSS	P	SSPP
Ceramium rubrum	Hoorntjeswier	--	----	----	P	SP-P
Fucus vesiculosus	Blaaswier	--	----	---P	S	SSDS

A5.3 Eco-X-Blocks (IJmuiden)

- after Paalvast 2011

Experimental setup

The eco-X-blocks (Figure A5-4) were placed at the sheltered location at a breakwater near IJmuiden (Havenhoofd IJmuiden). Half of the X-blocks surfaces were roughened, but also the smooth sides contained holes and crevices where water would remain at low tide. No difference was found in seaweed growth or composition, or macrofauna composition or density between the smooth and roughened surfaces of the X-blocks.

Figure A5-4. The eco-X-block with one roughened side and one side with a smooth surface.

Results

Seaweed

Table A5-2 shows the succession of seaweed species on the X-blocks. The highest seaweed densities were observed in the mid intertidal. This can be explained by the high exposure low in the intertidal and the short inundation time high in the intertidal. Bladderwrack was first observed at the end of summer 2009. After three years, it became the subdominant seaweed at sheltered places on the X-blocks in the mid intertidal.

Macrofauna

Three species of were observed on the X-blocks: 1) barnacles growing on all X-blocks low and high in the intertidal, 2) mussels, growing low in the intertidal and 3) a few Periwinkles. Paalvast et al. 2011 suggest that the three-dimensional structure of the X-blocks provide more diverse habitats than conventional concrete blocks. The unique and varied circumstances underneath the X-blocks provide a habitat for anemones, tunicates and sponges.

Table A5-2. Seaweed species on X-blocks during the monitoring period. Each letter represents one act of taking inventory. - = absent, R = rare, P = present, S = subdominant, D = dominant.

	Dutch name	Summer 2008	Winter 2008-2009	Summer 2009	Winter 2009-2010	Summer 2010
Ulothrix flacca	-	SP--	----	----	----	----
Blidingia minima	-	XDDD	DDDD	DDDD	SD	DSSS
Ulva intestinalis	Zeesla	DDDD	DDSD	DDDS	SD	DDDS
Gayralia oxysperma	-	---S	SSS-	PPPS	DS	ZPDD
Porphyra umbilicalis	Navelwier	----	RPPP	PPSR	--	RPR-
Bangia atropurpurea	-	----	----	---P	PP	P---
Fucus vesiculosus	Blaaswier	----	----	---P	AS	SSSS

A5.4 Elastocoast (Zuidbout and Petten)

Key sources: Lock/Arcadis (2008), Lock (2009)

Introduction

Elastocoast is a coastal protection material of Elastogran, BASF made from rocks with polyurethane. From a civil engineering point of view, the major advantage of Elastocoast is that it reduces the wave run up and the wave impact (Gu D.,2007). Because of these hydraulic properties a dike can be lower and still meet the safety standards, saving on building costs. Maintenance costs area also low because elastocoast is that is hardly susceptible to erosion (Sluijsmans R.W, 2009). Elastocoast can have different properties depending on the type of stone that is glued together.

From an ecological point of view a potential advantage of the rough structure of Elastocoast is that it may facilitate adhesion by seaweeds and provides shelter for small macrofauna. On the negative side, the reduction in wave run up may reduce the zone in which seaweeds and other marine macrofauna is able to survive. In the Netherlands, Elastocoast has been tested on four locations: Harlingen, Petten, Zuidbout and Bathpolder. Below, we focus on Zuidbout and Petten where experiments have been set up to test different types of Elastocoast under different environmental conditions.

Experimental setup

The experiments in Zuidbout and Petten were initiated in autumn 2007.

At Zuidbout approx. 500m2 of surface was covered with Elastocoast. Three different forms were tested:
- Granite fixed with poyurethane;
- Granite fixed with polyurethane and toped with sand;
- Granite fixed with polyurethane and topped with Vilvoordse limestone.

Sand and Vilvoordse limestone were added during the drying of the polyurethane.
In addition, three different thicknesses were tested varying from 10 to 30 cm to test what thickness was required to withstand strong wave action during the storm season. For comparison of species colonization, part of the orginial dike surface (covered with Vilvoordse limestone) was cleaned: all organisms were removed. On all created surfaces areas of 0.5x0.5 m were marked high and low in the intertidal to monitor the recovery of the colonization by species after the application of Elastocoast (See Fig. A5-5)

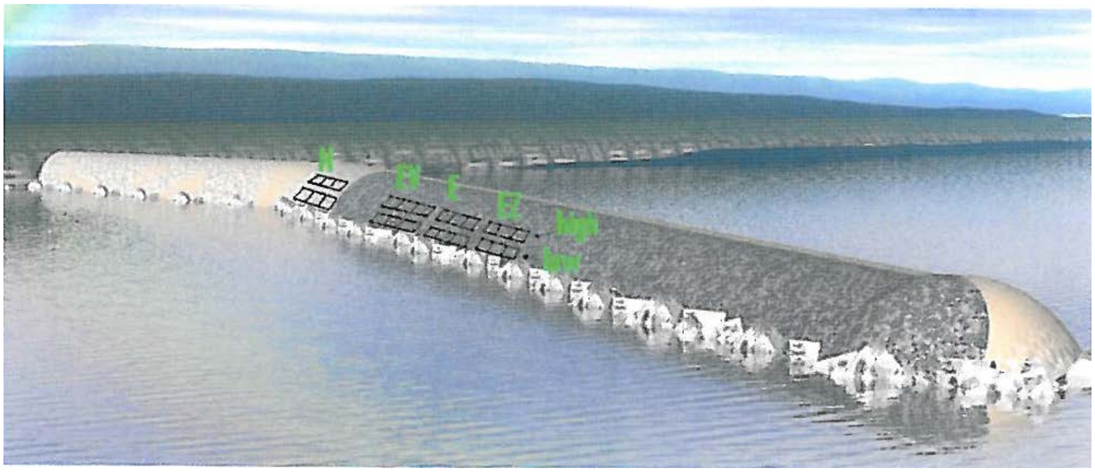


Fig. A5-5. Elastocoast experiment at Zuidbout. E: granite fixed with poyurethane ; EZ: granite fixed with polyurethane and topped with sand; EV: granite fixed with polyurethane and topped with Vilvoordse limestone. N: Vilvoordse limestone.

At Petten, 350 m^2 was covered with Elastocoast without topping, on a flat surface at -0,30 NAP. Eighteen areas were marked to examine differences in ecology related to differences in wave action etc. (See Fig A5-6).

Fig A5-6. Elastocoast experiment at Petten.

Both experiments (Zuidbout and Petten) were performed at exposed locations. No comparison was made with sheltered locations. Both areas were visited for monitoring from September 2007 (T0) to March 2008 (T1) and in April 2009 (T2).

Results

Colonization by Seaweeds

At **Zuidbout** at T1, *Blidingia minima* was the dominant species, and occurred in large patches. There was a strong zonation of these algae, both horizontally and vertically. Some patches were occupied with *Fucus spiralis* and *Enteromorpha compressa*. For T1 a comparison between the total seaweed coverage has been made between the high and low intertidal for the different treatments (see table A5-3).

Table A5-3. Total seaweed cover at Zuidbout at T1. Please note that total coverage was below 1% at all locations, since these measurements were performed just 25 weeks after the application of the test substrates.

Treatment	Low intertidal	High intertidal
Granite - No topping	+	--
Granite - Topped with sand	+	-
Granite - Topped with Vilvoordse limestone	+	0
Vilvoordse limestone	+	++

At T2 there was still strong vertical and horizontal zonation on the part of the dike which had been refurbished with Elastocoast. Seen from the top, the vertical zonation was marked by *Blidingia minima* and *Fucus spiralis*, which formed a very sharp boundary with the zone below (which was occupied by many snails and barnacles). Horizontally, there were areas which show the vertical zonation, and areas which hardly had any seaweed at all. Places where Elastocoast was covered by sand or Vilvoordse limestone showed a better recovery of seaweeds. These toppings make the surface of Elastocoast less smooth, creating better circumstances for seaweeds to attach. Seaweed fully recovered on the original dike with the Vilvoordse limestone. Where the Elastocoast covered with Vilvoordse limestone next to this area however, the seaweed community did not recover.

On the Northern part towards land the slope of the dike was steeper. This may have resulted in higher (wave) dynamics which in turn may have resulted in less favorable circumstances for algal attachment and survival. Indeed, especially on the most southern part of the dike biota recovered. The effect of wave dynamics may also explain the lack of algal growth on areas where the Elastocoast layer changes in thickness. Possibly waves are ‘bounced back’ at these areas, creating more difficult circumstances for algae to attach on the layer.

At **Petten** on T1 the Elastocoast layer was almost fully covered with Purple laver (*Porphyra Umbilicalis*), and Gutweed (*Blidingia minima*), which seemed to dominate in different areas. However, there were also areas with little growth. On T2 patches of *Blidingia minima* were present, and few places were covered with *Fucus Spiralis*. Purple laver was no longer present. Algal coverage was still quite zoned, the areas directed towards the sun being covered the most.

Colonization by mussels

At Zuidbout the abundance of mussels was not observed for either T1 or T2. However, at Petten on T2 the dike was mainly covered with mussels, which formed a dense layer on Elastocoast. Some areas were not covered with mussels and formed a distinct gap in which the Elastocoast layer was clearly visible. Taking the density of the mussels into consideration, it is quite likely that mussels were also present at Zuidbout, but had disappeared due to some kind of disturbance. Erosion of the polyurethane was also visible in these gaps.

Colonization by other macrofauna and birds

At Zuidbout on T1 and T2 periwinkles (*Littorina spp*.) were found all over the lower part of the Elastocoast layer. At T2 many barnacles also attached to the Elastocoast layers in the low intertidal.

At Petten, while no barnacles were reported for T1, for T2 numerous barnacles were observed in the gaps between the mussels and between algae. Isopods were found in the pores in the Elastocoast, burrowing in sand and parts of shells. It is likely that more organisms occupied the pores.

No data are available for foraging birds at Zuidbout. At Petten for T1 the common oystercatcher (*Haematopus ostralegus*) and the seagull (*Larus spp*.) were reported to forage on the dike.

Conclusions

At Zuidbout differences in wave dynamics possibly caused part of the horizontal zonation in algal coverage. To test this hypothesis, further research is necessary. To get the full picture of algal and macrofaunal colonization on Elastocoast further monitoring is necessary because full recovery of the biological community might take as long as ten years.

A5.5 C-star-blocks (Ellewoutsdijk)

– after De Kluijver and Vanagt (2010)

Experimental setup

C-star blocks are a new type of cover stones that can be fitted with 4 eco-tops. In 2007 Grontmij en AquaSense started an experiment to see if C-star blocks could enhance nature values on revetments. The experiment on the relatively sheltered dike near the harbor of Ellewoutsdijk contained 5 treatments: Standard C-star blocks (control); row A, C-star block with an eco-top of large lava stones; row B, C-star blocks with a small pool (about 10 cm); row C, C-star blocks with a small pool and eco-top of small lava stones and row D, C-star blocks with an eco-top of small lava stones (see Figure A5-7). Between 2008 and 2010, the colonization of seaweeds and macrofauna was monitored.

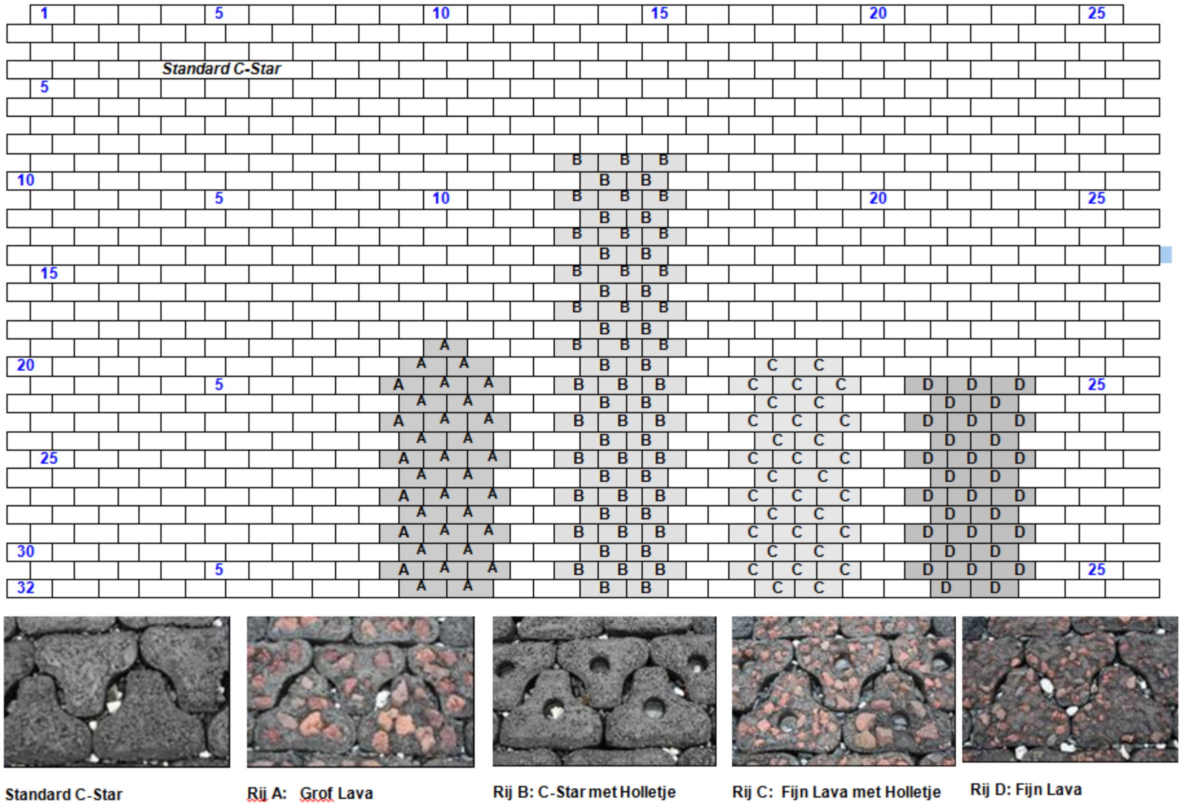


Figure A5-7. Schematic overview of the five C-start block treatments high in the intertidal at Ellewoutsdijk.

Results

Seaweed

In 2008 there were two typical pioneer seaweed species present *Enteromorpha* spec. and *Porphyra cf leucosticta* (Darmwier en Purperwier). In 2009 the pioneer seaweed community developed. *Porphyra cf leucosticte* is replaced by Bladderwrack (Blaaswier). On the C-star blocks (control) the cover of Bladder wrack remained stable or declined. On the C-star blocks with lava eco-top, Bladder Wrack cover increased further and remained as high as 90% up until October.

Macrofauna

The total number of seaweed and macrofauna species increased from 3 (see control) to 6 in 2009 (Table A5-4).

Table A5-4. Occurence of species on normal C-star blocks and C-star blocks with eco-top in 2009

Scientific name	Dutch name	C-star	Grof lava	C-sta-hol	Fijn lava-hol	Fijn lava
Enteromorpha spec.	Darmwier	X	X	X	X	X
Ulva spec.	Zeesla	X	X	X	X	X
Littorina saxatilis	Ruwe alikruik	X	X	X	X	X
Fucus vesiculosus	Blaaswier	X	X	X	X	X

Anurida maritima	Springstaart	X	X	X	X	
Littorina obtusata	Stompe alikruik		X			
Gammaridea	Gammariden		X			
Idotea spec.	Zeepissenbedden			X		X

A5.6 Other materials

Key sources: Postma (2010); IMARES monitoring reports; student report Gomes&Bouwmeester (2013)

Next to the materials that have been described above many different types of combinations of ecotops and more traditional building materials have been applied in the SW Delta. On hydroblocks alone at least five different ecotops have been used: lava; open colloidal concrete; basalt split; limestone; 'kuil' ecotop. Basalton is also used with several different ecotops.

In the Netherlands, the hydroblocks and basalton with limestone ecotop have been tested next to more traditional revetments at Tholen (Experiment Dijktuin II). After five years, *Fucus spiralis* and *Fucus vesiculosus* and *Actinia equina* were growing well on basalton with ecotop; *Enteromorpha spp*. was not present (Meijer, 2003). On the hydroblocks with ecotop Pacific Oysters dominate. Seaweeds do not grow well on this surface (Meijer, 2003).

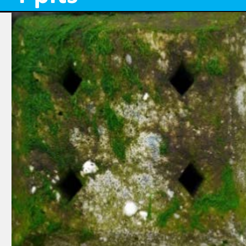
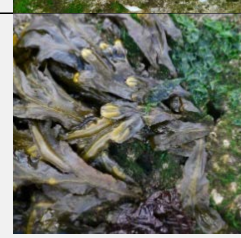
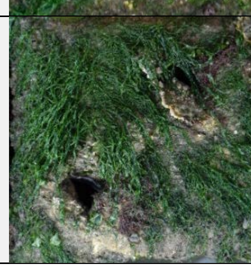
Additional information on the colonization by biota of these and other materials can be derived from field observations by monitoring programs and student assignments. The monitoring effort on new revetments in the Eastern Scheldt with ecotop has been very limited. Monitoring reports of IMARES include some transects on locations where new materials have been applied. A monitoring report is being prepared for plant and seaweed growth on all dike sections but this report will not be available until spring 2014 (Peter Meininger, pers. comm.).

For the Western Scheldt, data is available from a large inventarisation of plants and seaweeds (Meijer, 2011) and a report by HZ students (Gomes&Bouwmeester 2013). Data are too limited to draw conclusions.

Appendix 6. Seaweed growth on different types of BfN blocks at Yerseke. Summary of results.

In the context of the RAAK Building for Nature project (https://www.zeeweringenwiki.nl/wiki/index.php/RAAK-PRO-project_Building_for_Nature_(BfN)_VN) different types of concrete blocks with diamond-shaped pits (varying in proportions and number) were developed in order to provide refuge for invertebrates and a more complex surface so seaweeds can attach easily. The pits also influence the moisture retention of the blocks which may also facilitate seaweed growth. The blocks were placed in the Eastern Scheldt at Yerseke on a frame at three levels. The seaweed development was followed for over two years. Table A6-1 gives an impression of the seaweed growth on the blocks after 14 months. At the high and the middle level no major differences were observed between the blocks with and without pits. At the lowest level the pits stimulated the growth of leaf-like *Ulva* sp. and the red algae *Graciliaria* sp. and *Caulacanthus okamurae* (Fig. A6-1). The growth was stimulated most by the larger pits. These pits also enhanced settlement and growth of the Pacific Oyster (*Magallana gigas*).

Table A6-1. Development of seaweed and fauna on the different block types at t=14 months.

	1 pit	2 pits	4 pits	9 pits	standard
+1,85 m NAP					
+0,70 m NAP					
-0,55 m NAP					

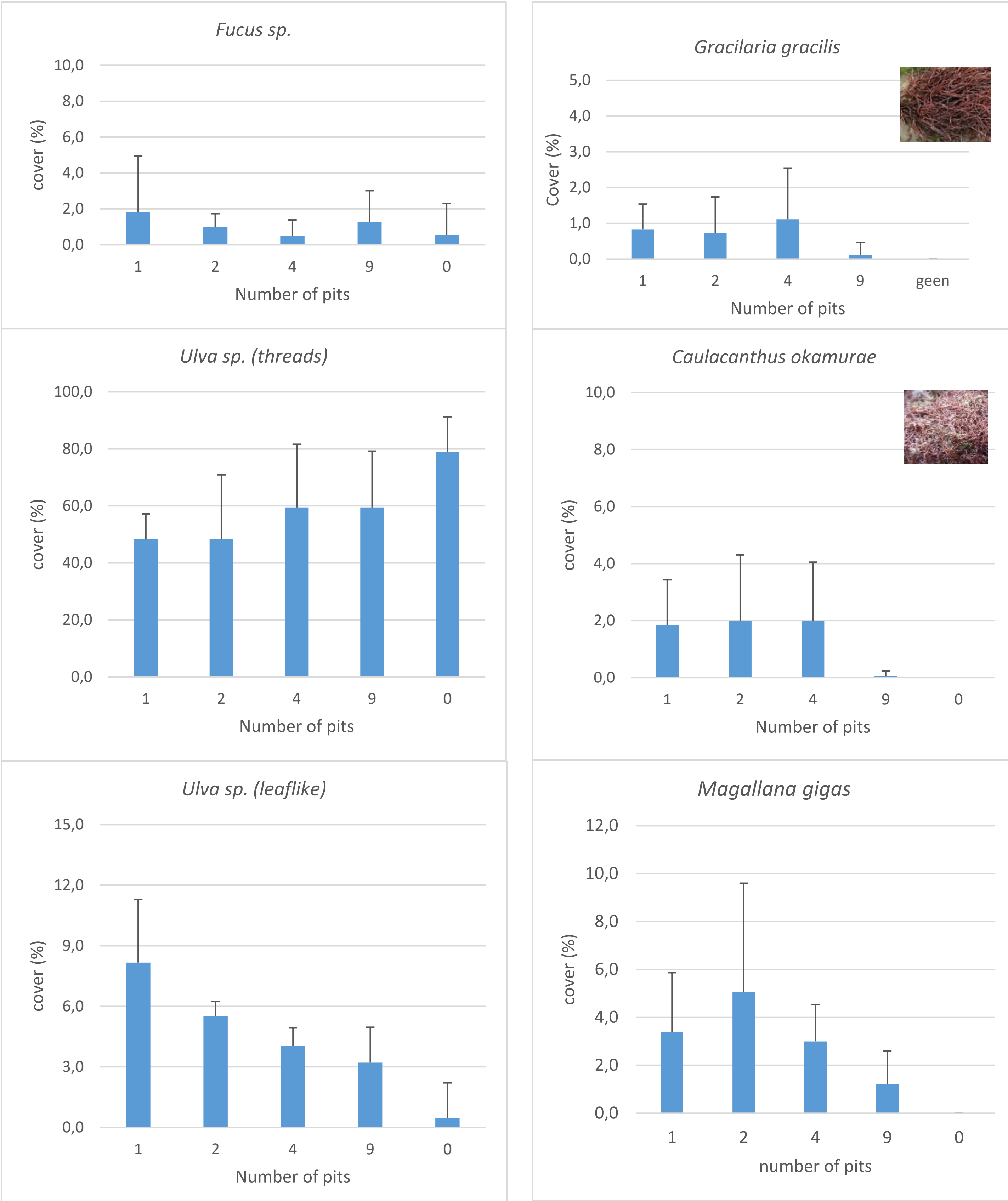


Figure A6-1. The %cover of different seaweed species and Pacific Oysters on the different BfN block types at t=14 months at the lowest level, -0,55m NAP (n=10).