Designing research experiments for the living breakwater landscape *the Banjaard*

ACT Group 3133
Living breakwater landscape the Banjaard

Alba Rodríguez Boltes, Sebastiaan 't Hoen, Rijn van Kampen, Marit Schapendonk, Evert Sprockel, Thom Verreijt, Vivien Vos.

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Contact information

Commissioner: Shared Concepts, represented by Idco Duijnhouwer & Renée Bron-Slis

Idco Duijnhouwer	t: +31 6 46671968	e: *iduijnhouwer@xs4all.nl*
Renee Bron-Slis	t: +31 6 13436228	e: *renee@sharedconcepts.nl*

ACT Group 3133

Sebastiaan 't Hoen (secretary)	t: +31 6 58948758	e: *sebastiaan.thoen@wur.nl*

Source of Cover page image: Aerial image of Blakeney Point, Great Britain. Illustrative image to show the potential of the Banjaard project in the future (BBC, 2015)

Preface

We would like to present our consultancy report commissioned by Shared Concepts. We were asked by Shared Concepts to investigate what experiments could be performed on a newly made sandbank in front of the Dutch coast using sand nourishments. Within our investigation, we considered coastal protection, seagriculture, and biodiversity enhancement. To achieve our goal, the report contains an in-depth overview of several biobuilders and seagriculture practices, further recommendations, and a roadmap for future actions.

Our consultancy team comprises seven people from different complementary master programs that work together for the course Academic consultancy training from Wageningen University and Research to provide a fitting consult for Shared Concepts. Our expertise mainly lies in the natural- and environmental sciences, and as a team, our qualities lie in clear communication, structured and detailed work, large brainstorming capacity, and the ability to produce a wide variety of high-quality end products. Our consultancy team's expertise is shaped by the individual skills and interests of the members.

This report contains many hours of research, a literature review, and conversations with various experts. Therefore, we would like to express our gratitude to our coach, Jettie Van den Houdt for the personal guidance during the process, our academic consultant, Tinka Murk for the advice on the academic quality of the report, and the various experts who generously shared their time, expertise, and insights to improve the quality of this study. Furthermore, we would like to thank Idco Duijnhouwer and Renée Bron-Slis from our commissioner Shared Concepts for providing us the opportunity to work on this project and their openness in sharing relevant information with us. We are confident that the insights in this report can inspire more students and stakeholders to work with nature-based solutions and to see the benefits of this project and how it could contribute to improving the future Voordelta.

We hope that this report will provide an incentive to take further action in investigating more nature-based solutions and to consider their positive impact on coastal environments and especially for the Banjaard to become a successful pilot project for the coastal protection of the coast of Zeeland.

Summary

Due to climate change, a sea level rise of one meter is expected by 2100. The coastal protection in the Voordelta needs to improve to ensure future safety. Because rigid coastal protection is insufficient, attention has shifted to natural protection by restoring former sand banks like the Banjaard. These have disappeared due to coastal erosion and sediment supply deficit. Restoring the Banjaard via a reinforced suppletion at the location of the former Banjaard as well as further development using a Building with Nature approach provides new opportunities for coastal protection. The purpose of this project, which is part of the Banjaard pilot and commissioned by the initiator Shared Concepts, was to design and propose feasible experiments. These experiments will be designed to increment the chances of success of the Banjaard regarding coastal protection, biodiversity enhancement and climate sustainability, while simultaneously creating new opportunities for sustainable food supply and societal value in several predetermined zones. This report will have more emphasis on the ecological aspect of the experiments than on the societal opportunities of the pilot.

The first three research objectives about increasing landscape-scale biodiversity on the island, suitable biobuilders with associated biodiversity, and sustainable aquaculture, entailed literature research for different possibilities of which the latter two were evaluated using a Multiple Criteria Decision Analysis (MCDA). Afterwards, the final three objectives were examined. To this end, the societal value of the Banjaard was explored, considering ecotourism and renewable energy. Next, the results from the MCDA were used to create a spatial plan, illustrated by using several suggestive zonation maps for the Banjaard, split up into proposed experiment zones and zones for habitat types. However, it is difficult to determine the settlement of different species and habitat development on the island, so the areas presented here are merely suggestive. Lastly, to make statements about the results from these experiments, monitoring indicators are suggested to use for a future monitoring program. In this report eleven zones are discussed for the Banjaard. In these zones experiments are monitored to look at wave attenuation, breakwater ability, sediment retention, biodiversity accumulation, biobuilder possibilities and different aquaculture practices.

In our advice we recommend creating a variability in habitat types using ecosystem engineers and pioneering species. After kickstarting these complex ecosystems with the help of man-made or hard structures, we recommend letting them evolve naturally. Furthermore, we advise to make use of a combination of several biobuilders, to use for experiments on their functioning in coastal protection. Next to that, it is recommended to implement solar panels for wave attenuation and renewable energy which adds to societal value. For seafood production, we recommend using integrated polyculture practices with vertical aquaculture methods that will minimize the harm to the ecosystem. In line with this, it is recommended to implement sea ranching rather than intensive aquaculture. Furthermore, we recommend a strategical placement of the combination of biobuilders and seagriculture practices, so they can support each other. Lastly, we advise to contact several expert parties and companies to gain more information about the most suitable methodology that can be used to kickstart different biobuilders and several suggested seagriculture practices and the facilitation of the man-made structures.

In addition to the advice on experiments and given indicators for a monitoring program, future studies are advised to make a hydromorphological model of the area around the island before and after the sand suppletion. Also, a stakeholder analysis is advised in which the already performed ideation session can be used as starting point. Lastly the legislation practices are advised to be identified, since the Banjaard is located in a Natura 2000 area and the water quality will be of importance for seagriculture.

Samenvatting

Door klimaatverandering wordt in 2100 een zeespiegelstijging van een meter verwacht. De kustbescherming in de Voordelta moet verbeteren om de veiligheid in de toekomst te waarborgen. Omdat harde kustbescherming onvoldoende is, is de aandacht verschoven naar natuurlijke bescherming door herstel van voormalige zandbanken zoals de Banjaard. Deze zandbanken zijn verdwenen door kusterosie en een tekort aan sedimentaanvoer. Het herstel van de Banjaard aan de hand van een zandsuppletie op de plek van de voormalige Banjaard en het door ontwikkelen met een Building with Nature aanpak biedt nieuwe kansen voor kustverdediging. Het doel van dit project, dat onderdeel is van de pilot de Banjaard en in opdracht is van initiatiefnemer Shared Concepts, was om haalbare experimenten te ontwerpen en te presenteren. Deze experimenten worden ontworpen om de kans van slagen van de Banjaard te vergoten op het gebied van kustbescherming, biodiversiteitsverbetering en klimaatduurzaamheid, terwijl ze tegelijkertijd nieuwe kansen bieden voor duurzame voedselvoorziening en maatschappelijke waarde in meerdere vooraf bepaalde zones. In dit rapport zal meer nadruk liggen op het ecologische aspect van de experimenten dan op de maatschappelijke kansen die de pilot kan brengen.

De eerste drie onderzoeksdoelen die gaan over het vergroten van de biodiversiteit op het eiland op landschapsschaal, over geschikte biobuilders en hun invloed op biodiversiteit en over duurzame aquacultuur, omvatten literatuuronderzoek voor de verschillende mogelijkheden waarvan de laatste twee zijn geëvalueerd met behulp van een Multiple Criteria Decision Analysis (MCDA). Daarna zijn de laatste drie onderzoeksdoelen behandeld. Hiervoor is gekeken naar de potentiële maatschappelijke waarde van de Banjaard, waarbij ecotoerisme en hernieuwbare energie zijn meegenomen. Vervolgens zijn de resultaten van de MCDA gebruikt om een ruimtelijk plan te maken. Dit plan is geïllustreerd aan de hand van suggestieve zoneringskaarten voor de Banjaard, opgesplitst in voorgestelde experimentzones en zones voor habitattypen. Het is echter moeilijk om de vestiging van verschillende soorten en de ontwikkeling van habitats op het eiland te bepalen, dus daarom zijn de gesuggereerde gebieden slechts suggestief. Om uitspraken te kunnen doen over de resultaten van de ontwikkelde experimenten worden er ten slotte monitoringsindicatoren voorgesteld om te gebruiken voor een toekomstig monitoringsprogramma. In dit rapport worden elf zones voor de Banjaard besproken. In deze zones worden experimenten uitgevoerd en gemonitord om te kijken naar golfdemping, golfbrekercapaciteit, sedimentretentie, biodiversiteit ontwikkeling, biobuilder mogelijkheden en verschillende aquacultuurpraktijken.

In ons advies bevelen we aan om met behulp van ecosystem engineers en pionier soorten een variatie in habitattypen te creëren. Na het kick starten van deze complexe ecosystemen met behulp van door de mens gemaakte of harde structuren, raden we aan de ecosystemen op natuurlijke wijze te laten evolueren. Verder adviseren wij om gebruik te maken van een combinatie van meerdere biobuilders, om hiermee te experimenteren naar hun bijdrage in kustbescherming. Daarnaast raden we aan om zonnepanelen te plaatsen voor golfdemping en duurzame energie, wat bijdraagt aan maatschappelijke waarde. Voor de productie van schelp- en schaaldieren raden we aan om geïntegreerde polyculture methoden te gebruiken met verticale aquacultuur, die de schade aan het ecosysteem tot een minimum beperken. Hieruit volgend wordt aanbevolen om waterlandbouw toe te passen in plaats van intensieve aquacultuur. Verder raden we aan om biobuilders en waterlandbouw mogelijkheden strategisch te plaatsen, zodat ze elkaar kunnen ondersteunen. Ten slotte raden we aan om contact op te nemen met verschillende deskundige partijen en bedrijven om meer informatie te krijgen over de meest geschikte manieren die kunnen worden gebruikt op het gebied van het kick starten van biobuilders, het kick starten van de verschillende waterlandbouw mogelijkheden en het faciliteren van onnatuurlijke structuren.

Naast de adviezen over experimenten en indicatoren voor een monitoringsprogramma, wordt geadviseerd om in vervolgonderzoek een hydromorfologisch model te maken van het gebied rond het eiland voor en na de zandsuppletie. Daarnaast wordt geadviseerd om een stakeholderanalyse uit te voeren, waarbij de reeds uitgevoerde interactieve brainstormsessie als uitgangspunt kan worden genomen. Ten slotte wordt geadviseerd de relevante wetgeving in kaart te brengen, aangezien de Banjaard in een Natura 2000 gebied ligt en de waterkwaliteit van belang zal zijn voor de waterlandbouw.

Resumen

Debido al cambio climático se espera que el nivel del mar haya incrementado un metro en 2100. La defensa costera en el Voordelta necesita mejorar para garantizar la seguridad futura. Siendo la defensa costera rígida insuficiente, la atención se ha desplazado hacia la protección natural mediante la restauración de antiguos bancos de arena como el Banjaard. Estos han desaparecido a causa de la erosión costera y el déficit en la supleción de sedimento. La restauración del Banjaard vía una supleción reforzada en la ubicación del antiguo Banjaard, junto a un mayor desarrollo usando un enfoque de *Building with Nature* (Construcción con Naturaleza), proporciona nuevas oportunidades para la protección costera. El propósito de este proyecto, parte del piloto Banjaard y comisionado por el iniciador Shared Concepts, es diseñar y proponer experimentos factibles para incrementar las oportunidades de éxito del Banjaard acerca de la protección costera, mejora de la biodiversidad y sostenibilidad climática; y, simultáneamente, crear nuevas posibilidades para el suministro sostenible de alimento y valor social en ciertas zonas predeterminadas. Este reporte pondrá mayor énfasis en el ámbito ecológico de los experimentos que en las oportunidades para la sociedad del piloto.

Los primeros tres objetivos investigados son el aumento de la biodiversidad a escala de paisaje en la isla, los *biobuilders* (bioconstrucciones) adecuados con la biodiversidad asociada a ellos y la acuicultura sostenible, involucraron investigación bibliográfica para diferentes posibilidades. Las opciones pertenecientes a los dos últimos objetivos se evaluaron mediante un Análisis de Decisión de Criterios Múltiples (*MCDA*). Posteriormente, se examinaron los tres objetivos finales. Con este fin, se exploró el valor social del Banjaard, considerando el ecoturismo y fuentes energía renovable. A continuación, los resultados del MCDA se utilizaron para crear un plan espacial, ilustrado mediante el uso de varios mapas de zonación de sugerencia para el Banjaard, divididos en zonas experimentales propuestas y zonas para los tipos de hábitat. Sin embargo, es difícil determinar el proceso de asentamiento de diferentes especies y el desarrollo del hábitat en la isla, por lo que las áreas que aquí se presentan son meramente una propuesta. Por último, para hacer declaraciones sobre los resultados de estos experimentos, se sugieren indicadores de seguimiento para usar en un futuro programa de monitoreo. En este informe se analizan once zonas para el Banjaard. En estas zonas, se monitorean los experimentos para observar la atenuación de las olas, la capacidad de rompeolas, la retención de sedimentos, la biodiversidad, las posibilidades para bioconstrucciones y las diferentes iniciativas acuícolas.

Recomendamos crear variabilidad en los tipos de hábitat utilizando ingenieros de ecosistemas y especies pioneras. Después de iniciar el desarrollo de estos complejos ecosistemas con la ayuda de estructuras duras artificiales, recomendamos dejar que evolucionen de forma natural. Adicionalmente, recomendamos hacer uso de una combinación de bioconstrucciones, para usar en experimentos sobre su funcionamiento en la protección costera. También se recomienda implementar paneles solares para atenuación de olas y producción de energía renovable que aporte valor social. Para la producción de alimentos de origen marino, recomendamos utilizar estrategias de multicultivo integrado (*IMTA*) con métodos de acuicultura vertical que minimicen el daño al ecosistema. En línea con esto, se recomienda la introducción de juveniles (*sea ranching*) en lugar de la acuicultura intensiva. Recomendamos una ubicación estratégica combinando bioconstrucciones y prácticas de agricultura marina para proporcionar servicios beneficiosos para el ecosistema. Por último, recomendamos contactar con varias partes, empresas y expertos para obtener más información sobre la metodología más adecuada que se puede utilizar para iniciar diferentes bioconstrucciones, las prácticas sugeridas de acuicultura y la elaboración de las estructuras artificiales.

Adicionalmente a los consejos sobre experimentos e indicadores dados para un programa de monitoreo, se recomienda realizar estudios futuros para hacer un modelo hidromorfológico del área alrededor de la isla antes y después de la suplementación de sedimento. Se recomienda un análisis de las partes interesadas, donde la ideación se puede utilizar como punto de partida. Por último, se recomienda identificar las implicaciones legislativas, ya que el Banjaard se encuentra en un área Natura 2000 y la calidad del agua será importante para el comercio de los productos marítimos.

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1. Introduction

1.1. The Banjaard pilot project

Due to the construction of the Delta Works from 1956 until 1972, hydrology has changed in the Voordelta, a Natura-2000 coastal area to the west of the Dutch provinces Zeeland and Zuid-Holland (Kohsiek & Mulder, 1989). The Delta Works were built in response of the North Sea flood of 1953 to protect the low-lying parts of the Netherlands, specifically Zeeland, from the sea (Maris et al., 1956). Sea level rise is expected to rise one meter by the end of the century (Lee et al., 2023), therefore rigid coastal protection using dams alone is no longer the most sustainable approach, as has already been a problem for the Hondsbossche zeewering (Smit et al., 2005). Historically, the surroundings of the Banjaard were naturally protected by sandbanks maintained by sediment influx from the Scheldt River (Kohsiek & Mulder, 1989). The balance of sedimentation compensating for erosion by the sea was disrupted by decreased inflow due to the rerouting of the Scheldt River and the placement of the Delta Works, eventually causing the sand banks in the Voordelta to disappear below the waterline (Brouwers & Oosting, 2008). However, this natural form of coastal protection had many additional advantages, and therefore it would be beneficial if the sandbanks could be restored via sediment suppletion to add to existing coastal defence.

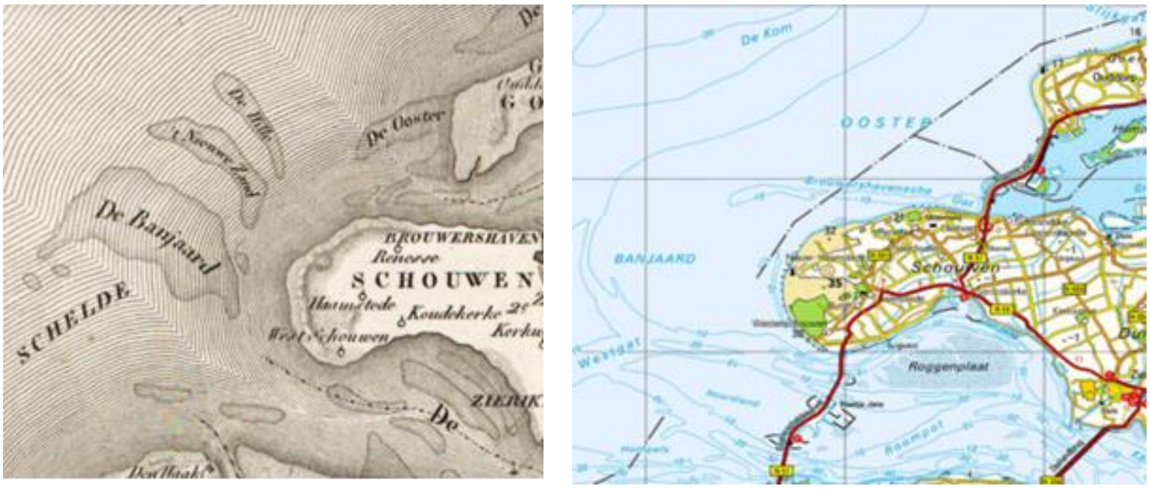

Figure 1 Left: a map of the Banjaard and surroundings in 1830 (left) and a map of the Banjaard and surroundings in 1996 (right), clearly showing the disappearance of the natural sand banks in the Voordelta over time. (Muller, 1830; Kadaster, 1996).

From previous artificial sand bank pilots along the Dutch coastline like the Sand engine project, the idea of restoring former sand banks in the Voordelta by adopting a Building with Nature approach gains strength, opening the door to exploring new opportunities for coastal protection through climate sustainable and biodiversity enhancing strategies. A multi-faceted sand bank can also add to the local economy by providing chances for e.g. local entrepreneurs, aquaculture businesses and boosting the (eco)tourism industry (Brière et al., 2016; de Leeuw et al., 2022; Shared Concepts et al., 2022). To examine whether this approach is feasible and does indeed have the intended effects, there is the idea to set up a pilot experimental sand bank located on the former Banjaard sand bank. Considering the urgency of climate change developments and the need for mitigation efforts, Shared Concepts' goal is to start developing the sand bank and start experiments in 2025.

1.1.1. Shared Concepts

The initiator of this project, Shared Concepts, is a coalition of people that have an interest in applying a modern and eco-friendly pilot for the coastal protection of Zeeland. In the short term (2025) the plan is to start a pilot in which sandbank the Banjaard - located 6 km off the coast of Schouwen-Duiveland - will be restored with a one-off nourishment. On the restored Banjaard, students, scientists and nature organizations can carry out experiments with biobuilders that will strengthen and morphologically guide the Banjaard. If this pilot proves to be successful, several islands will be constructed. These experiments will contribute to a dynamic island series that will serve as a breakwater to defend Zeeland and the Southwest Delta. The aim of this coalition is to "protect, shape and materialize our living environment" and Shared Concepts needs research projects to improve the knowledge and technologies on using Nature Based Solutions for this purpose (Shared Concepts, nd.). In addition to lobbying to the general public and politicians for this form of natural coastal protection, they challenge groups of students to provide ideas for the development of the Banjaard pilot project, from secondary school to university education, including variated backgrounds.

1.1.2. Outcome previous reports

Several reports have been written by students from Wageningen University & Research and the HZ University of Applied Sciences. In the reports of Shared Concepts et al. (2022a, 2022b) students focused on making a spatial configuration of the island. Here it was proposed that the barrier island should have an approximate width of 200 metres above water at high tide and it was estimated that a width of 500 metres would be expected on all sides of the island at low tide. They also designed the position and shape of the island based on the wind direction and velocity, wave direction and energy, tidal currents, bathymetry and nautical activities. The two shapes which were proposed were the crescent and the hook design. For this report the hook design has been used as basis. Another report mentioned that biobuilders can contribute in a significant extend to create and protect the Banjaard when it is has just been suppleted. It was advised to use the Pacific oyster for reinforcement of the island in the form of artificial reefs and to use sugar kelp for its wave dampening effects (Shared Concepts et al., 2023a). Also, Shared Concepts et al. (2023d) mentioned several biobuilders as defence layers such as suspended rope culture, submerged seagrass mats, emergent oyster reefs and a top layer of marram grass, aiming to defend the suppletion against erosion and capturing additional sediment. Biobuilders would be used in both the intertidal zone and above sea level to trap and retain the sediment. It was further proposed to use reef balls as a breakwater to protect the island and to conduct aquaculture for human consumption. Aquacultural activities can be done with Oysters (*Crassostrea gigas*), sea lavender (*Limonium platyphyllum*) and *Salicornia europaea* (glasswort) (Shared Concepts et al., 2023b; Shared Concepts et al., 2023c). Additionally, possibilities on ecotourism were explored by Shared Concepts et al. (2023b) and it was proposed to open up the island for visitors in a restricted manor, in which they can walk on hiking trails without disturbing flora and fauna.

1.2. Problem statement

To increase success rates of the pilot, tailored experiments should be carried out to explore the possibilities regarding coastal protection, increasing biodiversity, ecological value, and food production that lie in the restoration of systems like the Banjaard sand bank. However, the commissioner does not yet possess the required knowledge about 1) which experiments are suitable, and 2) what course of action should be taken to achieve a sustainable and multifunctional breakwater landscape at the Banjaard. Therefore, this project will focus on closing this knowledge gap by exploring the different possibilities there are for conducting experiments regarding coastal protection, biodiversity enhancement, climate sustainability while simultaneously exploring possibilities for sustainable food supply and societal value in several predetermined zones of the Banjaard. When successful, the Banjaard could then serve as an example for similar projects along the Dutch coastline and as an international reference.

1.3. Research objectives

In order to successfully close the knowledge gap presented by Shared Concepts and provide advice on the course of action, the following main research question was formulated:

What course of action can be taken to enhance coastal protection, biodiversity and climate sustainability while simultaneously creating new chances for sustainable food supply and societal value at the Banjaard?

To answer this question the consultancy team has formulated several research objectives. Working towards achieving these objectives will generate answers to the main research question presented above.

Objectives:

1. Create an overview of options for facilitating extra biodiversity development on and around the future Banjaard.
2. Create an overview of applicable biobuilder options that can support the development of a sustained breakwater island and biodiversity development at the Banjaard.
3. Create an overview of options for enhancing nature-inclusive, sustainable seafood harvesting around the future Banjaard.
4. Identify potential options for added societal value of the Banjaard, such as renewable energy production or sustainable ecotourism.
5. Design a spatial plan for the Banjaard with experiments applying the most suitable biobuilder components, biodiversity development and seafood facilitation.
6. Formulate critical indicators for breakwater function integrity, biodiversity development and sustainable seafood yield over time for a monitoring program with a time scale of at least 20 years.

2. Methods

2.1. Report structure

This report will aim to answer the main research question by completing six objectives (see 1.3. Research objectives) in a stepwise manner as represented in *Figure 2*. The chosen approach for reaching the final products can be roughly divided into two phases. The first phase aims to reach objective 1, 2 and 3 by performing a literature and case study. This will result in an overview of several options for 1) increasing biodiversity, 2) including biobuilders and 3) sustainable seafood production. The latter two will then be assessed through a Multiple Criteria Decision Analysis (MCDA) on their suitability for the indicated Banjaard site. This knowledge will be combined and integrated to continue to the second phase, which aims to reach objective 4, 5 and 6 by performing another literature and case study as well as conducting suggestive spatial design. The output for the fifth objective will combine the data gathered from the MCDA and translate this into a detailed zonation plan and suggestive spatial design for the Banjaard. Final recommendations will be provided at the end of the report.

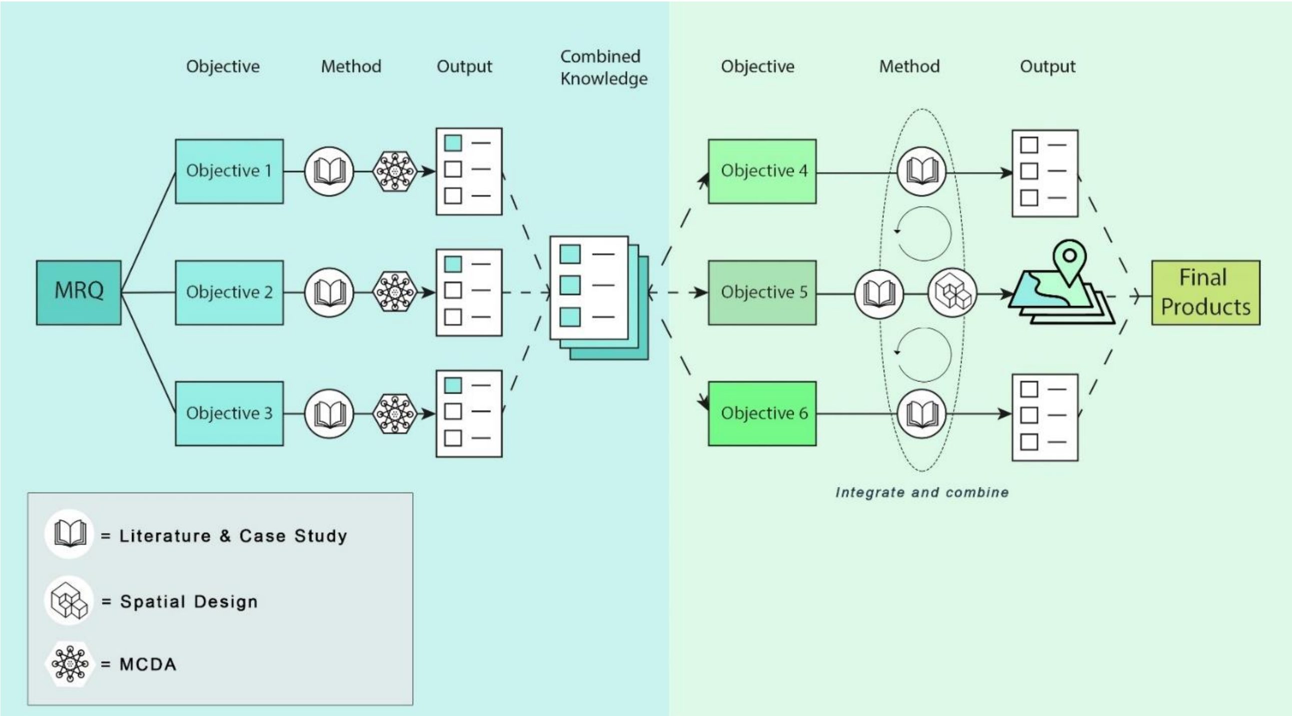

Figure 2: Diagram explaining the different methods used for answering the six objectives. The blue colored background indicates the first phase of literature research. The green colored background indicates the second phase of integration and combination of the literature research to the final products.

2.2. Introduction to MCDA

To make educated and rational decisions when selecting experiments for the Banjaard pilot, an assessment method can be used to evaluate and make management decisions. Belton & Stewart (2002) elaborate on an assessment method called *Multiple Criteria Decision Analysis (MCDA),* which provides a toolset for evaluating and making (environmental) management decisions. Like with performance matrices, multiple criteria are weighted and calculations to compare different scenarios are made. This will eventually help in the decision-making process.

To use MCDA in this report for assessing different options for 1) seafood production and 2) biobuilding, the MCDA method is simplified into a 5-step evaluation process and thereafter combined with the Simple Additive Weighting (SAW) method to roughly evaluate and compare the option given in *Chapters 4 & 5*. The steps are based on MCDA's exploration and application strategies by Belton & Stewart (2002):

1) **Define objective**: formulate the objectives for implementation of experiments at the Banjaard.
2) **Identify options**: Generate an overview of available options for the use of biobuilders and seafood production at the Banjaard.
3) **Identify assessment criteria:** Identify the criteria that will be used to evaluate the listed options for (1) biobuilder strategies and (2) seafood production methods. Limit the criteria to the most important and relevant factors.
4) **Assigning weights to the assessment criteria:** Assign weights to each criterion to reflect their relative importance. This will be done by using a simple scale (0-100%).
5) **Rate the given options and compare results:** Calculate an overall score for each option by applying the SAW technique and compare the overall scores between the different options to determine which option(s) would suit the Banjaard pilot best according to the objectives and criteria identified.

2.2.1. MCDA objectives

The objectives for the selection of experiments at the Banjaard using MCDA are in line with the research objectives for these specific subjects as defined in section *1.3. Research objectives*;

1. Create an overview of applicable biobuilder options that can support the development of a sustained breakwater island and biodiversity development at the Banjaard (Research Objective 2).
2. Create an overview of options for enhancing nature-inclusive, sustainable seafood harvesting around the future Banjaard (Research Objective 3).

2.2.2. MCDA criteria

For the MCDA assessment, five general criteria for both assessments were formulated. The assessment criteria are listed and elaborated on below:

1. Climate change – the adaptability of the evaluated option for the expected climate change situation. Sea level rise, ocean acidification and warmer weather are some of the conditions to take into account and the species resilience to them is considered here. It is valued positively any form of climate change mitigation such as fast rate of CO_2 fixation.

2. Biodiversity – it's evaluated whether an option includes species competitive in the nutrient uptake that hinders the development of other species populations, or if it provides shelter and facilitates the growth and habitat formation for species at risk in Europe. The facilitation of variety of habitats is considered positively here. Risks of toxicity for other species is considered as a negative characteristic on this criterion. Relative importance of the expected species and ecosystem in Europe and the Netherlands will be regarded positively, and roles as nursery for juveniles or migratory species.

3. Sustainability – Separately from climate change issues, the effort, investment and chances of successfully implementing the species in the Banjaard and for them to form a self-sustained ecosystem is pondered through this criterion. How the currents affect the species and whether the reproduction rate and number of offspring are enough to maintain the species presence on the island without human interference is evaluated. It is considered positive if the species can stablish without any extra juvenile or seed suppletion and still have enough population density for its purpose, for example on sea food supply species.

4. Coastal Protection – This criterion focuses on the species suitability and applicability as biobuilder for the island and wave protection. Features as sediment trapping, durability, resilience to currents and waves expected in the Banjaard are valued positively.

5. Profitability – Here the benefit is considered in respect to the investment needed to maintain the commercial option. Economic risks, value of the seafood product on the market, and investments needed are considered on this criterion.

2.2.3. Weighting

The weighting factors for the two overviews seagriculture and biobuilders differ, as the criteria are ranked different in priority. Considering the relevance, the criteria weight is not the same depending on which overview, biobuilders or seagriculture, is being assessed.

1. Common criteria – Criteria relating to climate change adaptation or mitigation, biodiversity, and sustainability have an equal weighing of a 20%, because their relation to biobulding and seagriculture is equally important. Additionally, these criteria reflect the three main pillars of the project.

2. Seagriculture weighting – The highest weight for sea food harvesting is the profitability, with a 30% of the weight. Without profitability on seagriculture solutions, companies will not be economically sustainable. Coastal protection has the lowest weight of a 10%, because experiments on seagriculture do not have this as primary objective and it is already evaluated on the biobuilder MCDA.

3. Biobuilders weighting – As the primary function of biobuilders can be regarded to be the enhancement of coastal protection by combating coastal erosion and/or improving sediment accretion, the coastal protection criterion is considered most important and therefore more heavily weighted with a 35%. When the incorporation of a certain biobuilder also contributes to a profit for seagriculture or enhances seagricultural processes, this is a beneficial side-effect. However, it is not the aim of implementing biobuilders and therefore not heavily weighted, only a 5%.

2.2.4. Assessment Matrix

In this section a blank MCDA table for the two overview options can be observed (t*able 1* & *2*). The total score will be in the range of 0-100. The assessment is the score given for each criterion after thoroughly examining benefits, opportunities, disadvantages and risks of every option and is in a range of 1-10. The score from every criterion is calculated for each assessment after applying the weight (see *2.2.3. Weighting*).

Table 1. Biobuilders overview blank MCDA table for the assessment development without criterion weights.

Biobuilders

Criteria	Climate change		Biodiversity		Sustainability		Coastal protection		Profitable		
Description	Is the solution adding to climate change adaptation or mitigation		Does the solution add to (local) biodiversity and ecological value?		Is the solution sustainable in terms of longevity, maintenance and self-sustainability?		Is the solution adding to coastal protection and functioning as a breakwater?		Is the solution profitable for sea food harvest?		
Weighting factor (%)											>adds up to 10
Options	Ass.	Score	Ass.	Score	Ass.	Score	Ass.	Score	Ass.	Score	**Total**
Seagrass		0		0		0		0		0	0
Kelp		0		0		0		0		0	0
Salicornia		0		0		0		0		0	0
Marram grass		0		0		0		0		0	0
Mussel reef		0		0		0		0		0	0
Oyster reef		0		0		0		0		0	0
Tubeworm reef		0		0		0		0		0	0

Table 2. Seagriculture overview blank MCDA table for the assessment development without criterion weights.

Seagriculture

Criteria	Climate change		Biodiversity		Sustainable		Coastal protection		Profitable		
Description	Is the solution adding to climate change adaptation or mitigation		Does the solution add to (local) biodiversity and ecological value?		Is the solution sustainable in terms of longevity, maintenance and self-sustainability?		Is the solution adding to coastal protection and functioning as a breakwater?		Is the solution profitable for sea food harvest?		
Weighting factor (%)											>adds up to 10
Options	Ass.	Score	Ass.	Score	Ass.	Score	Ass.	Score	Ass.	Score	**Total**
Sea ranging		0		0		0		0		0	0
IMTA/ Vertical thinking		0		0		0		0		0	0
Vertical oyster farming		0		0		0		0		0	0
Vertical mussel farming		0		0		0		0		0	0
Vertical seaweed farming		0		0		0		0		0	0
Horizontal seaweed farming		0		0		0		0		0	0
Seagrass (nursery)		0		0		0		0		0	0

3. Landscape-scale biodiversity at the Banjaard

Biodiversity is a widely used term today, but it is not always easy to interpret. In fact, it has many different context-dependent definitions. The terms biodiversity and species richness are often used interchangeably, but biodiversity goes deeper than just the number of species in an ecosystem. Biodiversity is about diversity of life at all scales: variation in ecosystems worldwide, in functional species groups within an ecosystem, in species within one functional species group, in distribution and sizes of populations within one species, in the behavior and genetics of individuals within one population, etc. (Begon et al., 2014; Campbell et al., 2020). Maximizing biodiversity can be approached from a top-down perspective, i.e., from the area as a whole, or bottom-up through small adjustments of other measures to facilitate additional biodiversity. This section looks at the former; how the Banjaard can be broadly designed to encourage biodiversity, using possible habitat types that could develop, their relevance or scarcity in Europe and how indicator species could help with monitoring ecological parameters.

3.1. Increasing biodiversity in practical management

Underlying high biodiversity is high ecological heterogeneity, which creates a wide range of habitats, in turn resulting in a great diversity of potential niches (Begon et al., 2014; Campbell et al., 2020; Hansson, 1997; Kolasa & Pickett, 1991). Combined with mitigation of major impact factors that degrade natural ecosystems, such as anthropogenic disturbance, climate change and overexploitation, this will theoretically create a rich area that can provide a major boost to the native species that occur in this area, or even provide new habitat for species that previously occurred in this area (Begon et al., 2014; Kolasa & Pickett, 1991). Practically speaking, in natural area management, creating heterogeneity often entails increasing the number of different habitat types and transforming sharp dividing lines between habitat zones into subtle transitions or gradients (Bijlsma et al., 2010; Kark, 2013; Schilthuizen, 2000; Smith et al., 1997, 2001).

The Marker Wadden are a cluster of several artificial nature islands in the Markermeer, constructed between 2016 and 2021. The Marker Wadden have similarities to the Banjaard pilot in several respects; they were also constructed for wave attenuation and to increase the ecological value of the surrounding area. From that perspective, the Marker Wadden can serve as an example for the Banjaard. In the zoning plan for the Marker Wadden (Gemeente Lelystad, 2013; Gemeente Lelystad & Natuurmonumenten, 2013), four ecological objectives were formulated: 1) zones with clear water along the Noord-Holland coast for submerged aquatic plants and associated benthic fish and invertebrate species, 2) gradual gradient from clear to silty water from Noord-Holland to Lelystad for the fish population and piscivorous birds, 3) large transition zones between land and water as hatchery for fish and habitat for many plant and animal species, and 4) strengthening the ecological relationships with the other parts of the Dutch delta, to give an impulse to the species richness of the ecological system of the Markermeer and IJmeer. These objectives lead to similar results as mentioned above: gradual transitions between a wide variety of habitats.

3.2. Habitat types

To make an accurate prediction of the habitat types that may develop on the Banjaard, and sequentially visualize a final goal in terms of maximizing biodiversity, it can be useful to take the Natura 2000 habitat types as a guideline. In addition to the fact that the area in which the Banjaard is located has already been designated as a Natura 2000 site, which means that strict regulations from the European Union apply, the habitat types provide guidance for nature development. Mainly because of the extensive profiles that have been described about associated vegetation types, abiotic prerequisites and relative importance of said habitat type within Europe.

The Natura 2000 areas close to the Banjaard are the Voordelta (site code: NL4000017) and the Kop van Schouwen (site code: NL1000017). Together, these two areas have been designated fourteen different habitat types, as listed in *table 3*. Morphologically similar areas to the intended set-up of the Banjaard pilot in other location can also be taken into consideration. The Banjaard is expected to be a highly dynamic nature reserve surrounded by seawater, consisting roughly of shallow coastal waters, dunes and salt marshes. Of the Dutch Natura 2000 reserves, the Wadden Sea area (site code: NL9801001) corresponds most closely to this. Twelve habitat types are designated for the Natura 2000 area of the Wadden Sea.

Of these habitat types, some can be excluded directly, such as the H1130 estuaries habitat type, which is characterized by downstream river systems influenced by tides, creating a freshwater – saltwater gradient. This habitat type will not develop on the Banjaard, due to a lack of freshwater. Several other habitat types will develop only in later successional stages with reasonably well-developed soils, such as shrub and forest vegetation. Possibly these could develop after several decades or a longer period, but they are not applicable to the initial phase of the Banjaard pilot. The remaining habitat types and defining characteristics are further described below in the table, as derived from the habitat profiles of Natura 2000 (Ministry of Agriculture, Nature and Food Quality, n.d.; Programmadirectie Natura 2000, 2014). One habitat type that does not occur in any of the three Natura 2000 sites mentioned above, but that could potentially be of interest to the Banjaard pilot, is the H1170 Reef habitat type. It is also included in the description below.

Table 3. different habitat types of the Voordelta, Kop van Schouwen and the Wadden Sea, including the H1170 reefs habitat type. In grey are the habitat types that are not likely to appear in the initial phase of the Banjaard pilot. Relative importance within Europe: +++ (very large), ++ (large), + (considerable). Descriptions of each habitat type can be found below the table.

Habitat code	Description (EN)	Description (NL)
H1110A +++	Sandbanks covered all the times	Permanent overstroomde zandbanken
H1130	Estuaries	Estuaria
H1140A +++	Mudflats and sandflats not covered by seawater at low tide	Silk- en zandplaten
H1170 +	Reefs of open sea	Riffen van open zee
H1310 +++/++	*Salicornia*, *Sagina* maritima and other annuals colonizing mud and sand	Zilte pionierbegroeiingen, zeekraal en zeevetmuur
H1320 +	*Spartina* swards (Spartinion maritimae)	Slijkgrasvelden
H1330A +++	Atlantic salt meadows (Glauco-Puccinellietalia maritimae)	Schorren en zilte graslanden
H2110 ++	Embryonic shifting dunes	Embryonale duinen
H2120 ++	Shifting dunes along the shoreline with *Ammophila arenaria* ("white dunes")	Witte duinen
H2130*	Fixed coastal dunes with herbaceous vegetation ("grey dunes")	Grijze duinen
H2150*	Dune heather with *Calluna vulgaris*	Duinheiden met struikhei
H2160	Dunes with *Hippophae rhamnoides*	Duindoornstruwelen
H2170	Dunes with *Salix repens* ssp. *argentea* (Salicion arenariae)	Kruipwilgstruwelen
H2180	Dune forests	Duinbossen
H2190 +++	Humid dune slacks	Vochtige duinvalleien
H6410	Molinia meadows on calcareous, peaty or clayey-silt-laden soils	Blauwgraslanden

H1110 Sandbanks covered at all times: Involves sandbanks in shallow parts of the sea that are continuously submerged, rarely more than 20 meters deep. Locally, hard substrates such as rocks and shell banks and other biogenic structures may occur. In clear water, photosynthesis can occur down to the bottom, allowing vegetation types of seagrass. Relative importance in Europe very large.

H1140 Mudflats and sandflats not covered by seawater at low tide: Shallow coastal areas that dry and re-flood through the action of tides. Consists of a mosaic of marine ecotopes with hard substrates of biogenic structures such as shell, mussel and cockle banks, and seagrass and *Ruppia* beds on high and low, sandy and silty flats. Relative importance in Europe very large.

H1170 Reefs of open water: Characterized by the occurrence of a geogenic, hard substrate consisting of large stones or coarse gravel. The limiting criteria are substrate size (>64 mm) and the presence of sessile organisms dependent on the substrate. Substrate with dimensions of 8-64 mm is included in this habitat type provided it is located in the vicinity of larger substrate and sessile organisms live on said substrate. Reefs of biogenic origin are not included in this habitat type (according to Dutch definition, which deviates from European definition), but fall under H1110 or H1140. Relative importance in Europe is considerable.

H1310 *Salicornia*, *Sagina maritima* and other annual plants colonizing mud and sand: Pioneer vegetation on saline soils where flooding creates dynamic and open habitats. Develop every year on bare soil. Two subtypes in vegetation, one containing *Salicornia* and the other mainly with *Sagina*. Latter of large relative importance, former of very large importance.

H1320 *Spartina* swards (Spartinion maritimae): Pioneer vegetation in which *Spartina* species dominate on periodically inundated mudflats. Usually grows in open structures of large tussocks, as well as continuous vegetations. Occurs naturally on saline mudflats and depressions in salt marshes, often in association with H1310. Originally native species *Spartina maritima* almost disappeared due to habitat loss and displacement by *Spartina anglica*. This displacement has reduced the relative importance in Europe to considerable.

H1330 Atlantic salt meadows (Glauco-Puccinellietalia maritimae): Saline grasslands on salt marshes. Consists of rushes (*Juncaceae*) and sedges (*Cyperaceae)* in addition to grasses (*Poaceae*), herbaceous plants such as *Limonium vulgare* and *Artemisia maritima*, and reed (*Phragmites australis*) in the more saline areas. Relative importance in Europe very large.

H2110 Embryonic shifting dunes: Species-poor pioneer dunes with vegetation of varying densities, consisting mainly of *Elytrigia juncea* spp. *borea-atlantica*. Occurs mainly on the beach at the base of the foredunes. Transitional zone from salt to fresh environment. Flooding occurs regularly to occasionally, causing the cover of vegetation to fluctuate. Flood mark vegetation with *Atriplex littoralis* and *Cakile maritima* are included in this habitat type. Relative importance in Europe large.

H2120 Shifting dunes along the shoreline with *Ammophila arenaria* ("white dunes"): Habitat type consists of dunes dominated by *Ammophila arenaria*, *Calammophila baltica* or *Festuca arenaria*, usually in foredunes. Forms via natural succession when H2110 has accreted sand to the point where the vegetation is out of reach of sea water, though influence of the sea in this habitat type is still significant due to salt spray. Can also develop in the opposite direction when more developed dunes are eroded or accreted too quickly. Relative importance in Europe large.

H2190 Humid dune slacks: Open water, low marsh vegetation, moist meadows and reed beds (*Phragmites australis*), occurring in low-lying areas within the dunes. Due to ecological variation, the number of characteristic species is large, which is for a large part depended on the lime content of the substrate. Can occur when beach plains are cut off from the sea by dune formation, or when blowouts reach groundwater level. Relative importance in Europe very large.

3.3. Indicator and guideline species

Indicator species are widely used in research to monitor environmental changes, evaluate the effectiveness of management strategies, and serve as warning signals for impending ecological shifts (Siddig et al., 2016). Meesters et al. (2008) described 34 indicator species for the Wadden Sea, North Sea and delta region, consisting of birds, fish, marine mammals, and bivalves. Using organisms that are relatively high up the food chain provides a top-down perspective: because organisms in all trophic levels below must be present for these species to occur, it may be possible to infer that these levels are in good shape when the indicator species are present in an area (Green & Elmberg, 2014). More often, indicator species are used because of a sensitivity to an environment attribute, since this provides a more direct causal relationship (Siddig et al., 2016).

However, the use of indicator species is not always adequate. Meta-analyses have shown that the choice of indicator species is sometimes quite arbitrary (Siddig et al., 2016), and that single species can rarely, if ever, represent the full complexity of an ecosystem (Lindenmayer & Likens, 2011; Niemi et al., 1997), making indicator species alone insufficient to accurately reflect changes in the environment. Apart from the challenge of finding an appropriate biological indicator for its intended application, it nevertheless remains a reliable and cost-effective way to monitor environmental changes (Siddig et al., 2016).

Monitoring of Natura 2000 sites is largely based on the use of guideline species; in the Netherlands, 36 guideline species are used in the habitats directive, and 95 guideline species in the birds directive (Programmadirectie Natura 2000, 2014). Guideline species can serve as biological indicators, but are also considered valuable and are sometimes vulnerable or endangered species that require protection. A Natura 2000 site is designated a selection of guideline species, all of which have been assessed for 'state of conservation', which is a measure of the sustainability of a population. Examples of guideline species designated to the Voordelta include the allis shad (*Alosa alosa*), a fish from the Herring family (Clupeidae); the sea mammal harbour porpoise (*Phocoena phocoena*); and the birds Eurasian spoonbill (*Platalea leucorodia*) and ringed plover (*Charadrius hiaticula*).

4. Ecosystem engineers as biobuilders at the Banjaard

This chapter aims to create an overview of biobuilder options that can support the development of a breakwater island and can contribute to biodiversity development at the Banjaard. Firstly, ecosystem engineers and their theoretical background will be explained, after which the different options and species of biobuilders will be introduced.

4.1. Theoretical background on biobuilders

Ecosystem engineers are species with the capability to modify their physical environment directly or indirectly by the structures they build or the behaviour and properties they possess. These species can help to stabilize a rough, dynamic aquatic environment by trapping the sediment particles between their structures, consequently providing a base for vegetation to grow, or assisting in wave attenuation, coastal erosion reduction and vertical sediment accretion (Borsje et al., 2011; Jones et al., 1994; Walles et al., 2016). Jones et al. (1994) make a distinction between two major types of ecosystem engineers: autogenic engineers and allogenic engineers. Autogenic engineers are species that modify the physical environment by their built physical structures (e.g., shellfish and seagrass species), while allogenic engineers modify their physical environment by transforming biotic- or abiotic matter to a new physical state (e.g., benthic macrofauna, protozoa of marine species, algae).

Ecosystem engineering species can be used as biobuilders to reshape or restore ecosystems in a way that is beneficial for humans. In this pilot, a major goal for which biobuilders can be used, is to enhance existing coastal protection systems or to create a new form of soft coastal defences. Due to expected sea-level rise, an emerging need for cost-effective and sustainable defence methods has shifted the interest towards these biobuilder species as they might provide a more sustainable solution. Additionally, biobuilders can stimulate local biodiversity as they facilitate conditions for other species to thrive as well, in contrast to the construction of hard structures like breakwaters, dams, and dykes. By doing so, they might therefore be a fruitful and less impactful implementation (Borsje et al., 2011). Borsje et al. (2011) mention that even though there is sufficient literature on using biobuilders in coastal protection projects, the application in such projects remain quite scarce. They imply this might be due to the low number of actual pilot projects and experiments conducted with biobuilders. The experiments designed for the Banjaard pilot project, and the research findings that come out of those, might therefore be a very valuable addition to the advancement of the use of biobuilders in coastal projects elsewhere as well. If the environmental conditions at a given location are too harsh, this may prevent the (natural) settlement and development of biobuilder colonies that may benefit coastal protection and increased biodiversity (Chowdhury, 2019; Crain and Bertness, 2006; Lai et al., 2018). This could be kickstarted using artificial structures (section *4.3. Man-made structures to facilitate biobuilders*).

4.2. Overview of potential biobuilder species for the Banjaard

Several types of species could be relevant and provide benefits for the Banjaard pilot. Bivalves for example, which are often keystone species in coastal habitats, form three-dimensional reef structures on top of intertidal and subtidal seabed sediment or substrate. They can be regarded as autogenic biobuilders due to the impact their built structures have on the direct living environment (Walles et al., 2016). These physical structures largely affect local hydrological and morphological dynamics (Ysebaert et al., 2019). Bivalve species (e.g., mussels and oysters) are a great example of widespread and common reef-builders. Ysebaert et al. (2019) state that "*by influencing hydrodynamics, oysters and mussels modify the sedimentary environment far beyond the boundaries of the reef, affecting morphological and ecological processes up to several hundreds of meters*". In other words, these bivalve reefs serve as natural breakwaters and thereby mitigate the impact of extreme weather events and common wave attenuation on coastal environments. Due to this, bivalve reefs are increasingly used as nature-based solution for coastal protection (combating coastal erosion) and preventing ecosystem degradation.

Another reef-building animal that may positively affect natural coastal protection is the tubeworm, which builds tubes from its surrounding sediment and forms a reef that helps to stabilize sand or mud beds and assists in sediment accretion (Sterckx et al., 2020). In addition to these animal species, there are several autogenic biobuilding plant and seaweed species that can be used in both the aquatic and terrestrial zones of the island. This section will discuss the biobuilding potential of seaweed, several plant species (seagrass, *Salicornia,* and marram grass), reef-building bivalves (mussels and oysters) and tubeworms for their use as biobuilders. First, a general introduction to the species and its functioning in the ecosystem is given, whereafter its biobuilder characteristics and conditions will be elaborated on.

4.2.1. Mussels

Mussels are a common native ecosystem engineering bivalve found along the shores of the North Sea. Mussels are epibenthic species, meaning that they mainly live above the sediment or substrate. Most common is the blue mussel (*Mytilus edulis)* (*figure 3*), which is also known as the common mussel. Besides these the species *Mytilus galloprovincialis* and *Mytilus trossulus* can also be found in (parts of) the North Sea. Mussels are considered important ecosystem engineers and have a large potential for increasing biodiversity. As filter feeders they purify the water, remove nutrients and toxins, and by forming large beds they also shape their surroundings (Buschbaum et al., 2009), even though the free-floating mussel larvae do need a hard substrate like rock or other shells to settle on (Widdows, 1999).

Figure 3. Mytilus edulis growing on rocky substrates in the intertidal zone. From: Baker, 2021.

Deposition as a consequence of the mussel's filter feeding, as well as a reduction in current speed through structuring of the substrate, causes a higher deposition of fine sediments (Leeuwen et al., 2018). This leads to a lower average sediment particle size and increased organic content (Kochman et al., 2008). After the deposition they have the ability to climb to the top of the newly deposited layer of substrate, increasing the height of the sandbank they settled on, and adapt to rising sea levels (Reise et al., 2017a). Fixing the substrate and raising its organic content facilitates many other benthic invertebrates like tubeworms for example, which play a further role in developing the ecosystem (Kochman, 2008).

Apart from that the hard shells of the mussels are used as a substrate by other organisms like algae, all kinds of macroinvertebrates, as well as other bivalves (Markert et al., 2010). This can lead to a diversification of habitat types, especially in an environment where otherwise there would only be soft sediments present (Buschbaum et al., 2009). The structures created by their shells serve as hiding places for many types of organisms (Market et al., 2010). Some studies show this can lead to a higher abundance, species richness, and diversity. While on most mixed bivalve reefs (mussel and oyster), as well as at oyster reefs (Christianen et al. 2018), the biodiversity is higher within the beds themselves (Sas et al., 2010), studies show that in the case of mussels the diversity is higher on the sandy patches. However, the species composition is completely different between these two habitats, so the overall diversity of an area is much higher if both mussel beds and sandy patches occur (Arribas et al., 2014, Buschbaum et al., 2009). Mussels are also an important food source for aquatic organisms, as well as many species of coastal birds like oystercatchers (Markert et al., 2010; Waser et al., 2016). Some effects of bivalve reefs on the ecosystem are visualized in *figure 4*.

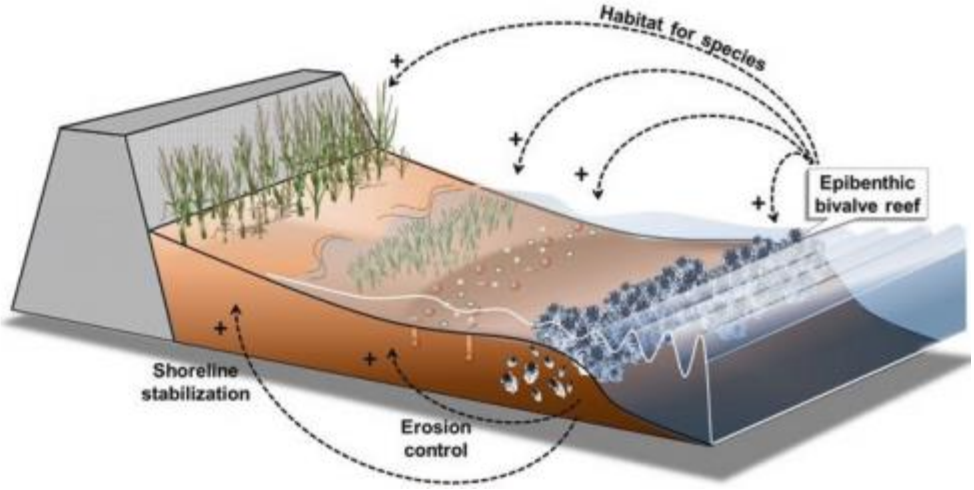

Figure 4 Visual of the effects of epibenthic bivalve reefs. From: Ysebaert et al., 2019

4.2.1.1. Biobuilder characteristics of mussels

As stated in section *4.2.1. Mussels*, mussels are important ecosystem engineer species that function as water purifiers by their filter feeding behaviour, increasing the local water quality and decreasing turbidity. With their byssal threads they clump together or attach to hard or sedimentary substrates (Buschbaum et al., 2009) to form mussel reefs. These reefs affect the physical hydrodynamical environment and contribute to coastal protection.

The physical structure of the reef traps sediment and fixes substrate or sediment by anchoring it (van Leeuwen et al., 2010). Mussels trap sediment through their filter feeding ability, turning filtered material into faeces which is deposited between the shell clumps (EcoShape, 2023). As mentioned in section *4.2.1. Mussels*, mussels have the ability to climb onto this newly deposited sediment, elevating the mussel bed as it grows (van Leeuwen et al., 2010). A growing reef thus adds to sediment accretion in marshes in several ways, which are also visualised in *figure 5*. Next to this, the physical structure attenuates incoming waves. The main factor for the level of attenuation is mussel bed roughness and bed height (Donker et al., 2012). Furthermore, Donker et al. (2012) found that mussel beds establish naturally in a way that wave power on the mussel bed is minimal, as they observed minimum wave forcing locations to overlap with the seaward location of the mussel bed.

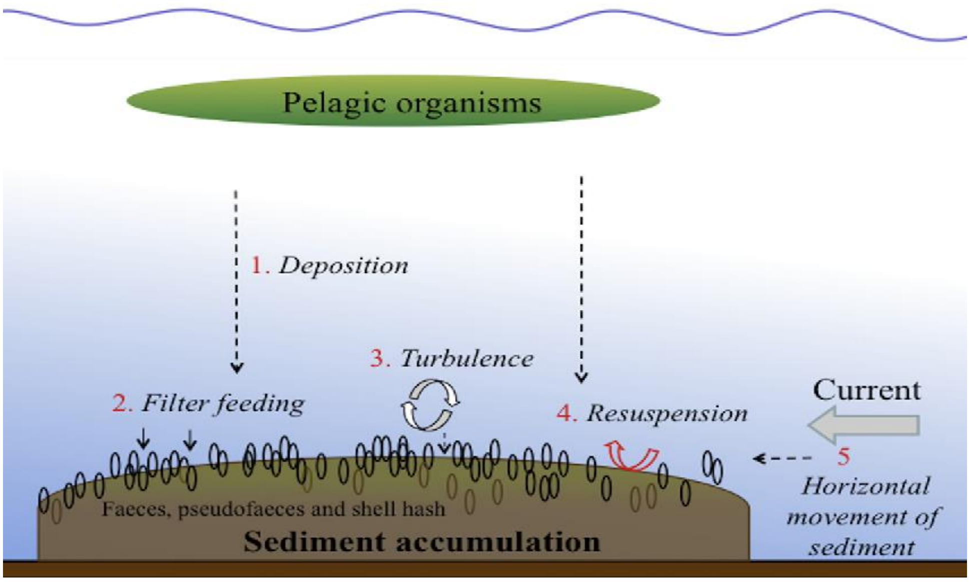

Figure 5 five sediment processes that may occur on a hypothetical bivalve reef. From: Kent, 2017

4.2.2. Oysters

The second important ecosystem engineering bivalve species common to the North Sea waters are the Pacific oyster (*Crassostrea gigas) (figure 6)*, an invasive species, and the rarer native European flat oysters (*Ostrea edulis*). Also being a filter feeder, oysters provide a similar filtration service within the ecosystem as mussels. Their shells also serve as (settlement) substrate, hiding places and foraging areas for other organisms (Market et al., 2010).

Figure 6 Crassostrea gigas reef in the intertidal zone. From: Schultz, 2023

Oysters can only settle on and attach to hard substrates such as rocks and other shells, whereas mussels can attach themselves to sedimentary substrates using byssal threads. Oyster larvae are usually found to settle on the shells of either live or dead oysters (Pogoda et al., 2019; Reise et al., 2017b), as well as on top of mussel beds (Markert et al., 2010, Diederich, 2005). When the sediment level rises, older oysters get buried and the newer generation can grow on top of their shells (Reise, 2007). Oyster shells are quite large, especially when compared to mussel shells. This, in combination with their more vertical attachment characteristics, allows oyster beds to grow into large reef-like structures (Diederich, 2005; Markert et al., 2010).

Apart from a completely different species composition compared to mussel beds, oyster reefs have a higher macrofauna species richness, diversity, abundance, and biomass compared to the surrounding sandy flats (Market et al., 2010). (Have et al., 2019) even found a 60% increase in epibenthic species in the presence of an oyster reef. Besides this, oysters serve as an important food source for birds, even though there seem to be slightly better protected to predation compared to mussels, and there are several avian species which mostly avoid oyster beds (Waser et al., 2016).

The North sea's native oyster, the European flat oyster (*Ostrea edulis*) almost completely disappeared due to overfishing, disease, and pollution (Sas, 2017). A Shortage of shells for settlement due to poor management has also contributed to this process (Pogoda et al., 2019). In the 1970's the Pacific oyster (*Crassostrea gigas*) was introduced in the North Sea, which wasn't susceptible to the same diseases, and quickly spread (Markert et al., 2010; Reise et al., 2017a).

4.2.2.1. Biobuilder aspects of oysters

Like mussels, oysters are epibenthic reef-builders and their reefs add to sediment accretion (as described in figure 5), reduction of salt marsh retreat and erosive wave attenuation by altering hydrodynamic and physical dynamics of their direct environment (Scyphers, 2011). In contrast to mussels and like stated in section *4.2.2. Oysters,* oysters are only able to settle on hard substrates (e.g., stones or shells of other bivalves) and can therefore not grow directly on sedimentary seafloor or mudflats (Pogoda et al., Reise et al., 2017). Apart from the ability to settle on top of each other, oysters can produce a calcium carbonate cement that allows them to clutch or even bond together and have extensive multidimensional reef expansion (Piazza, 2005). Oysters' massive spawning events generate new available recruits (spats) rather fast, as the oyster spat set increased from 0.5 spat/shell in July 2002 to a peak of 9.5 spat/shell in October 2002. This allowed the oyster reefs to be self-sustaining (Piazza, 2005).

When settling soft substrates mussels form an epibenthic layer that can rise with sedimentation (Reise et al., 2017a). Even though this makes them very flexible and allows them to establish new reefs relatively easily, their stability temporarily decreases during this process, making them vulnerable to high current velocities during storms (Commito & Dankers, 2001). Oysters on the other hand, glue themselves to shells of previous generations. These shells often end up getting completely buried by newly deposited sediment. This process is a lot less flexible and more time consuming, but it creates a strong anchor for the reefs that often exceeds the resilience against waves of mussel beds, especially when this process spans multiple generations (Reise et al., 2017). Like stated in section *4.2.2. Oysters*, this also allows oysters to create huge reefs that can grow to heights of several meters (Commito & Dankers, 2001). This makes them more suitable as wave attenuators, especially during high wave energy situations.

The success for oyster reef building lies in their environmental conditions. It was seen that the growth of oyster reefs is dependent the accumulation of sediments and an upper limit for tidal range, also called a growth ceiling (Rodriguez et al., 2014). Oysters were unable to grow above the growth ceiling because they require a certain amount of time submerged in water to thrive.

Sedimentation also influences the performance of oyster development. The more sedimentation in oyster reefs happen, the more habitat loss will occur. The sediment particles settle on the oyster reef, which smother the oysters preventing them from feeding and breathing. This leads to reduced growth and survival. To prevent this, the reef needs to be initiated at a certain height, so the influences of sedimentation are minimized (Rodriguez et al., 2014).

The Pacific Oyster survives and grows in salinities ranging at a preferred concentration between 25‰ and 30‰, however they can also survive in higher or lower concentrations (Silvestre et al., 2021). In general, a salinity level lower than 5 Electric Conductivity (EC) and water temperature higher than 30^{o}C have a negative impact on the development of oysters (Rybovich et al., 2016).

Oyster reefs are known for their ability to stabilize coastal areas prone to erosion. Wiberg et al. (2018) for example investigated the wave attenuating ability of oyster reefs in the shallow coastal bay of Ramshorn Bay and South Bay near the Virginia, USA. Here they restored four intertidal oyster reefs, which were able to reduce wave heights by an average of 30%-50% in water depths of 0.5m-1.0m. The deeper the oyster reefs were, the less wave attenuation was seen. This can be of help as breakwater component, but looking at the hydrodynamics, it will also influence the development of oysters. Feeding, growth and survival are in that way affected in a positive way, since more food will be available for oysters the higher the flow rate. However, too strong currents can cause physical damage and have an opposite effect on the survival of oysters (Campbell & Hall, 2018).

4.2.3. Combined reefs of mussels and oysters

When the Pacific oyster was spreading thorough the North Sea, colonies were mostly established on existing Native blue mussel (*Mytilus edulis)* beds, since this was the only hard substrate available to them. It was hypothesized that the invasive oysters would quickly overgrow the mussel beds, suffocating them in the process (Diederich, 2005). In practice however, both species appear to be able to co-exist (Reise, 2007), and sometimes even form symbiotic relationships. The invasive oysters settling on top of the native mussels, it turned out, actually protected them against predation from birds, providing food availability was high enough to sustain them both (Reise, 2017b; Sas et al., 2017). Detachment of the Pacific oysters led to the creation of more substrate, which led to the mussel beds no longer being preferred for larval settlement, and the different beds existing side by side (Reise, 2007). Because of the different species compositions between the two types of bivalves this could mean a huge boost to biodiversity (Kochman et al., 2008; Markert et al., 2010). The shells of the Pacific oyster in turn led to the return of the native European flat oyster to the North Sea, by providing them with a suitable substrate for settlement (Christianen et al., 2018; Have et al., 2019). In 2016 an oyster bed was found at the Blokkendam where the two species are co-existing (Sas et al., 2017; Have et al., 2019).

4.2.3.1. Ocean Acidification

A higher global temperature is not the only effect derived from the excessive release of CO_2 to the atmosphere, its increased presence in the air also leads to ocean acidification (OA) (OCEAN, nd.c). The hydrolysis of CO_2 in seawater has reduced the pH by 0.1 compared to preindustrial conditions and it is forecasted to continue dropping 0.3-0.4 units more (Orr, 2005). pH being a logarithmic scale, a 0.1 reduction means a large increase in the proton's concentration ($[H^+]$). A decrease in pH from 7 to 6.7 pH means a doubling on the ($[H^+]$) in the marine waters all around the world.

The acidification of the waters causes the carbonate ions ($CaCO_3$) to be less abundant (NOAA, nd.b) due to the following reaction: $CO_2 + CO_3^{2-} + H_2O \rightarrow 2HCO_3^-$ (Orr, 2005) where the hydrogen is more likely to bond with the carbonate due to the decreasing pH (the equilibrium of the reaction switches towards the bound molecule instead of free protons), less $CaCO_3$ will be available for calcifying organisms to form biogenic calcium.

Currently, oyster reproduction processes such as gametogenesis are resilient to the seasonal variations of pH, but they are vulnerable to more severe acidification of the water. In their study, Boulais et al. (2017) concluded that the near-future expected conditions of acidity in the coast will not be affecting the oyster's reproduction. Nonetheless, since OA is expected to worsen due to climate change (Boulais, 2017), it could become a problem for their proliferation in the Banjaard. On the other side, a higher rate of CO_2 fixation is expected locally with the introduction of the biobuilders and the development of ecosystems around them. This introduces a possible experiment to study whether the local acidity of the water allows a reproduction rate for oysters that can keep open the opportunity for its harvesting for seafood supply without compromising their biobuilder role. A monitoring of population can give details of the effect that an increased CO_2 concentration, produced by human intervention, has on oyster and mussel populations.

The same problem applies to mussels and specifically the formation of larvae shell, one of its most vulnerable life stages. According to the research from Ramesh et al. (2017), there are consequences including the decrease in shell growth, and even shell dissolution when mussel larvae are exposed to OA. This species should also have a monitoring program linked to CO_2 concentration in the atmosphere and OA to forecast the effect on their biobuilder role and the suitability for them to become part of the local food supply.

4.2.4. Tubeworms

Tubeworms aggregate sediment into tubes in which the worms live. The Polychaete species *Lanice conchilega* (*figure 7*), the sand mason worm, is a tube-building worm that can grow up to 16 centimetres in height. *L. conchilega* can grow in sandy and muddy environments, ranging from 1900 metres water depth to the intertidal zone. Their tubes are formed of sediment combined with shells (Alves et al., 2017). *L. conchilega* is widely distributed along the North Sea and the Voordelta specifically in microbenthic samples taken in 2000 and 2001 (van Hoey et al., 2008). Tubeworms are highly influential ecosystem engineers, and *L. conchilega* is a good example of this, altering its environment in several ways, in some cases even creating biogenic reefs extending 10-40 cm above the seafloor (van Hoey et al., 2008). This species changes hydrodynamics, stabilizes the sediment, and their tubes provide shelter from predation and a substrate for the settlement of all kinds of organisms (Zuhlke et al., 1998; Callaway, 2006; van Hoey et al., 2008).

Figure 7 Lanice conchilega (sand mason worms) From: (Decleer, 2006)

The presence of *L. conchilega* can have a positive impact on the local biodiversity (Sterckx et al., 2020). Especially in sandy intertidal areas dominated by soft sediment, the differentiation in substrate the tubes offer can make a big difference. For example, spat of the *Mytilus edulis* can attach to the tubes and use them to colonize a patch of soft sediment and start forming a mussel bed in a spot where otherwise this wouldn't be possible (Zuhlke et al., 1998; Callaway, 2003). Even though they especially have a large effect on the benthic communities in groups, a single member of the species *L. conchilega* can bring about a change in species composition, leading to higher species diversity and abundance (Callaway, 2006). The decrease in flow velocity causes settling of larvae, benthic species and detrital food next to the entrapment of sediments. Those are in turn food for other animals. Furthermore, they oxygenate the surroundings due to tube irrigative action of the worms (Alves, 2017). The biodiversity keeps increasing up to a critical density of 500 to 1000 individuals per m^2 (van Hoey et al., 2008).

Intertidal beds of *L. conchilega* also serve as feeding grounds for birds (Godet et al., 2008). (de Smet et al., 2008) showed a density of wading birds that was 46.6 higher on areas occupied by tube worms compared to areas without tubeworms. This was attributed to the much higher abundance and biomass of microbenthic species living on these biogenic reefs. For this same reason areas populated by *L. conchilegga* also serve as good feeding grounds for fish (particularly flatfish) (Godet et al., 2008).

4.2.4.1. Biobuilder aspects of tubeworms

Lanice reefs can be effective biobuilders as they consolidate sediments and thus stabilize the bed (Sterckx et al., 2020). As stated in section *4.4. Tubeworms*, tubeworms have multiple effects on sediment dynamics and hydrodynamics. Firstly, the horizontal velocity in the stream direction is attenuated by *L. conchilega* considerably both up- and downstream of the tubes (Friedrichs & Graf, 2009). Therefore, these structures will cause wave attenuation and act as an effective breakwater. Due to the lowered stream velocity, there is a net deposition of sediment between the tubes. Both for a high and low density of tube worms, sediment will accrete. Furthermore, tubeworms act as a sediment stabilizer as less sediment reworking due to waves will occur in their presence (Alves et al., 2017).

The effectiveness of the aforementioned effects depends on the density of *L. conchilega*. The density of the species can vary a lot but is important to consider. A coverage density (ratio tube worms' area to total patch area) up to 40% has been observed in field studies (Nicolaidou, 2003). If the coverage density is lower than 1%, turbulence will cause net erosion, but if the coverage density is larger than 1% sediment will be deposited within the tube patch (Rabaut et al., 2009). According to a modelling study (regarding different tube densities) the flow velocity decreases fast with an increasing tube density, especially at densities lower than 1000 individuals per m^2 this effect is large. In the model a tube diameter of 0.5 cm was used (Borsje et al., 2014). Thus, a density of 1000 individuals per m^2 can be rewritten as a coverage density of approximately 2%. When implementing *L. conchilega* as biobuilders to effectively attenuate waves, accrete sediment and increase biodiversity, the aim for the density should be 1000 individuals per m^2 or a coverage density of 2%.

L. conchilega juveniles are found to settle on adult tubes (Callaway, 2003). Introducing the species in a new environment might therefore be difficult. However, interesting experiments are performed by Coastbusters (Wyns et al., 2020) in growing larvae on substrata. Small scale implementation on several substrate have been executed and the results are promising. The larvae of *L. conchilega* are pelagic (aulophore larvae) for the first two months of their life, after which they move to the benthic juvenile stage where they attach to adult tubes. The step from aulophore larvae to the benthic juvenile stage is crucial for the introduction of *L. conchilega* on a new site. Coastbusters (Wyns et al., 2020) investigated the attachment of larvae to different substrata of geotextiles. The larvae should be two months old and have five to seven tentacles to be able to attach to adult tubes or substrata. No difference in attachments to the different geotextiles was found, but it was found that the geotextiles do attract larvae. Further in-depth investigation into different substrata might be necessary to understand the potential preference of larvae attachment (Wyns et al., 2020).

4.2.5. Seaweed


Figure 8 Saccharina latissima (Sugar Kelp), one of the major kelp species present in the North Sea. From: (Visch, 2019).

Seaweed, also known as macroalgae, are species of multicellular algae that thrive in marine environments. They can be divided into three subgroups: 1) green macroalgae, 2) brown macroalgae and 3) red macroalgae. The most common species found in the North Sea include *Ulva lactuca* (Sea lettuce), *Saccharina latissima* (Sugar kelp) (*figure 8)*, *Palmaria palmata* (Red dulse) and *Laminaria digitata* (NIOZ, 2023).

Macroalgae strongly influence ecosystems. Especially in areas with an otherwise homogeneous substrate the added variety can create suitable habitats for many species of fish and invertebrates (Theuerkauf, 2021), like the kelp forests at the Scottish coast accommodating birds, seals and otters (Smale et al., 2013). Apart from serving as a food source and substrate for settlement, the three-dimensional structure of the seaweed, whether it's floating or fixed to the bottom, creates a host of gradients in many variables, and with it an increase in biodiversity (Smale et al., 2013). The canopy protects from light and heat, decreases current velocity, and mitigates the effects of the tides, both in the case of water levels that are too high and too low for certain species (Umanzor, 2019).

Besides this, seaweed can remove large amounts of nutrients from the water. In eutrophicated coastal waters this can be a major help in stabilizing the ecosystem (Roleda et al., 2019). The green macroalgae (*Ulva lactuca)* has been shown to have a positive effect on its surroundings by preventing the bloom of several harmful algal species (Tang & Gobler, 2011).

Even though areas holding a lot of seaweed have a higher diversity and abundance compared to adjacent barren areas (Theuerkauf, 2021), the total diversity of an area still largely depends on a variation in habitats. Barnes (2010) reported a large amount of seagrass dying in a South African estuary by being overshadowed by massive seaweed growths, leading to a large shift in species composition. The importance for variation in habitat types is also visible further up the food chain. Where large seaweed beds are a hotspot for birds that are adaptive feeders, those that need clear vision to hunt fish usually stay away from these areas (Besterman et al., 2020; Martinez-Curci, 2022).

4.2.5.1. Biobuilder aspects of seaweed: kelps

Kelp is one of the largest subgroups of seaweeds and are known to be effective ecosystem engineer plants in temperate and polar coastal regions worldwide (Graham et al., 2007). In the North Sea, one of the dominant kelp species is *Saccharina latissima,* commonly known as sugar kelp (NIOZ, 2023; Lüning & Mortesen, 2015). This species can grow up to 5 meters long and has a width of approximately 20 centimetres (Dickinson, 1963). It grows on top of rocky seabed or hard substrates, to which it attaches by root-like holdfasts.

Besides habitat creation and providing several other ecosystem services as mentioned in section 4.2.5. Seaweed, kelp has an important function regarding natural coastal protection. Due to their flexibility, kelps can adapt and reconfigure under strong flow velocities and currents while still reaching relatively large sizes (Morris et al., 2020). In their turn, kelps and kelp beds do not only adapt to wave motion but also influence the wave motion and currents in their direct environment. According to Morris et al. (2020), kelps (and other aquatic macrophytes) "*have a significant effect on the structure of mean currents and surface waves through exerting drag in the water column"*. This drag created by kelp assists in wave attenuation in near-shore environments as well as helping to reduce sediment transport, which positively affects coastal protection.

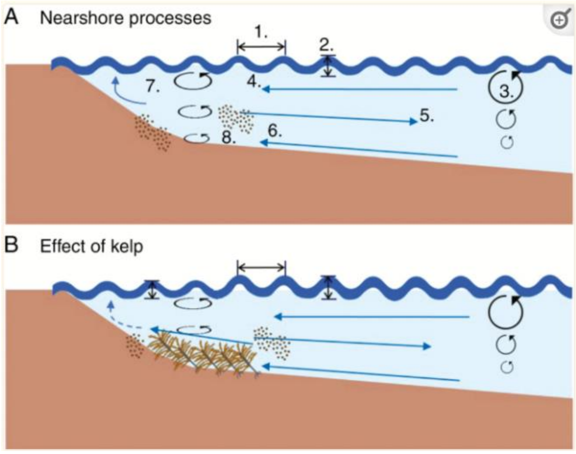

Figure 9 Graphical explanation of the effects of kelp on orbital current motion and drag in the water column. From: Morris et al., 2020

Next to exerting drag, kelp can also lower the orbital motion of near-shore water. *Figure 9* shows the effects of kelp for natural coastal protection. The impact of this is dependent on the site-specific physical- and hydrodynamic conditions (e.g. wave period and water depth), as well as the characteristics and morphology of the species of kelp (e.g. flexibility and leaf surface area) (Morris et al., 2020). Kelps and other seaweed species also provide cultivation opportunities that may be very interesting and plausible in the waters of the North Sea, something that is already being experimented with in front of the Dutch coastline (North Sea Farmers, 2023).

4.2.6. Seagrass

Seagrass beds are biodiverse ecosystems that occur worldwide in both tropical and temperate seas (McKenzie et al., 2020; Short et al., 2007). Two species of the seagrass family (*Zosteraceae*) occur in the Netherlands; *Zostera noltii* and *Zostera marina (figure 10)* (Duistermaat, 2020), the latter being most important to the temperate North-Atlantic bioregion (Short et al., 2007). Both species were abundant in Dutch coastal waters (65-150 km^2 in the Wadden Sea around 1900) but have declined significantly (<1 km^2), mainly over the past hundred years (de Jonge et al., 1996; Den Hartog, 1987; Den Hartog & Polderman, 1975). Several causes have been proposed and proven to some degree, including the so-called 'wasting disease', eutrophication, trawler fishing, overgrowing algae, closing of the Zuiderzee, and even natural population fluctuations, but as of yet there is no conclusive theory for the decline (Den Hartog, 1987; den Hartog, 1994; Den Hartog & Polderman, 1975; Katwijk et al., 1999). Besides these two *Zostera* species, *Ruppia maritima* and *Ruppia spiralis* also occur in the Dutch coastal zone (Duistermaat, 2020), though it seems the growth rate of these species decreases considerably at the salinity of undiluted sea water (Verhoeven, 1979).

Figure 10 Zostera marina meadow in clear coastal waters. From: (TU Denmark, 2019)

Seagrass beds have beneficial effects on biodiversity and the ecological value of their direct environment. For instance, seagrass provides shallow-water habitats for a wide diversity of organisms, provides an important food source, and functions as a nursery for several fish species' newborn and juveniles. Lastly, seagrasses support sediment stabilization and water filtration (Bertelli & Unsworth, 2014; Lilley & Unsworth, 2014; Polte et al., 2005, 2005). Polte & Asmus (2006) have found that seagrass was significantly more effective in adhering fish eggs compared to brown algae; the concentration of the herring spawn (*Clupea harengus*) was twenty times higher in seagrass. Besides this, herbivorous birds (e.g., *Branta bernicla*, *Anas penelope*) feed on the seagrass while waders and other waterfowl (e.g., *Calidris canutus*, *Haematopus ostralegus*) feed on the organisms associated with this vegetation (Nacken & Reise, 2000; Unsworth & Butterworth, 2021). Additionally, the beds filter nutrients and trap sediments, which stimulates benthofauna (Asmus & Asmus, 2000). There is clear evidence that patchiness of seagrass beds and connectedness with surrounding habitats increase species diversity (Bouma et al., 2009; Duffy, 2006). Understanding how seagrass supports biodiversity requires consideration of landscape-scale spatial connections (Whippo et al., 2018).

Kim et al. (2014) found that, in the Jindong Bay, Korea, *Z. marina* reproduces exclusively using seedlings on sites in relatively deep water, with the older plants completely dying of during the winter. In contrast, in shallow water shoot recruitment was primarily achieved by asexual reproduction. These life history traits of *Z. marina* would characterize this species as an intermediate between an annual and perennial plant, likely as a strategy to achieve persistence under less favorable environmental conditions (Kim et al., 2014). This is supported by research from Gagnon et al. (1980), which has shown no genetic difference between the annual and perennial forms. According to findings of a planting experiment on intertidal mudflats in the Dutch Wadden Sea, the plants also exhibit an annual life cycle (M. Van der Kamp, personal communication, June 15, 2023). This may be explained by adaptation of *Z. marina* to less than favorable conditions for a perennial life history strategy. The remaining natural patches of *Z. marina* in the Wadden Sea mainly consist of individuals of the perennial form (de Jonge et al., 1996).

According to De Jonge et al. (1996), the water quality in the Wadden Sea does not negatively affect the growth of seagrass to at least 60 cm below mean sea level. The most suitable depth, however, is between 20-40 cm below mean sea level (de Jonge et al., 1996). In line with these claims, another report describes the limits of annual *Z. marina* beds in terms of sea depth to be between mean sea level and 30 cm above it (limited by desiccation), to a couple decimeters below the mean sea level (limited by water dynamics, e.g., wave energy, current velocity, but also fisheries) (van Katwijk et al., 2000). The perennial *Z. marina* beds occurred in the deeper parts, as it is more susceptible to desiccation, but never occurred more than 20 cm below mean low tide, where light availability and currents become most limiting factors. Reintroduction seems most realistic in sheltered areas and bays, since the flow velocity tolerated by seagrass is rather low. Higher currents in shallow waters lead to higher erosion and increased turbidity, which results in lower light transmission through the water column (de Jonge et al., 1996; de Jonge & de Jong, 1993). *Z. marina* can tolerate a maximum of 1.2-1.5 m/s current velocity (Fonseca et al., 1983).

4.2.6.1. Biobuilder aspects of seagrasses

Seagrasses cause energy dissipation by extra friction and wave breaking. Furthermore, they cause energy reflection in the offshore direction. Due to the lower energy availability the flow speed decreases and thus seagrass will trap sediment. Besides this, the sediment resuspension by the waves will decrease in the presence of seagrasses (Ondiviela, 2008). Both biological and physical factors influence on the effectiveness of seagrass functioning as a breakwater. Optimal energy attenuation is reached when seagrasses occupy a high proportion of the water column, both vertically and horizontally. As the interaction area between the seagrasses and the water is highest this way. Furthermore, the density, biomass and plant stiffness are important factors for the effectiveness of seagrasses as a breakwater. In general, more biomass and bigger, stiffer leaves result in more energy attenuation. Therefore, *Z. marina* might be a better option to implement than *Z. noltii*. The highest wave attenuation and sediment trapping by seagrasses are found in moderately energetic environments, with low wave energy (Ondiviela, 2008).

Seagrasses do not grow under stressful hydrodynamic conditions and a reintroduction of the species might therefore be difficult. It may be more beneficial to transplant juvenile or adult plants from a donor site to a receptor site instead of sowing (e.g. by the '*Kitspuit'* technique) new plants. However, this is highly dependent on the site-specific hydrodynamic and physical conditions (M. van der Kamp, personal communication, June 15, 2023). Seeds best settle in muddy and sheltered environments with enough light availability and areas that have a permanent layer of water during low tide. Furthermore, when sowing it is important that a sufficient number of new seeds is produced in the next season to maintain the population. To enhance the settlement and development of sowed/transplanted seagrasses, other physical structures may assist in stabilizing the sediment for optimal development conditions. Mussel beds could provide shelter for seeds to settle (van Katwijk, 2003; van Katwijk et al., 2016). Another option could be a mat made of Seacrete or similar materials on the seabed in which some adult seagrass plants are introduced. This way, seeds can settle more easily in between the adult seagrass plants and existing plants have a more fixed sediment to develop a root and rhizome system in (A.J. Murk, personal communication, May 31, 2023).

Rijkswaterstaat is working on seagrass recovery in the Wadden Sea. Here the seeds are injected in the seabed with an adapted sealant gun in which the seeds are mixed with mud ('*Kitspuit*' technique). This method was successful in the Wadden Sea and is therefore a good opportunity at the Banjaard (Rijkswaterstaat, 2022). The seagrasses used in the project by Rijkswaterstaat are annual plants, meaning that they disappear during the winter season (M. van der Kamp, personal communication, June 15, 2023). The seagrass bed thus is bare during winter season, diminishing the breakwater effects of the seagrasses. However, due to increased hydrodynamic forcing, its necessity is at its highest during this period (Ondiviela, 2008). This might impose some problems when using seagrasses as biobuilder. As the seeds best settle in a muddy, sheltered environment like the lagoon behind the island, seagrasses might not be that effective as a biobuilder for enhancing the direct line of coastal defence in a breakwater landscape.

However, since other designed experiments will have an impact on the strength of the currents and will function as coastal defence, seagrass might be used as direct breakwater dependent on the outcomes of the other experiments. When the conditions are favourable enough, seagrass can potentially be grown on the west side of the island. When this will be established, seagrass can also help in sediment trapping and wave attenuation on the western side of the Banjaard.

Seagrass might be flourishing under climate change conditions of elevated CO_2 concentrations. According to research an increased dissolved CO_2 concentration promotes seagrass growth. Therefore, it might be easier to grow seagrass in the future (Palacios & Zimmerman, 2007).

4.2.7. Glasswort (*Salicornia*)

Salicornia europaea (figure 11), better known as Glasswort or Samphire, is a species of intertidal halophytes that thrive in brackish and saline environments like intertidal mudflats, salt marshes and other alkaline flats. *Salicornia* has a high tolerance for saline conditions up to 3% NaCl (Patel, 2018), making it a very (climate) resilient plant that can settle under harsh conditions as pioneer species. *Salicornia* has historically been important in the glass-making process, as the plants' ashes contain sodium carbonate used in the glass-making process. Nowadays, *Salicornia* is mostly used for human consumption as this crunchy and salty plant has proven to be beneficial for a wide range of health aspects and diets (Patel, 2018).

Figure 11 Salicornia europaea. From: Great Bay National Estuarine Research Reserve.

Salicornia is also a key pioneer species that regularly is the first to colonize Northwestern European salt marshes and other barren alkaline flats. In doing so, it facilitates better conditions for other perennial salt marsh vegetation to settle by trapping seeds and sediment. This supports the growth of plants like *Spartina anglica* (Common cordgrass)*, Puccinellia maritima* (Common salt marsh grass) and *Limonium platyphyllum* (Sea lavender), which in their turn are key species for the establishment of a diverse vegetation community (van Regteren et al., 2020). Baptist et al. (2021) found that salt marsh vegetation such as *Salicornia procumbens* prefers soft sediments for settlement. The sowing of *Salicornia* on mudflats can kickstart an artificial salt marsh. Since salt marshes and mudflats significantly contribute to coastal protection by trapping sediment and wave attenuation (EcoShape, 2023; Marin-Diaz et al., 2023), the use of *Salicornia* as a biobuilder to kick-start such ecosystems can be highly valuable for future coastal protection.

To stimulate the growth of salt marshes by the establishment of pioneer *Salicornia* species, it requires proper site identification, which according to van Regteren et al. (2020) is mainly defined by a set of boundary conditions. These conditions are sediment dynamics, hydrological conditions, temperature, precipitation and inundation frequency and regime. The germination of seeds depends on temperature (higher than 10.5 degrees Celsius), precipitation (seeds germinate better with fresh water input) and inundation frequency (germination starts at 2 days of no inundation) (van Regteren et al., 2020). These conditions need to be taken into account when kickstarting the growth of *Salicornia* and therewith the salt marsh.

4.2.8. Marram grass (*Ammophila*)

Marram grass (*Ammophila arenaria*) (*figure* 12) is a terrestrial pioneer species that is mostly planted close to the shoreline to trap windblown sediment. As *A. arenaria* is a pioneer species, it can easily grow in newly created environments, like the Banjaard. As it will trap sediment, it stimulates dune formation (Borsje et al., 2011). Another important characteristic of this species is its burial and flooding resistance since the rhizomes are expanding vertically (Valérie et al., 2019). With increased dune formation, the stability of the island enhances, which results in a higher success rate of the Banjaard as a breakwater island. However, there are also dune mobility restoration programs going on, for example in Vlieland (Bergman, 2022). This is performed to increase the dune mobility and thus the flexibility of the coast. Another reason to destabilize the coast is to increase the biodiversity as stabilized coasts cause a decrease in biodiversity (Arens et al., 2013). If the Banjaard is aimed to have a flexible dune system, the sand will likely be dislocated in the surrounding sea as the island is rather small. To enhance the long-term quality of the Banjaard as a breakwater landscape it is suggested to plant marram grass and thereby stimulate stable dune formation.

Figure 12 Ammophila arenaria (Marram grass) growing on sand dunes. From: RTE, 2020

4.3. Man-made structures to facilitate biobuilders

To generate a regime shift towards a more stable physical environment, stress-resilient species like some ecosystem engineers can be introduced to ‘kick-start’ the creation of habitable environments for other species (Borsje et al., 2011; Crain and Bertness, 2006). However, sometimes physical conditions are not suitable for immediate introduction of biobuilder species as the conditions are too harsh for proper settlement. An example is when the sediment is highly dynamic due to currents and waves, and therefore vegetation is unable to root in the sediment and thus cannot settle properly. Human interventions might assist in the kickstart of a biobuilder species colony by facilitating the proper settlement conditions for the species. This can for example be done by introducing man-made structures that provide a substrate for settlement (Borsje et al., 2011). To elaborate on the different available implementations and their possibilities, a shortlist of man-made structures designed to facilitate biobuilders is developed below.

4.3.1. Shellfish Gabions

For the creation of epibenthic bivalve reefs like oyster and mussel reefs, a hard substrate is necessary for the settlement of spat (free-floating bivalve larvae) as they need to attach themselves to a structure before they will develop into filter feeding juveniles and adults. These, in their turn, provide new substrate with their shells even after death. This allows a reef to continue growing (Walles et al., 2016). To be able to establish or recover bivalve reefs on barren and sandy seafloor, gabions (closed cages) containing shells of oysters or mussels can be placed on the seabed to provide a fixed substrate to settle on (*figure 13*) (EcoShape, 2015). These gabions are made of steel wire and will corrode over time, leaving only the shells and the newly formed reef. These intertidal reefs have been proven to prevent erosion and stimulate local sedimentation. The downside is that a lot of sand is trapped, which eventually may cause problems for the existence of the reef according to EcoShape (2015), who experimented with these in the Eastern Scheldt (NL) already and obtained promising results.

Figure 13 Gabions filled with oyster shells provide a substrate for new reef formation. From: www.ecoshape.com

4.3.2. Artificial Reef Structures

Artificial Reef Structures are hard, man-made structures that help to facilitate the start or recovery of reefs by providing shelter, substrate, and protection from strong currents as well as functioning as a hub for new food sources for marine life (Layman & Allgeier, 2020). Several artificial reef structures were designed and succesfully pilotted during the last 10 years. Examples include Reef Balls, 3D-printed reefs, Modular Sealife Systems (MOSES), Endless Reefs and Reef Enhancing Breakwaters (REBs) (Boskalis, 2023).

1. Reef balls are preconstructed concrete balls that are hollow on the inside (*figure 14*). According to Warzecha (1997), these are *"hollow dome-shaped structures resembling natural coral heads produced by some coral species. They have holes of different sizes which allow fish and other marine organisms to enter the interior"*. Reef balls, next to providing hard settlement substrate, thus also provide a habitat for a wide variety of other marine species. The holes in the ball are designed in such a way that a vortex is created within the chamber inside the dome, allowing feed influx for corals and invertebrates (Warzecha, 1997). However, due to the void space in the middle of the reef ball mainly big species live here, or the oxygen is depleted due to organic matter accumulation. This could be overcome by adding concrete building blocks to the void space (Hylkema, 2022).

Figure 14 Reef balls create a habitat for a wide variety of marine life on a barren seafloor in Bali. From: Matthew Oldfield photography.

2. Several projects succeeded to make predesigned, 3D-printed reef structures from concrete (XtreeE, 2023; Boskalis, 2023) which have optimal crevasses and surface areas to *“maximize the reproduction and population of the target underwater species”,* according to XtreeE (2023). These large structures can be placed in the water as a whole which can be seen in *figure 15*.

Figure 15 3D-printed artificial reef ‘X-Reef’in the Calanques National Park,

3. Modular Sealife Systems (MOSES) are hexagonal tubes that can be linked together to build artificial reefs and serve as habitat for aquatic organisms (*figure 16*). The tubes provide space to hide, forage and mate, whilst the outside has a rough texture that allows for larvae settlement and vegetation growth. Every single unit has the possibility to be modified and adjusted to a specific microhabitat to target a single species. These are made from Blast furnace concrete, reducing the CO2-emissions by 50% over traditional concrete (ReefSystems, 2023).

Figure 16 MOSES reef placed in the Wadden Sea. From: ReefSystem (2023)

4. Another solution by ReefSystems is the ReefPool, which is a *“structural performing armor units that can be used for dike reinforcements while promoting population growth of marine organisms”* (ReefSystems, 2023). These pools function as intertidal rock pools on hard coastal protection structures like dams and dykes and fill up with new water during the daily high tides. They contain shells on the inside that create a settlement substrate for bivalve species and vegetation. The pools create a habitat for several crustaceans, mollusc and algae species during low- and high tide and with it improve the ecological value of the dyke or dam (*figure 17*). The outside has a rough surface with dents as well to promote habitat creation (ReefSystems, 2023).

Figure 17 Reef Pools placed on a dam during low tide. From: ReefSystem (2023)

5. Reef Enhancing Breakwaters (REBs) are lego-like ReefBlocks developed by Reefy that can serve as breakwater while simultaneously providing shelter, substrate and foraging spots for a wide variety of aquatic organisms as EcoBlocks are placed between the breakwater blocks (*figure 18*). This is a modular and adjustable system like MOSES, and can be tailored to a specific site or target species. They are monitoring the first pilot in Rotterdam (the Rotterdam Reef) currently (Reefy, nd.).

Figure 18 ReefBlock and Eco-blocks designed by Reefy as units for modular artificial REB system (Reefy, nd.)

4.3.3. Concrete Slabs

When designing (partly) submerged concrete structures for dams, dykes and bridges, concrete slabs or plates can be mounted on these structures (*figure* 19). Creating a different texture by making indents or holes in the concrete slabs will provide better physical conditions for small organisms to settle. Organisms like algae, barnacles, mussels and periwinkle snails may inhabit these nooks and crannies when placed in intertidal zones. The improved settlement of algae and macrobenthos adds to improved ecological value on a micro scale which supports larger (meso-scale) organisms that function as ecosystem engineers (Borsje et al., 2011; Martins et al., 2010).

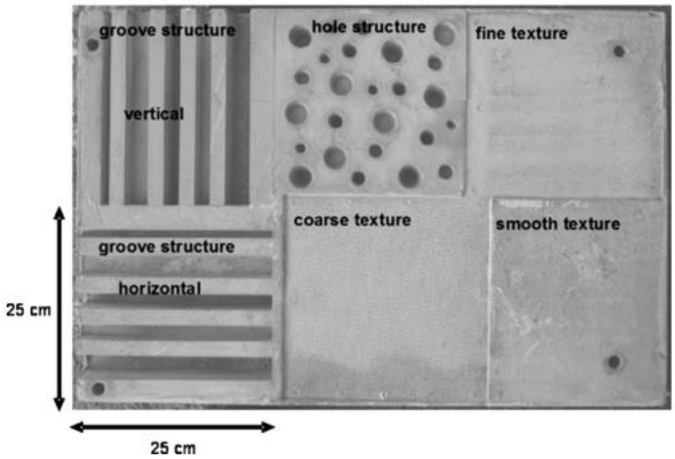

Figure 19 Different structures and textures on a slab that can be mounted on concrete constructions. From: Borsje et al., 2011.

4.3.4. Seacrete

One of the most recent developments in artificial reefs is the creation of Seacrete, a substance made of a mixture of concrete substances and ground shellfish shells to make a more sustainable and cyclical material for the construction of artificial reefs (AJ. Murk, personal communication, May 31, 2023). One of the most important contents is REEFGLUE®, an adhesive product designed by WUR inspired by the proteinaceous complex coacervate glues created by sandcastle worms (*Phragmatopoma californica*) to build their structure (WUR, 2023). Since this is a product still under development, not much has been written or found about it and the effects or implications that may come with the use of this product. However, the first pilots are looking promising (AJ. Murk, personal communication, May 31, 2023).

4.3.5. Brushwood groynes

Brushwood groynes are made by putting poles into the ground in two rows. Between the poles there is 40 centimetres of space to fill with bundled brushwood, mainly branches from willows (*figure 20*). These groynes can be used to create a lee so that when a new reef or saltmarsh needs to be built the waves are subdued. Because the waves and currents are attenuated when building the dam perpendicular to the current, the sediment is kept in place and the reef has the chance to grow. If you would not construct these groynes before creating for example a new shellfish reef, it will immediately be damaged and will not get a chance to flourish. The dams should be installed at low tide water level. The total height of the dam should be as high as the water level during the spring high tides. After the reef is fully developed the groynes can be removed. However, because they are made of natural materials they will slowly decay. After five years, the brushwood in between the poles will be decayed and after fifteen years the poles are gone as well (R.W. Pol, personal communication, June 23, 2023).

Figure 20 Brushwood groynes at the saltmarshes in Delftzijl (Nature-based salt marsh development in the port of Delftzijl, n.d.).

4.3.6. Sinking matress

A Sinking mattress, 'zinkstuk' in Dutch, consists of a large braided mat made of brushwood and poles with a sheet of geotextile or a burlap cloth in between. Geotextile is made of plastic whereas the burlap cloth is not and is therefore recommended as introducing it will do less damage to nature (R.W. Pol, personal communication, June 23, 2023). This burlap sheet will let water pass, but sand will not be able to go through. Brushwood are twigs from the willow tree and the mat has a cross over pattern (*figure 21*). This mat is designed to keep the sediment of a dike or on an eroding beach in place and to prevent currents and wind to erode the beach away. Van Aalsburg BV, a Dutch coastal protection company works with these sinking matrasses and already did a successful similar project in front of the Belgium coast at Wendruine (Zinkstukken Wenduine, 2023).

Figure 21 Installation of a sinking mattress at the beach of Wendruine (Zinkstukken Wenduine, 2023).

5. Seafood production options at the Banjaard

The pilot project aim of using Nature Based Solutions (NBS) to introduce a breakwater landscape will develop into a new ecosystem with options for aquaculture and seagriculture, contributing to a local food supply source. Aquaculture is the "breading, rearing, and harvesting of fish, shellfish, algae, and other organisms in all types of water environments" (NOAA, nd.a), since this initiative is taking place in the North Sea the seagriculture concept is introduced. The aim of this chapter is to explore the possibilities that are feasible in the Banjaard to produce commercial seafood without harming the ecosystem.

To fulfil this objective the chapter will be developed using the following methodology: a short introduction of the current seagriculture in the area, and an overview of species and seafood initiatives that can be found or applied to the Banjaard. Among the initiatives explained seagrass farming, seaweed farming, sea ranching, bivalve production, and Integrated Multi-Trophic Aquaculture (IMTA) systems are included.

5.1. Current seagriculture at the Banjaard area

Figure 22 Current oyster farming in the Eastern Scheldt (Zeeuwse oesters|Oesterij, n.d).

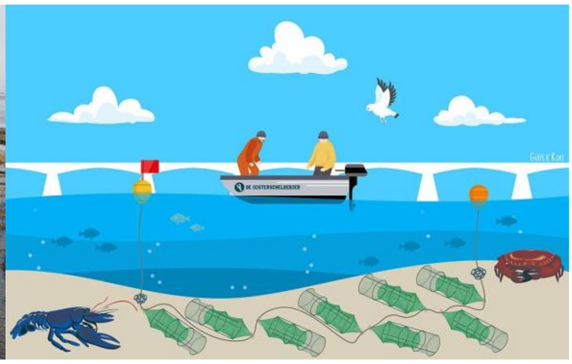

Figure 23 Schematic overview of how lobsters are caught in the Eastern Scheldt using traps (Pieter Van de Zande, 2022).

Zeewaar is the first seaweed farm that sustainably and biologically farms seaweed in the Netherlands. Zeewaar was first established in 2013 in the national park of the Eastern Scheldt, close to the Jacoba harbor, which is close to the future location of the sandbank Banjaard. The seaweed produced here is mainly meant for consumption for humans. Last year the company was sold to the Seaweed company, which is currently trying to expand its production of seaweed and advertise the use of seaweed to grow the market. Currently, the seaweed farm covers two ha, and the harvest is locally processed (DPG Media Privacy gate, n.d.).

Oyster farming is also widespread in the Eastern Scheldt (*figure 22*). Especially near Yerseke, many oyster farms can be found. For example, the Oesterij was founded in 1906 by the family Dhooge, who specialized in farming shellfish. Much time and energy are invested in researching different cultivation techniques and cultivation areas to improve the oyster production of the farm. The type of oysters currently grown near the Eastern Scheldt is the *Crassostrea gigas*, using a bottom culture (here they grow the oysters on the bottom instead of on ropes). All forms of bottom culture are in principle harmful, because once you harvest the shellfish, you will kill many predators and smaller animals that live around the shellfish. Furthermore, Mussels and oysters generally grow faster on ropes (AJ. Murk, personal communication, June 24, 2023; Zeeuwse oesters|Oesterij, n.d).

Furthermore, small sustainable fishermen can catch Eastern Scheldt lobsters and the North Sea crab in the Eastern Scheldt between the end of March and July (*figure 23*). Only a select number of fishermen can catch lobsters, and the area is divided into separate sections, which are raffled between the fishermen per season. The fishermen are only allowed to use traps. Fish waste from the fish trade is often used as bait, such as cod or salmon heads, which is a favorite meal for both lobsters and crabs (Pieter Van de Zande, 2022).

Fishermen working with towed nets are not that common anymore in the Eastern Scheldt, and the number of fishermen that use this technique is still declining, mainly because there are fewer permits available as ships with towed nets harm the environment when they go over the bottom of the sea. For the fishermen that still use this technique. The Eastern Scheldt is a good fishing spot in case of bad weather conditions because of which they cannot fish on the North Sea. However, the area in which they can fish within the Eastern Scheldt is limited due to the draft, the distance between the waterline and the deepest point of the boat, of the ships, and oyster and lobster farms. The main species they catch are flounder, lobster, and eel. This method of fishing only occurs in dynamic areas with low biodiversity, because using towed nets damages the plants and reefs that grow on the bottom and there is a lot of bycatch that does not survive (Goudswaard, 2007). As a result, biodiversity decreases in areas where they perform these fishing methods.

Unfortunately, because of the creation of the storm surge barrier, climate change, human influence, and because several rivers are no longer connected to the Eastern Scheldt, the water quality of the Eastern Scheldt is decreasing. Because of the decreasing water quality, the production of seaweed and shellfish in the area could be negatively affected. That is why the farmers that are currently operating in the Eastern Scheldt are also open to investigate if new areas outside the Eastern Scheldt might be used for seagriculture, for example, around the Banjaard (Provincie Zeeland et al., 2018).

5.2. Seagrass farming

5.2.1. Theoretical background of seagrass farming

"Seagrasses provide shelter and food to an incredibly diverse community of animals, from tiny invertebrates to large fish, crabs, turtles, marine mammals and birds". It has been used in the past "to fertilize fields, insulate houses, weave furniture, thatch roofs, make bandages, and fill mattresses and even car seats" (OCEAN, nd.a), but nowadays there is no need to harm the ecosystem for these products (AJ. Murk, personal communication, June 24, 2023). Seagrass belongs to the monocotyledons, just as the terrestrial grass, having roots, leaves, flowers, and seeds. They also have a horizontal rhizome that grows parallel to the ground, inside the sediment.

Seagrass flourishes in salty or brackish environments that have gentle slopes and protected shallow coasts, usually 1-3 meters depth. The species of seagrass are diverse in morphology and several other characteristics, but they also have a lot of similarities. The small species of seagrass also have small rhizomes, a short lifespan and produce a large number of small seeds. On the other hand, the large-bodied have large and thick leaves, longer lifespan and produce fewer large seeds (OCEAN, nd.a).

The genus *Zostera* of seagrass is formed by nine species, has a large presence worldwide and in the North Sea, they have been widely researched. *Zostera marina* is the predominant species in the North Atlantic, and usually grows as monoculture although it can co-occur with *Z. noltii* in shallow intertidal and subtidal areas as the Banjaard (Larkum, 2006).

Table 4 Morphological comparison of the two seagrass species expected to settle on the Banjaard. Source Larkum et al. (2006).

Species	Average length (cm)	Width (mm)	Leaf tip	Seed length (mm)
Z.marina	80	3-12	Rounded	3-4
Z. noltii	20	0.5-1.5	Rounded often notched	1.5-2

5.2.2. Advantages

Besides its suitability as ecosystem engineer, seagrass was in the past a source for seagriculture (OCEAN, nd.a). However, the area around the Banjaard that is available to bring back the seagrass would likely not be large enough to sustain a healthy ecosystem and at the same time be harvested for humans needs. The seagrass fields in the Wadden Sea would be more suitable for harvesting seagrass as they are a lot larger. Therefore, it would be better to keep the seagrass plants around the Banjaard untouched and instead focus on harvesting the animals that come live in this type of habitat in a balanced way (M. van der Kamp, personal communication, June 15, 2023).

Since seagrasses have roots, they help stabilize the sediment, protecting against the erosion, and the leaves do the function of wave attenuators. Through the absorption of nutrients and photosynthesis they also improve the water quality and fixate CO_2 (OCEAN, n.d.a). For CO_2 sequestration, previous research from Harahap et al. (2021) investigated how much CO2 is sequestered in a squared meter covered with a monospecies *Enhalus acoroides* in less healthy conditions on the coast of Central Tapanuli Regency. The results estimated stored CO_2 in a range of 257.87-290.90 g C_{org}/m2, which can be used to give an indication of the amount of CO_2 that can be stored in the seagrass field surrounding the Banjaard.

Moreover, the presence of a leafy underwater canopy becomes an attractive shelter for juveniles, small invertebrates and fish, this is why seagrass ecosystems are regarded as nurseries. From a seagriculture perspective having a nursery increases biodiversity and helps to the regeneration of the harvested species of the seafood supply. (OCEAN, n.d.a) Therefore, an extra analysis into the possible menaces is here developed (OCEAN, n.d.a).

Studies like Bertelli et al. (2014) analysed which species find seagrass an adequate habitat for their juvenile stage. This research was performed on Wales coast in the UK, and resulted in the identification of juvenile pollack, whiting, bib/pout, saithe, cod, plaice, brill, herring and mullet, being plaice, pollock and herring the most abundant among them. It is still unknown which juvenile commercial species will stablish on a seagrass ecosystem in the Banjaard.

These are not the only species that can inhabit a seagrass ecosystem formed by *Zostera marina*, the list also includes other commercially important fish and shellfish species. The decline of species like cod, flounder and scallops in the North Sea is actually associated with the amounts of *Z. marina* diminishing during the last decades (Larkum, 2006). The introduction of *Z. marina* in the Banjaard could have a nursery effect on the previously mentioned species in the North Sea. This species of seagrass could be regarded as a way to create a new habitat suitable for sea ranching if the juvenile fish and shellfish that refuge in the seagrass are harvested when they become adults (see 5.6. Sea ranching).

5.2.3. Risks

In the 1930s the Z. marina population across the North Atlantic region was reduced by approximately 90% under the influence of a pathogen, among other reasons. There have been several attempts to restore seagrass ecosystems, 50% of which consisted of Z. marina beds. Grovers et al. (2016) studied the infection susceptibility of this specie by Phytophtora, a genus of plant-damaging oomycetes, using temperature and type of sediment as analysed variables. Among the studied Z. marina there were included samples from Oosterschelde, meaning the results from their research are relevant for the Banjaard pilot project. It is estimated that these pathogenic oomycetes species are responsible for a 44% germination reduction of the seagrass restorations in the Wadden sea. According to Grovers et al. (2016), low temperatures and sandy sediments make *Z. marina* more susceptible to infection (*figure 24*). To ensure the island and ecosystem integrity, an implementation of a control on the presence of these pathogens during winter could be useful. Other options proposed in their research are anoxia conditions during incubation or seed treatment with copper-based compounds or phosphonates (Grovers, 2016).

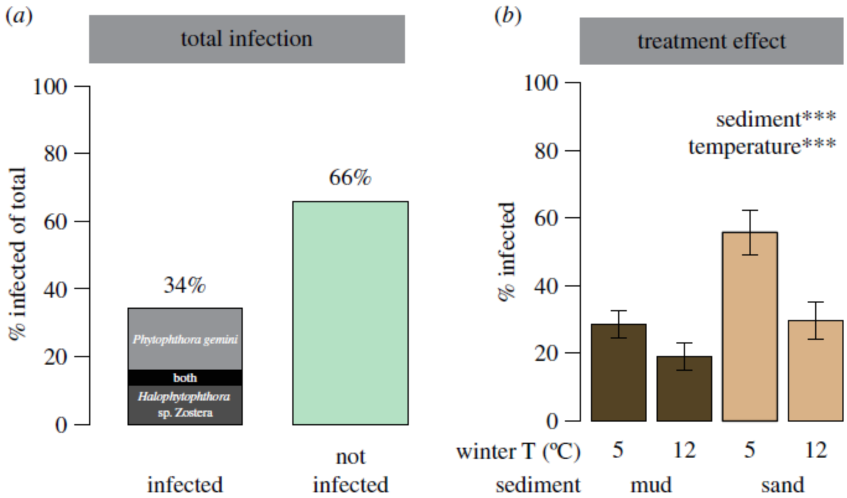

Figure 2422 Results of the study from Groevers et al. (2016): (a) shows the average infected percentage and the species of oomycetes they were infected with, (b) indicates the result for infection efficiency regarding variables as temperature and sediment type.

Animals such as rays and physical disturbances such as strong waves can affect the seagrass development by affecting its binding to the ground, but human influence is the major factor that diminished the presence of this ecosystem. The large amounts of fertilizers and pollution in the water cause algal blooms, the high density of algae blocks the light for the growth of seagrass, while the anchors and propellers harm sections of the seagrass beds, fragmenting the habitat (OCEAN, nd.a). Surprisingly, seagrass species that occur in the North Sea show that temperature rise of the water has little influence on the plants, which makes them relatively resistant against global warming (M. van der Kamp, personal communication, June 15, 2023).

5.3. Seaweed farming

5.3.1. Theoretical background of seaweed farming

Currently, China, Indonesia, and the Philippines are at the forefront of global production in terms of volume of seaweed. However, seaweed farming is practiced in numerous countries worldwide, such as Tanzania, Sweden, Chile, and the United States. The majority of these farms operate in shallow coastal waters, where they contend for space with fishermen and other activities. Seaweed cultivation offers a simple, adaptable, and advantageous solution to benefit ocean ecosystems. It serves as an efficient method for producing nutrient-rich food to meet the needs of a growing population. Unlike traditional crops, seaweed farming eliminates the need for fresh water, fertilizers, land, and pesticides, while also exhibiting rapid growth rates. Certain marine algae can be harvested in as little as six weeks. Furthermore, seaweed can act as an underwater forest, where it plays a crucial role in absorbing nitrogen, carbon, and phosphorus, thereby serving as a valuable ally in the fight against climate change (Farmed Seaweed | Industries | WWF, n.d.).

One of the key challenges in growing seaweeds in natural sea water is to ensure attachment. Typically, seaweed has the ability to attach to ropes, strings or nets. The way in which these nets or ropes are placed in the sea however depends on the tidal range conditions and growth requirements of the seaweed. One choice entails whether to grow seaweed along ropes that run vertically into the sea or grow them on horizontal nets (Pereira & Yarish, 2008). In the case of horizontal nets one can adjust them in different ways (*figure 25*):

1. To attach nets to fixed poles such that they are under water at tide and at the surface at low tide.
2. To suspend them from semi-floating posts such that seaweed is at water surface at high tides and slightly above the surface at low tides.
3. Suspend nets from completely floating rafts such that the seaweeds are at the water surface at both high and low tides.

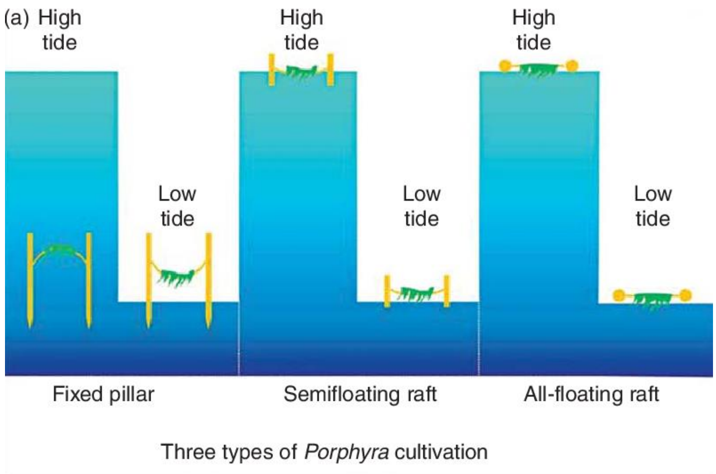

Figure 2523 Three types of Porphyra cultivation. Derived from Pereira & Yarish (2008)

5.3.2. Species used for seaweed farming

Ulva lactuca, or sea lettuce, is a seaweed which is known to grow in the North Sea. Because of its promising ability to fixate nutrient abundance (Lubsch & Timmermans, 2018, as cited in Holdt and Kraan, 2011), it can thrive in conditions where nutrients are produced or excreted in great abundance. IMTA systems generally have a high amount of nutrients because of the high abundance of fish that are fed. Therefore, it would work well to grow and harvest *Ulva lactuca* within the IMTA system as it can survive under the created conditions. *Saccharina latissimi* L., *Palmaria palmata* L. and *Laminaria digitata* L., also grown in the North Sea, are other examples of seaweed which can be used for the same purposes (NIOZ, 2023). *Saccharina latissimi*, also named sugar kelp, is known for its cultivation in the North Sea, as it is an endemic species and spores can be easily bought from suppliers (North Sea Farmers, nd.). Another examples which is consumable, but not grown in the same area is *Porphyra spp*.

Another function of seaweed is that it can be used in the production of agar. This can be eaten but also used as basis for growing cultures in petri-dishes in labs. Agar is extracted from species of *Gelidium*. Because of their high-quality agar content, they are perfectly suited as bacteriological agar, used in microbiology laboratories as growth medium. *Gelidium* is grown around the world and are also grown in regions of Europe in for example France. They are used to seasonal temperatures ranging between 10 and 25 °C, prefer partly shaded habitats, strong tides and sea currents (Mouga & Fernandes, 2022).

5.3.3. Advantages

As discussed earlier, a few initiatives have already been started to cultivate seaweed in the North Sea, there companies like North Sea Farmers and The Seaweed Company are experimenting with growing seaweeds. At the Banjaard these options can also be of great importance since it will give a multifunctional purpose in the areas around it. Seaweeds are important autotrophs which can function as a hiding place and food source for organisms in the water (Mahadevan, 2015). However, they can also be used for human consumption. Seaweeds can contribute to water treatment, as it is capable to remove the excess of nitrogen and phosphorus from the water, counteracting to high concentrations which can pose a threat to the ecosystem. Seaweeds can also be used as human food source, NIOZ (2023) identified seaweeds which are already grown in the North Sea for human consumption.

5.3.4. Risks

Besides the advantages, cases are also known in which seaweeds have a negative impact on the environment as they can overgrow a habitat, especially when they have as characteristic to be fast growing. The main problem is that when seaweeds are not harvested, and the density is not maintained this can lead to problems. Seaweeds can experience an excessive growth, which can be harmful for nature, since the seaweed blooms can cause mortality among flora and fauna (Charlier et al., 2008). In addition, Barnes (2019) mentioned that *Ulva spp*. can cause harmful blooms in response to coastal eutrophication, leading to hypoxic conditions and release of toxic compounds (Barnes, 2019, as cited in Ridgway, 2015; van Alstyne, Nelson, & Ridgway, 2015). Cultivated seaweeds can also be a threat when introduced in a new habitat and therefore the consequences need to be investigated (Eggertsen & Halling, 2021).

In the same way as terrestrial crop production, weeds and diseases can impose a threat to crop growth, this is also the case for seaweeds. In terrestrial crops, pesticides are normally used to counteract weeds and pests. Of course, the application of pesticides is not sustainable in general, and it is hardly impossible to apply for seaweeds, since pesticides will drift away from their target. In that way it would not be contributing to disease and weed control but polluting the environment with unnecessary pesticides. There are several ways to control pests by using herbivores, which should be weed specific and not eat the crop. Control of the environment is another option in which shading and nutrient availability need to be monitored and controlled. Besides that, the desiccant resistant species can be used in intertidal areas (Bernard, 2018).

Currently, researchers at WUR are performing a study called SEASeeds in which the attachment of seaweed seedlings from sugar kelp are tested on cultivation lines. In this way they want to get more insight on the effect of seaweed cultivation on the marine ecology. The small-scale cultivation of seaweeds and their variable detachments results in a cultivation which is inefficient and unpredictable. Besides of high costs is currently unknown how this will impact the marine ecology (WUR, 2022).

5.4. Glasswort (*Salicornia*)

5.4.1. Theoretical background of *Salicornia*

Salicornia species, are fleshy plants and found at the edge of wetlands, seashores, saltmarshes, mudflats etc. Especially at places where saline conditions occur. *Salicornia* is also known as glasswort, pickleweed, samphire, or sea asparagus. *Salicornia* only includes halophytes and are usually composed of almost monospecific plant communities. Generally, *Salicornia* occurs in the innermost part of the saltmarsh, because in that location it is submersed for longer periods. For their taxonomy, two series have been identified traditionally. The first is diploid, and secondly, tetraploid, each of them has numerous species and micro-species (Koyro et al., 2011; Accogli et al.,2023).

Historically, *Salicornia* has been used as a source of soda in glass making. It is also known to have medical uses. For food usage it is used in salads, since it characterizes from its saltiness and crunchiness. Within Europe, this plant is mainly used by harvesting it in the wild, while only in Portugal, The Netherlands, and France the plants of *Salicornia* are cultivated. In Italy, the first attempts of *Salicornia* cultivation for family consumption started already forty years ago around the Lesina lagoon (Apulia, Southern Italy). *Salicornia* can, like other halophilic species, induce the synthesis of metabolites because it can handle the stress of the alkaline environment. This synthesis of metabolites can be useful to humans for their anti-inflammatory and antioxidant power (Accogli et al.,2023).

5.4.2. Advantages

One of the advantages of *Salicornia* cultivation is that they are able to grow in saline conditions. Because these plants can grow in salt water, it saves fresh water that can be used for other practises. Furthermore, *Salicornia* has great economic potential and can grow in saline environments, which are currently not used yet for food production (Koyro et al., 2011). This characteristic will be of advantage in using it as a food source and cultivation around the Banjaard. Only the shoots are harvested, and multiple harvestings per year can be made. In an experiment by Ventura & Sagi (2013) plants were cut in a 3-week interval and showed the highest harvest potential during a 6-month period. Among *Salicornia* species the total number of harvest cycles differed per growing period. *Salicornia* can be grown in different conditions, from seawater irrigated, and wetlands to sand dune conditions with drip irrigation (Ventura & Sagi, 2013).

Moreover, *Salicornia* can be a very profitable crop because the oil made of the seeds of *Salicornia* can be used as a biofuel and as an edible oil source. This would be a good reason to start cultivation of this crop around the Banjaard. Furthermore, cellulose in *Salicornia* biomass is presumed to be a good source for bioethanol production and the plant can be used as food or in cosmetics and pharmaceuticals. Another advantage of *Salicornia* is that it has important economic uses in ecology as a biofilter or for phytoremediation (Cárdenas-Pérez et al., 2021).

5.4.3. Risks

Salicornia is normally harvested by picking plants in the wild and therefore, it needs a large area to grow. This type of agriculture is not very effective and can, therefore, increase the costs of the product and will make it harder to have a constant supply of *Salicornia* to the market and consumers. Slowly, more options for *Salicornia* cultivation are being investigated in several countries. However, producing *Salicornia* for the market is still relatively new, and the machinery and knowledge available to increase the production of this crop is limited to increase production of this crop. In the future, more research should be done to see which *Salicornia* species can be used best for harvesting. Furthermore, the discovery of more uses for the product could increase the market value and make the cultivation of *Salicornia* more profitable (Accogli et al., 2023; Singh et al., 2014).

5.5. Shellfish production

In this sub-section there will be an overview of the seagriculture options in the two main bivalves considered on the report: oysters and mussels. There is a large practice of this kind of shellfish aquaculture already all around the world due to their attachment to surfaces and ropes, and for their capacity to filter water. (OCEAN, nd.b)

5.5.1. Theoretical background of shellfish production

5.5.1.1. Oyster production

There are two main oyster species with commercial value produced in the North Sea: the Pacific oyster (*Crassostrea gigas*) and the European oyster (*Ostrea edulis*) (Kamermans, 2020b). *O. edulis* is a native species from the North-Eastern Atlantic, including the Mediterranean basin and the North Sea. It has a long story of consumption and commerce that goes back for at least 6000 years. They are commonly found on firm ground in shallow waters like estuaries forming beds on muddy-sand, muddy-gravel and rocks up to 20 meter deep, yet on larval stage can move by the currents and reach other coasts and areas (Lapegue, 2006).

The *O. edulis* dominance in the North Sea has switched towards *C. gigas* for several reasons. European oyster natural beds got damaged due to over-exploitation and cold winters during the 18th and 19th centuries. (Lapegue, 2006) To maintain the production, oyster farmers introduced *C. gigas* as an exotic species in the Oosterschelde which expanded in the 70s forming Pacific oyster beds in the intertidal and subtidal zones of the Oosterschelde estuary. (Smaal, 2009) Both oyster species have considerable difference on market price, being *O. edulis* 3 to 5 times more expensive because the available supply is lower. This type of oyster is now considered a luxury seafood product. (Lapegue, 2006)

There are several production techniques of oysters applied on the Netherlands, being bottom culture where organisms are cultured on the bottom of the sea, and off-bottom culture where the organisms are cultured in a basket or container. (Kamermans, 2020b) These two cultivation methods influence on its role as a biobuilder, being the bottom reef structure more compact and adequate as a biobuilder and the off-bottom as a more harvestable distribution. The culture is based on hatchery production or natural recruitment. Hatchery depends on several factors such as temperature, salinity of the water and other environmental factors. In the North Sea, the Netherlands is the largest producer of both European and Pacific oysters, followed by Denmark and the UK respectively. (Kamermans, 2020b)

5.5.1.2. Mussel production

Mussels are a kind of shellfish which is highly valued in this project both as a seafood product and as biobuilder. They attach to solid surfaces through a proteinaceous thread called byssus and cluster in mussel beds in shallow seas, obtaining nutrients through filtration of water and at the same time facilitating habitats for other sea species. By filtering water, they also ingest pollutants and other suspended particles, fact that makes them a useful vehicle for water quality and contaminants analyses. (Inoue, 2021)

Of the aquaculture species, *Mytilus edulis* or blue mussel is produced along the North Sea intertidal and subtidal areas. (Kamermans, 2020a) Another species that occurs, although not as often, is the Mediterranean mussel or *M. galloprovinciallis*. The Mediterranean mussel is important to mention too since the boundary for *M. edulis* might move further north due to climate change, becoming a habitat more dominated by *M. galloprovinciallis*. Juvenile blue mussels are commonly harvested as seeds for bottom and long-line cultures and adults as seafood products (Kamermans, 2020a). The common method for seed fishery consists of towing a dredge on top of wild mussel beds where the juveniles will be captured in order to be transplanted to a different culture site. (Smaal, 2021).

In the Netherlands the intertidal bottom culture is dominant, with a longer cultivation time and farming area than the Danish suspended culture. Stock density and, consequentially, mortality are also higher in the Netherlands. (Kamermans, 2020a)

*Table 5 Characteristics summary of the main commercial shellfish in the North Sea. *FW stands for Fresh Weight and the N removal is measured in gN per cultivation per organism. Sources: Kamermans, 2020a; Kamermans, 2020b.*

Species	Cultivation (days)	Live weight (g FW*)	Shell length (cm)	N removal (gN)*
Blue mussel	794	25,0	8,8	0,60
Pacific oyster	900	64,8	9,8	1,67

5.5.2. Advantages

Shellfish grow faster in off-bottom cultures such as ropes than in on-bottom. As it is presented in *table 6*, mussels farmed in Denmark with off-bottom farms compared to The Netherlands with on-bottom farms, being the cultivation cycle of more than double duration for on-bottom method (Kamermans, 2020a). Another advantage of hanging or off-bottom farming is the avoiding and reduction of the loss of predators and risk of 'by-catch' or the destruction of the habitat while harvest (AJ. Murk, personal communication, June 24, 2023). Their capacity to filtrate algae, nutrients and suspended matter from water, making the surroundings cleaner and improving water quality (The Nature Conservancy, nd.).

Table 6 Data comparison between Dutch and Danish blue mussel cultivation methods. Source: Kamermans, 2020a.

Country	Cultivation (days)	Farm area (ha)	Stock density (u/m^2)	Mortality (cycle^{-1})
The Netherlands	794	16,3	5000	98%
Denmark	365	8	300	40%

5.5.3. Risks

There are additional risks for the production and commercialization of shellfish. It is common for fast-growing microalgae in areas with an excessive suppletion of nutrients such as nitrogen to have an algal bloom (Global Seafood, nd.a). This has happened in de Wadden Sea due to a large suppletion of nutrients from major

European rivers, but it has reduced during the last decades (Van Beusekom, 2019). During the period between March and October, algal blooms occur in the North Sea. They occur mostly in the southern part of the Dutch North Sea and disappear as fast as they appear (Noordzeeloket, nd.). These algal blooms might lead to a temporary regulatory closure of the shellfish market for health purposes (Global Seafood, nd.a).

A technology that combines sensors and open-ocean data into a model to predict and apply preventive measures for algal bloom occurrence. This machine learning technology has been running on trials in Portugal and could be implemented in other sites once given enough data from weather conditions, water temperature, currents, etc. (Global Seafood, nd.a).

5.5.3.1. Tetrodotoxin

Tetrodotoxin or TTX is a biotoxin or poison commonly found in some kinds of seafood such as globefish and in some shellfish. The ingestion of this toxin with food of water causes interference with nervous signals and can cause paralysis. (NIOSH, nd.) After the study (Kamermans, 2020a; Kamermans, 2020b) performed for TTX production on shellfish in the Oosterschelde it was concluded that there was no evidence of a trigger on production or releasing of the toxin as effect of salinity and temperature. However, the results show that its production might be linked to the temperature-sum, average daily temperature of the year, which is expected to be affected by climate change in the future years (Kamermans, 2020a). Among the shellfish, oysters accumulate more of this toxin than mussels. By keeping the shellfish in clean water, they go through a toxin depuration prosses. The specific times of depuration still need to be stablished (Kamermans, 2020a).

To ensure a healthy and sustainable food supply chain of shellfish, further studies about the impact of t-sum on the production of TTX and the depuration time needed can be performed in the Banjaard during its ecosystem development stage.

5.6. Sea ranching

5.6.1. Theoretical background of sea ranching

One of the options for sustainable seagriculture at the Banjaard could be sea ranching. Sea ranching is an approach where marine animals are cultivated and harvested in their natural habitat. *Sea Ranching* is defined as the release of cultured juveniles in unenclosed estuarine and marine environments, after which they are monitored for health and size until they have reached the desired size, and they can be harvested; this is also called "put, grow, and take" operations. Here the fish introduced into the natural system as juveniles are not fed by the farmer but survive on the natural resources of the habitat. Sea ranching can be compared to traditional agriculture on land where seeds are planted, and crops are grown until they are ready to be harvested. However, the seeds are juvenile marine organisms in sea ranching (Johann et al., 2008).

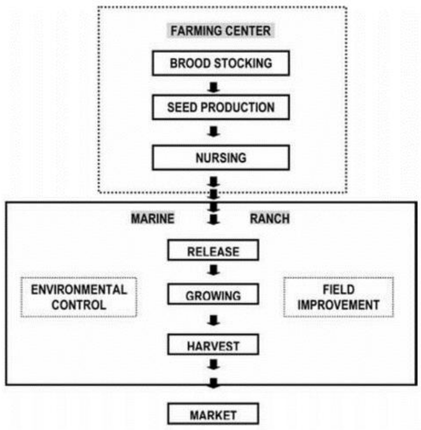

Figure 24 A schematic overview of harvest sea ranching (Mustafa, 2003)

Sea ranching is used for several species, primarily bivalves and different types of fish and other marine invertebrates. The most common species cultivated using sea ranching worldwide are shrimp, salmon, scallops, crabs, oysters, and sea cucumbers. However, the species chosen to be sea ranched in a specific area depends on several factors, such as ecological sustainability, local regulations, and market demand (Upton, 2010).

An example of feasible sea ranching in the past was the sea ranching of the edible tropical sea cucumber (*S. monotuberculatus*) in front of the Chinese coast. Because of the sea cucumber's high nutritional and medical value, there used to be much overfishing, and the sea cucumber population was declining as a result. After releasing juveniles in the tropical coral reef, most died in the first month due to inadaptation to the changing environment from the hatchery to the ocean. Nevertheless, a substantial amount of the released juveniles could grow to commercial size during the first year and could be harvested after, making this a profitable enterprise (Xu et al., 2022).

There are two types of sea ranching; the first is called Harvest-sea ranching (*figure 26*), which is mainly used for crab, shrimp, scallops, sea cucumber, and clams. First, seeds or juveniles are placed in marine water and harvested once they reach the correct size. To ensure the repeated success of seeding and harvesting, improving the environment and the fishing zone is crucial while efficiently recapturing the released organisms (Mustafa, 2003).

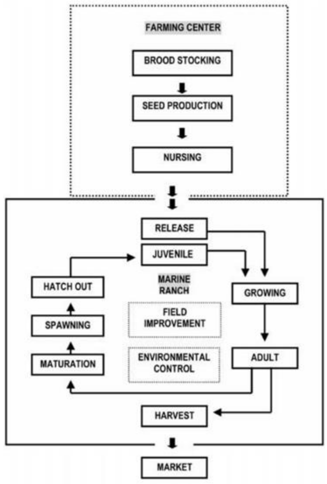

Figure 25 A schematic overview of recruitment sea ranching (Mustafa, 2003).

The second type is called Recruit-sea ranching (*figure 27*), which first introduces seeds in the marine environment, then these animals grow and start reproducing after reaching maturity. When a native population has been supplemented with extra released animals, the new population can withstand the fishing pressure, and the supply of juveniles introduced into the system stops. Here, only some of the adult animals are recaptured. A proper management plan should be in place to make this type of sea ranching work (Mustafa, 2003).

5.6.2. Species that can be used for sea ranching

5.6.2.1. Eastern Scheldt Lobster (*Homarus hammarus*)

The Eastern Scheldt lobster is a clawed lobster that lives in the Eastern Scheldt, also called the European lobster or *Homarus gammarus*. They are crustaceans with powerful claws, a dark blue or green-brown color, and distinctive spines and knobs. An adult lobster can become up to 60 cm long and weigh a few kilos. They generally live in dynamic and diverse marine environments with a gravelly or rocky bottom. They need crevices, burrows, or rocky reefs to seek shelter during the day and hunt for food at night. The lobsters are omnivorous scavengers that hunt for different organisms, for example, small fish, crustaceans, molluscs, carrion, and worms. The Eastern Scheldt lobster goes through complex life cycles; after hatching from the egg, the larvae drift in the ocean until they settle on the ocean floor and develop into juvenile lobsters that gradually grow and molt their exoskeleton. The main threats the lobster faces are overfishing, changing environmental conditions, and habitat loss and degradation.

A study from Jørstad and Farestveit (1999) investigated the opportunities for sea ranching of the Eastern Scheldt lobster around Norway. They concluded that for local lobster stock enhancement, it is important to minimize changes of genetic characters to the wild stock that already lives in the area. Therefore, there needs to be a genetic control of the broodstock that was selected from the local wild stock and a large amount of broodstock to prevent genetic changes by chance. The designed hatchery facilities and the operation should reduce selection because of environmental conditions by ensuring their similarities with the receptor environment. Moreover, for commercial lobster ranching a high productive stock is needed, regardless of specific local lobster stocks. When wanting to conserve the genetics of local lobster stocks, commercial ranching operations should be located in areas where the genetic differentiation is small.

The economic viability of sea ranching of the European lobster is currently not deemed feasible in Norway and the UK, mainly because of the low recapture rates. There are several strategies to overcome this constraint. For example, using a chip to track the lobsters or by building an artificial reef with shelter for the lobsters, so it is known where to find them (Moksness et al., 1998). Previous research from Conrad & Danoff-Burg (2011) showed that the Lobster house design used by Reef check (*figure 28*), helped increase the Spiny Lobster population in the Caribbean and made the aquaculture practices using lobsters more sustainable. On top of the lobster house there is an opportunity for bivalves to settle.

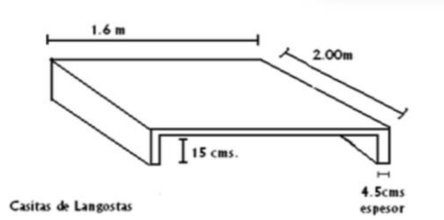

Figure 28 Lobster house design used by Reef Check, Dominican Republic. (V. Galvan, 10 june 2010)

5.6.2.2. The North Sea crab (*Cancer pagurus*)

The North Sea crab, also known as brown crab, edible crab, or *Cancer pagurus*. The crab is commonly found in the North Sea and is considered to be a seafood delicacy, and is therefore regarded as an important source for food. The North Sea crab has a distinctive appearance with a hard dark brown to reddish color. It has an oval shaped carapace which can become 25 cm wide and is covered with small spikes. The North Sea crab prefers sandy or rocky habitats, and lives in shallow coastal waters up to a depth of 100 meters. Furthermore, it is often found inhabiting holes and cracks in rock formations, but occasionally also in open areas (MarLIN, n.d., Brown & Bennet, 1998).

It is a scavenger and predator that eats mainly crustaceans, mollusks, carrion and small fish, but also algae and plant matter. The life cycle of a North Sea crab starts when an adult crab produces eggs which are fertilized in the water by the male. These fertilized eggs hatch into larvae that float in the water column until they settle on the sea floor and turn into juvenile crabs, after several years the crab reaches maturity, which is commonly a bit later for female crabs than male ones (Brown & Bennet, 1998).

5.6.2.3. The Atlantic cod (*Gadus morhua*)

The Atlantic cod or *Gadus morhua*, is a fish with an elongated long body, a chin barbel (fleshy growth near the mouth) and two anal and three dorsal fins. The Atlantic cod has a greenish-brown color and can grow up to 1.8 meters with a weight of 90 kilograms. They can reproduce when they are 2 to 3 years old and they spawn, producing 3 to 9 million eggs, near the ocean floor between winter and early spring. The Atlantic cod is a top predator in the bottom ocean community that feeds on a variety of fish and invertebrates, like shrimps, herring mackerel and other things (NOAA Fisheries, n.d.).

The Atlantic cod lives in the North Sea because of the colder water (temperatures between 0 and 10 degrees Celsius). Cod primarily inhabits the seafloor. Juvenile cod lives mainly in shallow waters whereas adult cod can be found at depths from a few meters up to several hundreds of meters. Cods can live on muddy, sandy or rocky bottoms. Cods are often found in kelp forests, artificial reefs, or rocky outcrops which provide shelter and food. Spawning grounds are often shallower near shore waters, but this depends on the population (NOAA Fisheries, n.d., Rozemeijer, 2023).

5.6.2.4. Sea Bass (*Dicentrarchus labrax*)

The Sea Bass, also known as *Dicentrarchus labrax*, is a fish that lives in the North Sea in front of the Dutch coast among other regions. They are versatile in their choice of habitat, for example in rocky shores, estuaries, muddy or sandy seabeds, and nearshore areas. They prefer areas with structures, like wrecks, reefs and submerged vegetation. Because they provide hunting grounds and shelter. These fish also migrate between different habitats during their life cycle. The Sea Bass is a euryhaline species, so they can tolerate a variety of salt concentrations. Furthermore, the Sea Bass is a predator that can thrive in various conditions.

They feed on crustaceans, smaller fish, and cephalopods. When sea bass grows from juveniles to a mature fish they move from the offshore open water towards the nearshore areas.

5.6.3. Advantages

Sea ranching can offer several advantages; first, it can reduce fishing pressure on wild fish stocks when introducing more fish into the area. Adding new juvenile fish to the habitat allows the wild population to recover, and a new ecological balance can be found. Secondly, sea ranching can be organized and managed to increase ecological sustainability; This can be done by carefully selecting species for sea ranching and using good management practices and proper monitoring, which can help increase biodiversity in the area. Moreover, Sea ranching gives more control over the production cycle compared to catching wild species. Ranchers can regulate the number of released seeds and monitor their growth. As a result, a consistent and reliable supply of marketable organisms is ensured. The introduced production cycle can help meet the market demand (Kitada, 2018; Murk, 2023).

Another advantage of sea ranching is enhancing and restoring degraded habitats. When juveniles are released into an environment that needs ecological rehabilitation, sea ranching can help to rebuild the marine ecosystem. Furthermore, letting organisms grow up in their natural habitat instead of in a small cage or container is more animal friendly. However, sea ranching cannot only improve the ecology in the area but also has an economic advantage as it can provide economic opportunities for people that live near the coast and create new jobs in that area, like hatchery operations, seed collection, harvesting, and ranch maintenance. Additionally, ranching can attract tourists and recreational activities (Kitada, 2018).

5.6.4. Risks

However, there are also some challenges with using sea ranching; first, when you use the type of sea ranching where you keep on releasing farmed species into the wild to catch them again at a later stage: they can dilute the genes. This dilution of genes means they can reduce genetic diversity when farmed and wild organisms start interbreeding, which can have long-term effects on the resilience and adaptation of natural populations. However, when you use another type of sea ranching, where you only introduce juveniles to kickstart a healthy ecosystem, so the chances of survival for the newly introduced species are a lot higher, this risk for dilution of genes becomes negligible. After a healthy ecosystem is established, it will be possible to start harvesting multiple species in an eco-safe and dosed manner.

Furthermore, increasing the population of a particular species in an area increases the risk of disease outbreaks and parasite transfer. Also, if the seeds of the introduced farmed animals are not gathered at the same location where they will be released, it can drive the wild population to extinction when they carry certain new diseases or are better adapted to the environment. Therefore, it would be wise to first harvest the seeds, from which juveniles are grown in the lab in the same area as the place where you would like to introduce them later on. This way, you prevent disease outbreaks and gene dilution but increase the survival rate of the juveniles significantly. Another disadvantage of sea ranching could be the dependence on wild-caught juveniles or seeds, which puts additional pressure on wild populations. When seeds are overharvested, this can have very negative impacts on the ecosystem functioning as donor and the natural population (Grant, 2017; Mustafa, 2003; Kitada, 2018).

When looking at the economics of sea ranching where you continuously introduce new juvenile species, it is an advantage that the fish no longer need expensive infrastructure and don’t have to be fed daily. However, it does require a significant investment in technology and ongoing maintenance to keep introducing juveniles into the wild. However, when building a new healthy habitat, fish that live in the surrounding area can also come to live in the new habitat. If this results in a new healthy population of multiple species living here it would be possible to start harvesting them, which reduces the investment in technology and maintenance significantly. Moreover, the economic viability of sea ranching depends on several other factors as well, like, fluctuations in seafood prices, market demand, and competition from other sources, which is sometimes hard to estimate (Kitada, 2018).

Sea ranching could be possible around the Banjaard as there is already much knowledge on aquaculture in the Netherlands, with several hatcheries, fish farms, and research institutes. Furthermore, in 2021 the number of people in the Netherlands that regularly consumes fish increased, and 162.5 million kilograms of fish and shellfish were eaten. This rise in people that consume fish on a regular basis shows that there currently is a large market for fish in the Netherlands (Nederlands visbureau, n.d.). Previous research from the RIVM in 2016 showed that salmon, tuna, and cod are the most popular fish species among Dutch people (RIVM & Bureau Risicobeoordeling & Onderzoek, 2019). Furthermore, species that currently have a high market value are the Eastern Scheldt lobster, oysters, crabs, and several clams, all occurring in the North Sea.

5.6.5. Artificial reef

An artificial reef can form a habitat designed in a way that would suit all species mentioned before (*figure 29*). To perform profitable sea ranching, an artificial reef can be created near the Banjaard to boost biodiversity, function as a breakwater, and create an opportunity for animal-friendly and sustainable aquaculture. The artificial reef can be a home for different species used for sea ranching, for example, the Eastern Scheldt lobster, Sea Bass, North Sea crab, oysters, mussels, and cod. However, because this artificial reef is built, other species not mentioned here will also benefit from the new habitat and be attracted to the area. Since the animals in such an artificial reef have much space to move, the chance for diseases to occur is much smaller, and other fish can help them get rid of parasites.

Figure 29 The modular sea life system installed on the ocean floor. From: Living Breakwaters – ReefSystems, 2023.

The Eastern Scheldt lobster and the North Sea crabs can be caught with cages containing bait just outside the artificial reef. The oysters and mussels can be hand-picked from the rocks around the island. The fish, like cod and Sea bass, can be caught using a fishing line or hand lines where a hook with bait is attached so the artificial reef is not damaged when fishing. It will take five to ten years to create an artificial reef with different species that can be used for sea ranching. However, after the reef is established, fishermen should only harvest some animals to find a balance, so the local population stays balanced. This farming type is much more sustainable as it takes less energy than fishing with a trawl, and lobster no longer has to be transported from Canada (Murk, 2023).

The modular sea life system and reef pool (see chapter 4) can be a sound basis for such an artificial reef, where the species that can be harvested using sea ranching live peacefully from their juvenile stage until they reach maturity and are harvested.

5.7. IMTA systems

5.7.1. Theoretical background of IMTA systems

In Integrated Multi-Trophic Aquaculture (IMTA) systems, the waste of animals, such as left-over feed and faeces from fish farming is used in lower trophic levels as nutrients source. For example, seaweeds can absorb and assimilate dissolved nutrients originating from fish leftovers and waste. Bivalves and sea cucumbers function as filter feeders and are able to keep the water clear and lower the turbidity. This has as advantage that more sunlight can penetrate the water, which would be of advantage for seaweed photosynthesis and growth (Troell et al., 2009).

Aquaculture is covering more and more of the seafood market with time, but it comes with environmental and socio-economic issues derived from the intensive farming. Impacts such as the organic enrichment of the water and the sediment due to the release of dissolved nutrients led to the implementation of new aquaculture strategies to mitigate them and promote sustainability (Papageorgiou et al., 2023).

The principle of IMTA systems is that the wastes of fed or by-product organisms are the nutrients for the growth of the cultured species (Pereira et al. 2013). Consists in an aquaculture strategy that combines extractive or non-fed species with fed species (Papageorgiou et al., 2023). In these systems, which can be very complex and divers, the fed species are or generate the nutrients for the extractive. Examples of extractive species are macroalgae, filter or detrital feeding organisms (Pereira et al. 2013).

5.7.2. Advantages

Seaweed cultivation can be practised either in a vertical rope system or in a horizontal net shape system (see 5.3. Seaweed farming). Bivalves will be introduced and hang upon ropes vertically. As they filter out the water of (over)growing phytoplankton, resulting from higher nutrient concentrations, they prevent too much phytoplankton in the water and thereby stop the development of harmful algal blooms (Papageorgiou et al., 2023). Sea cucumbers are detritivores and will utilize the detritus coming from the fish. The choice of introducing a detritivore in the system will also be of economic importance. Since sea cucumbers can be eaten besides being a detritivore, this option is preferred. As sea cucumber species the *Cucumaria frondose* is suggested, because of their high economical value (Nelson et al., 2012). All species mentioned are already native to the North Sea (Bos et al., 2016), and with species selection it is assumed that no threat is expected to disturb the natural balance, however this needs to be tested since, for example, small numbers can still be ‘’leaked’’ into the environment.

Fish could be kept in open sea cages and Atlantic cod (*Gadus morhua*) and sea bass (*Dicentrarchus labrax*) could be used since these fishes are native in the North Sea and both have a good economic value (see 5.6. Sea ranching). IMTA results in the additional production of biomass, which not only holds direct economic value for multiple production units but also provides ecosystem services.

The mutual dependence of trophic levels within the IMTA system makes sure that this dependence will offer a significant reduction in the release of inorganic nutrients found in the effluents of intensive aquaculture systems. These effluents can pose ecological problems by contributing to coastal eutrophication and the formation of algal blooms (Pereira et al., 2013).

5.7.3. Risks

The bathymetry of the sea bottom around the Banjaard has been mapped by WUR-students and stated that the depths vary between -6m to +0.1m (Shared Concepts et al., 2022a). It is therefore wise to explore opportunities in deeper waters and to make a working station near the island to maintain these IMTA systems.

With the activity of intensive fish farming an increased risk of disease spread is seen among fish populations. This can also be the case in IMTA systems. Since large populations will be kept in an open sea cage, the risk of disease spread is significant. A potential solution would be to the usage of antibiotics. However, this can give rise to antibiotic resistance, and among that a large portion of antibiotics could effluent to the open sea which would not profit the meant fish population, increasing pollution consequences (Cabello et al., 2013). Other solutions can be explored to tackle the problem of antibiotic resistance. However, one solution can be a good intermediate solution to IMTA. Instead of intensive fish farming in nets, fish can also be caught into traps. However, fish traps are hard because this practicality is prone to predation. With that the timing of harvesting will also be a risk since fish are trapped at different moments. Fish cages needs to be emptied and monitored at frequent intervals to prevent that fish are too long in captured state and die.

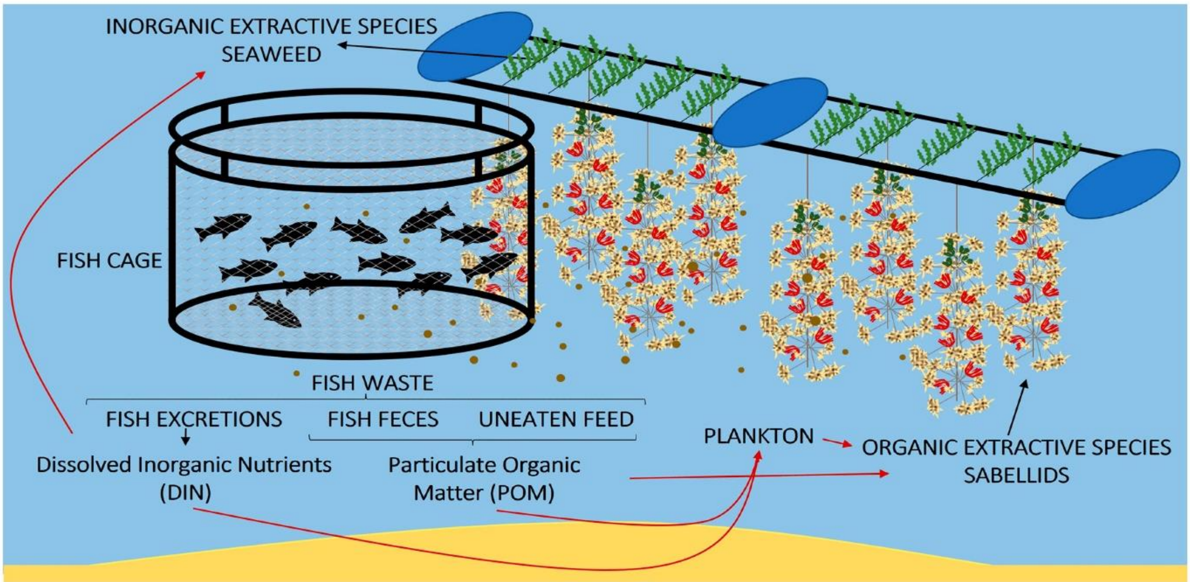

Figure 30 Black arrows indicate the extractive species. Red arrows indicate the direction of DIN and POM flows. Instead of sabellids, bivalves will be used as organic extractive species. Derived from Mileti et al. (2023).

5.7.4. Vertical aquaculture with IMTA

Vertical aquaculture is usually implemented for a culture with a single species harvested, in Singapore, for example, they produce shrimps on vertical tanks that also have seaweeds in order to clean the water and digest excess of organic matter (The Fish Site, 2020).

A type of vertical aquaculture is IMTA. The general idea of IMTA is that nutrients from fish in cages supplies the growth for other harvestable species such as seaweeds and shellfish. However, it is not always desirable to implement this into the system, because keeping a large number of fish in a cage together can result in disease outbreaks. The general idea of vertical thinking is that aquaculture is approached for monoculture, while IMTA is a combination of different aquacultural disciplines (Troell et al., 2009).

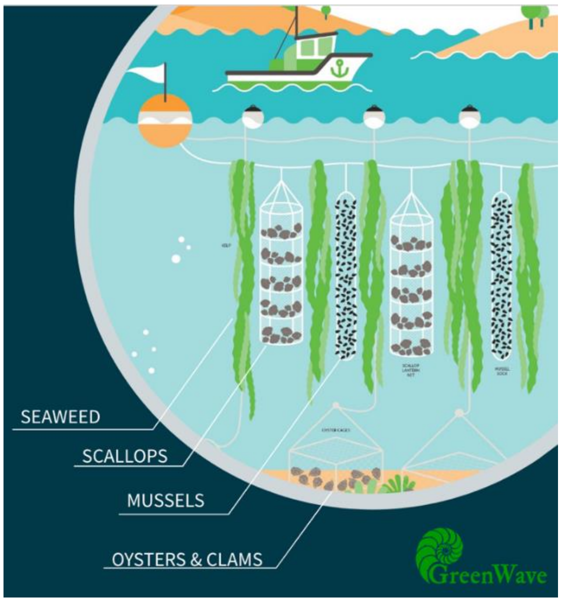

Figure 31 Vertical aquaculture (Green wave,

By combining the polyculture approach from IMTA and not implementing cages, a more sustainable method could be designed. It is proposed to combine seaweed culture and bivalve culture, besides other seagriculture initiatives such as sea ranching. This can be advantageous, in the way that bivalves will filter the water from algae and suspended matter, clearing it for seaweed growth (The Nature Conservancy, n.d.). More sunlight can penetrate the water, leading to better photosynthetic possibilities for seaweed growth under water. Furthermore, fish will find in the vertical seaweed a nice hiding spot and will be able to find food surrounding the ropes with shellfish. As a result, the fish will provide enough nutrients for the seaweed to grow with their faeces. These fish and crustaceans that live on the bottom can be caught using a fishing line and can be used as an extra source for income as long as they are harvested in a dosed way (see section *5.6. Sea ranching*) (Murk, 2023).

6. Added societal value of renewable energy and ecotourism

This chapter will aim to reach objective 6 by proposing and developing few ideas that could add to the local societal value of the pilot plant by evaluating other possibilities for economic or social development. In this chapter renewable energy production and ecotourism options in the Banjaard will be evaluated.

6.1. Energy production

In this subchapter, the transition to renewable energy worldwide will be introduced, together with the relevance and applicability or Floating Photovoltaic (FPV) panels in the sea. An overview of the state-of-art, possible problems, solutions and opportunities for seagriculture will be developed.

6.1.1. Transition to renewable energy

The pressure generated by the dependence on fossil fuels and the politico-economical risk it entails, together with the damage its usage supposes for the environment derived from the high CO2 emissions and its condition as a non-renewable resource, are the reasons why the world is transitioning towards alternative energy sources. (Neacsa, 2022; United Nations Climate Change, n.d.) This energy transition aims for a larger implementation of renewable energy initiatives and methods that help stop or even mitigate problems such as the global warming. (United Nations Climate Change, n.d.)

After realizing the extent of the consequences that the planet could suffer for this short-sighted use of non-renewable resources, countries started uniting to create countermeasures and policies that facilitate and endorse eco-friendly energy sources. (Neacsa, 2022) An example of it is the legally binding international treaty on climate change signed and adopted by 196 parties in 2015, the Paris Agreement. To prevent the increased severity and frequency of climate change impacts such as droughts and heatwaves, this treaty sets a clear goal: "to limit the temperature increase to 1.5°C above pre-industrial levels." (United Nations Climate Change, nd.)

The reason why energy is this relevant to prevent this limit to be surpassed is because it accounts for two-thirds of the global greenhouse gas emissions. This transition, however, will be affecting more than the energy sector since the actual society depends completely on energy. (Bali Swain, 2022)

The main issues applicable to most of the renewable energy alternatives are limitations on space and development time. Characteristics as potential for generation, conversion, distribution, and storage take a large amount of those two resources. Energy demand will also increase the land demand, this problem is leading towards strategic landscape design solutions which use the features of the landscape and location to have the maximum energy possible per unit of area (De Waal, 2015).

6.1.2. Solar energy from the oceans

Among the renewable energy alternatives, the most abundant and available is solar power (Hu, 2016). That is why solar energy contribution to electricity supply is expected to reach 22% in 2025, compared to the 2.4% from 2018. There are some technical limitations to cover this expected contribution if conventional solar PV systems are implemented, which are the extensive land usage and the decrease of energy conversion efficiency that can reach a 30% in summer radiation temperature conditions (Golroodbari, 2020; Rosa-Clot, 2010). Other complications from the common solar photovoltaic (PV) panels that affect the efficiency are related to maintenance, for example cleaning dust and leaves, which takes time and can also be costly energetically (Rosa-Clot, 2010).

The development of Floating Photovoltaic systems aims to solve the problems previously mentioned for inland PV. Firstly, it saves land that could otherwise be used for crop cultivation or housing. Solar energy can't be collected yet in a three-dimensional setting, unlike the distribution of households. A large density of population needs more energy production, therefore more area is needed, but it is not sustainable to keep investing land area on solar PV panels (Golroodbari, 2020; Vo, 2021). Therefore, a promising solution for land availability are the FVP systems offshore. This is also in tune with the demographic distribution of the world population, for 50% of the humans live within 100 km from the coast. (Vo, 2021) The contact with this large water body that is the ocean would also increase the conversion efficiency through cooling (Golroodbari, 2020; Vo, 2021) and refraction index of the water layer (Rosa-Clot, 2010). FPV have been installed and operated in water bodies like lakes and reservoirs, but when it comes to marine renewable energy other options have been researched in more detail. Wind, waves, and tides can provide energy, nonetheless, it is estimated that 70% of primary energy supply for oceans proceed from sun radiation (Vo, 2021).

There have been several studies performed about the energy conversion efficiency from FVP offshore respect inland PV. In the study from Golroodbari et al. (2020), a model was developed comparing the performances and getting as a result a 13% higher relative annual average output energy for FVP. The reason behind it is the cooling capacity of the sea and the constant cleaning of light interferences by the waves. Additionally, Rosa-Clot et al. (2010) dug further in the light reflection and how the presence of a water layer doesn't only clean light interferences but also increases the light absorption by the PV panels. There is more absorption of light, and, therefore, energy conversion to electricity, when PV are submerged few centimeters in water. The glass refraction index (1.53) is higher than the one from water (1.33), the switch on insidence angle of light after this water layer diminishes the ratio of reflected light and allows the partial recovery of the light reflected by the glass. (Rosa-Clot, 2010) In other words, there is higher energy absorption per PV area when submerged.

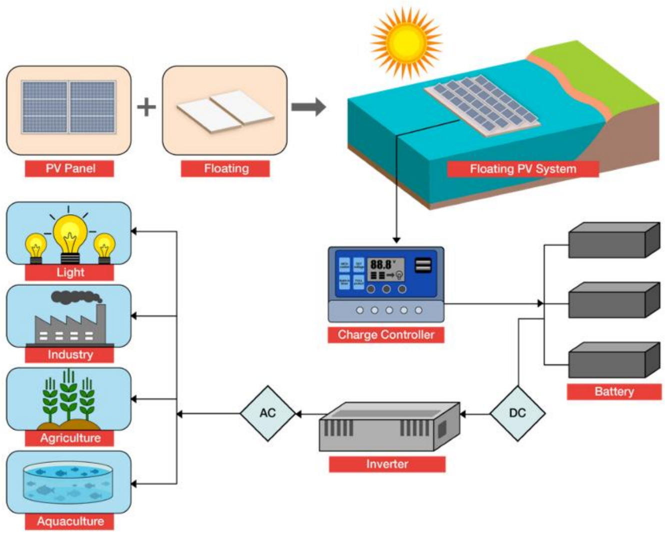

Figure 32 Block diagram summarizing the main components of Floating PV systems and their utilities. Source: Vo et al. (2021).

6.1.3. Solar floating photovoltaic systems at the Banjaard

Although offshore FPV panels are an innovative energy conversion system, there are some places that have already started implementing them. Among the pioneers there is the Dutch company Oceans of Energy (Oceans of Energy, nd.) and the Norwegian Sunlit Sea (Sunlit Sea, nd.).

The difference between lakes and offshore FPV consists basically in the load generated by waves and wind. If the systems were left alone, they would drift away. Therefore, a mooring system that anchors and attaches the components together is needed. A mooring system is comprised of anchor, connectors, and a mooring line (connects anchor to a floating structure), which is supposed to ensure the durability of the PV system on top of the floating system in the same location (Choi, 2015; Ringzone, nd.). The materials that form the mooring system are determined by environmental factors and the load they can generate, being chains the most common mooring line for waters of less than 100 m depth and steel wire rope for greater depths. While the type of anchor depends on the sea floor soil and the digging depth. (Rignzone, nd.) Depending on the bathometry of the intended location in the Banjaard the more suitable material could change. Nonetheless, considering the large surface of the FPV it could have a role as a first wave attenuating barrier if placed at a certain distance from the island to avoid generating shade on the biobuilders or affect the ecosystem but close enough to provide some protection. It would also be necessary to evaluate the adequate type of anchor, which will depend on the soil characteristics after the sediment suppletion.

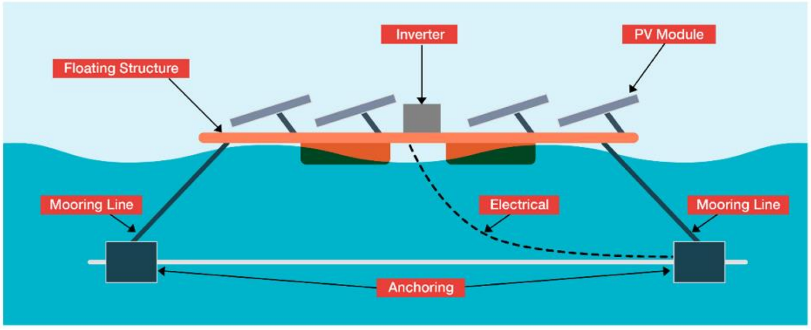

Figure 33 Schematic design of the parts and its distribution for the FVP functioning. Source: Vo et al. (2021).

Oceans of Energy has already developed pilot projects on the North Sea with FPV systems near-shore (less than 1 km) and offshore (15 km from the coastline). Through these projects they tested their technology which can withstand 13-meter-high waves, wind speeds of 115 km/h and tidal currents of 2 m/s. (Oceans of Energy, nd.) Considering the current conditions at the Banjaard location, the FPV system could be implemented.

It is possible to combine the FPV systems with seagriculture opportunities, as the Blue Acceleration project is investigating in the Belgian coast where a pilot project is being developed with ropes hanging from the solar panels for aquaculture purposes. (Solar Magazine, nd.; POM, nd.) The possibility of developing an off-bottom shellfish farming on ropes would promote the dual use of water-derived resources, which has a high unused potential. (Pringle, 2017) Shellfish are suggested for they do not have direct dependency on sunlight, they have detectors for regulating their circadian cycle (Global Seafood, nd.b). Nonetheless, FPV systems do not completely block the light for certain separation can be placed between the panels, together with the refraction and the changing incidence angle from the light beams will suppose a small volume where the light does not reach. Being shellfish organisms that do not need much light, they could grow bellow the FPV systems attached to ropes at the Banjaard.

6.1.4. Risks

There is an added complication related to most renewable resources but specially on solar energy, which is the variation in supply and demand. In terms of energy, winter season always brings higher consumption and at the same time there is less daylight hours. (De Waal, 2015) Even at a smaller timescale there are wide oscillations in electricity consumption and generation. The evolution of electricity generation technology must be followed by distribution and storage to ensure all the converted energy is used where it is needed and to avoid unnecessary losses in each of the steps from the FPV to the consumer. That is the reason why the infrastructure option for distribution and storage must also be assessed locally. (De Waal, 2015)

Due to water presence and the possibility of the electric generator to be immersed, the protection of the junction box should be carefully examined to avoid short-circuits, leakage or premature end of the useful life of the system. (Rosa-Clot, 2010) Additionally, the long-term influence that FPV systems might have on marine life and ecosystems is still unknown and studies to ensure their presence does not bring harm to the local flora and fauna might be needed. (Pringle, 2017)

6.1.5. Opportunities

On the material context, the current PV panels use cadmium chloride ($CdCl_2$), which is poisonous and costly due to the presence of cadmium, a heavy metal. The placement of these FPV on the sea could reduce the usage of this compound for it contains magnesium chloride ($MgCl_2$), which can substitute $CdCl_2$. (Vo, 2021)

On the storage context, contact with companies as Elestor, a Dutch start-up innovating on flow batteries, could help solve the intrinsic problem from renewable sources, the lack of a constant supply and demand. To avoid the loss of the exceeding electricity when there is a production peak, it should be stored. The main strategy followed so far for the compensation of low-production seasons or high-demand periods was to implement more power generating systems. That strategy leads to facilities that are not operative most of the time, because the distribution infrastructure would not be able to handle the electricity peak. With a low-cost electricity storage, the amount of space needed for renewable energy sources could be reduced if the exceeding electricity could be stored. (Elestor, nd.)

6.2. Tourism

The local population and also the local tourism will also be involved when the Banjaard is established. A part of the Banjaard and surroundings can be used for tourism purposes. When the Markerwadden were designed, a part was reserved for pedestrian paths and boat trips around the island. People can visit a tourist centre and even can sleep on the island, taking in mind the fragile ecosystem they are in. The other parts were left untouched for human interference. (Natuurmonumenten, 2023). In this way people will get more conscious about the project Markerwadden, the created and still evolving biodiversity.

As this looks like a good plan, first some implications need to be researched. How will the island behave on its dynamics in the sea, were will birds and other species establish themselves on and around the island? This will be of importance in placing the tourism opportunities, but also for farming purposes.

In the first days, when the island is evolving, tourism possibilities on the island need to be minimized as much as possible. This has as reason that the ecosystem still needs to be established. Boat trips around the island can be made, however cannot intervene with the experiments around the island. When the island is in a more advanced state of development developed, bird watch towers can be placed on the parts of the island which are continuously above water. It is advised not to place a tourist centre on the island, since the security of the building cannot be guaranteed. Nota bene: the Banjaard will function as breakwater and tourism options on the island cannot be copied directly from the Markerwadden. As a solution to this, the tourism centre could be placed on poles to be high enough and avoid flooding. In this way tourists have an option to get to the toilet and have a drink after their visit to the Banjaard. Fresh water will be supplied by a saltwater purifier. No water can be pumped out of the ground since this is salt water and a supply line from the mainland will be too expensive. Power will be locally produced by solar panels, or can even be used from the floating solar panels in front of the Banjaard.

The Banjaard can be reached by boat and excursions can be arranged for people to get a tour on and around the island when natural regulations allow. It is possible to place special paths on the island which excursions and bird watchers can use. In the case this is realized, a small floating dock need to be constructed for boats.

Another opportunity lies in the zone where artificial reefs are created. The main goal is to stimulate biodiversity development and creating a thriving ecosystem. This creates the perfect possibility for reef diving. New possibilities are expected for tourism around the island which can be facilitated by businesses on the mainland. Diving can also be done in the lagune part of the island in which seagrass is grown. As earlier described in 4.2.6., seagrass can serve as nursery for fish and other species. With that a second zone can be combined with ecotourism and biodiversity development.

7. Zonation

The literature review on biodiversity, biobuilders, and aquaculture in chapters 4 and 5 was analysed according to MCDA guidelines, as described in the methodology. The reasoning behind the MCDA, including scores for each provided option, can be found in Appendix 1. The selected options were divided into eleven zones spread across the Banjaard, as shown in *figure 35*. The chosen zonation is explained via four cross sections on each side of the island:

1. Offshore site (west)
2. Erosion site (south)
3. Tidal flat (east)
4. Accretion site (north)

The locations of the zones were determined based on the characteristics and habitat suitability requirements of the selected options, combined with data on sediment elevation in the current situation and various water and weather parameters (e.g., current direction and speed, average wind direction), as far as this data was available.

It is expected that the hydrodynamics around the Banjaard will be similar to the current situation at the coast of the mainland, such as at the Kop van Schouwen, resulting in erosion on the southern side and sedimentation on the northern side of the island, due to the northeast longshore current (*figure 34*) and prevailing southwest winds (J.G.W. Beemster, personal communication, 19 June 2023). The zonation plan is based on this assumption. However, the hydrodynamics will change when the Banjaard is realized in front of the Kop van Schouwen with sand nourishments. It is highly suggested to model the implementation of the Banjaard in a hydromorphological model to be able to visualize the hydrodynamical and morphological changes. This might also give a better substantiated support for the design of the experiments.

The results from the literature review on added societal value was not assessed through a MCDA because the research did not include all the possible options such as tourism into the zonation. However, some of the options were incorporated into the plan after the zonation of the experiments such as the FPV panels.

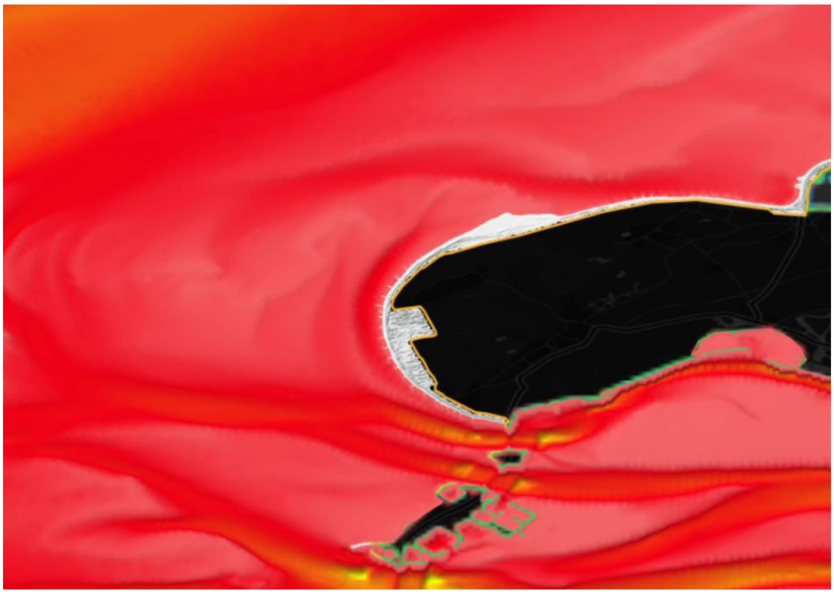

Figure 34 Bathymetry map of the area around the Kop van Schouwen (Bathymetry, 2023).

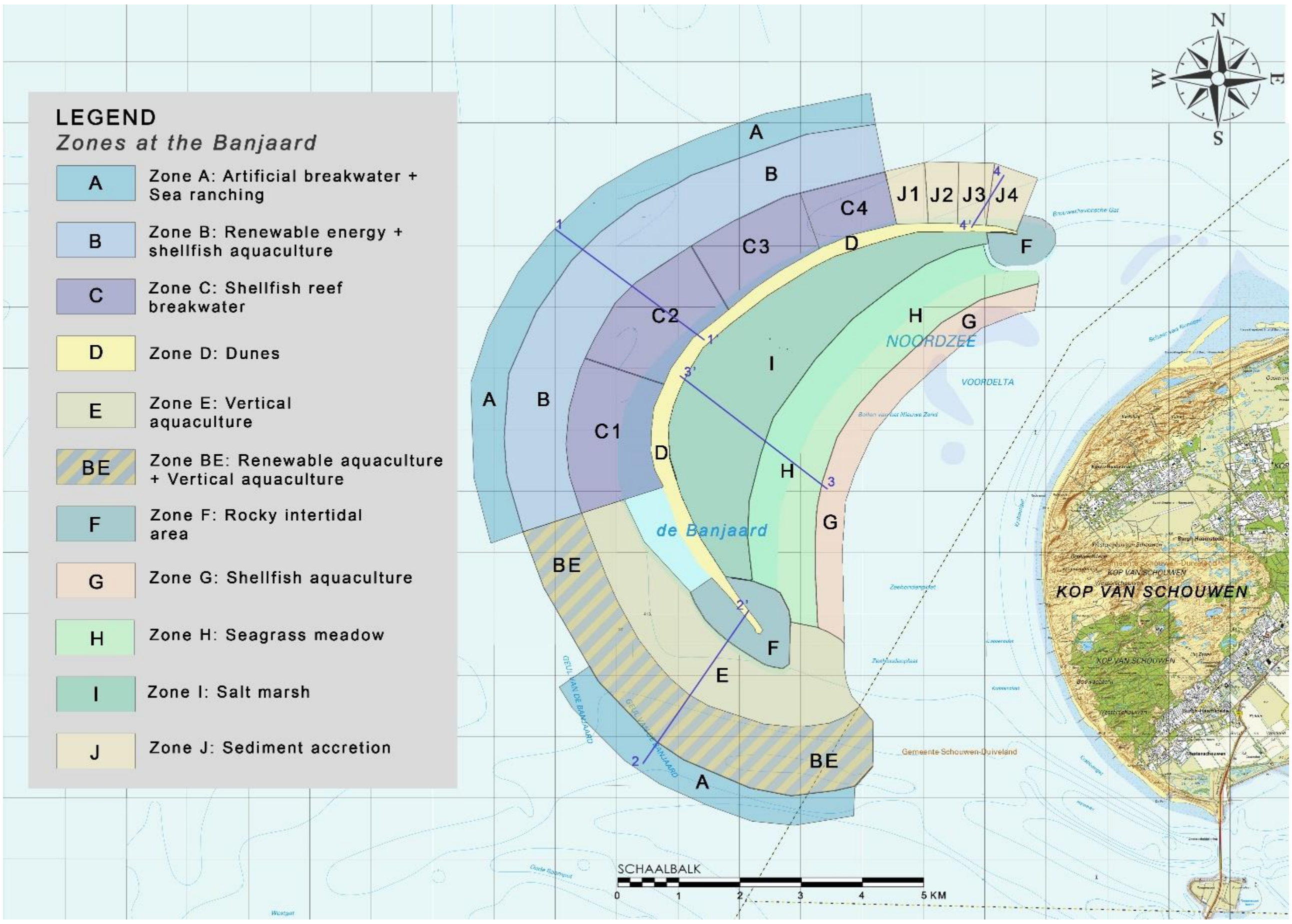

Figure 35 Zonation plan of the Banjaard, indicating 10 defined zones on and around the artificial sand bank and showing the locations of the four cross sections. Zone BE is a combination of zones B and E.

Figure 35 shows the zonation plan of the Banjaard. The map contains four cross sections through the different zones with suggested experiments. Below an elaboration on the cross sections with the different experiments will follow. It should be noted that the y-axis' of the cross sections are vertically exaggerated, in order to elaborate on several vertical features and graphics in the images.

7.1. Cross section 1: Offshore site

For the offshore site four different experiments are suggested. This section (*figure 36*) is approximately 3 kilometers long and will be described from deep (west) to shallow (east). It consists of an artificial reef, floating solar panels, a shellfish reef and marram grass respectively.

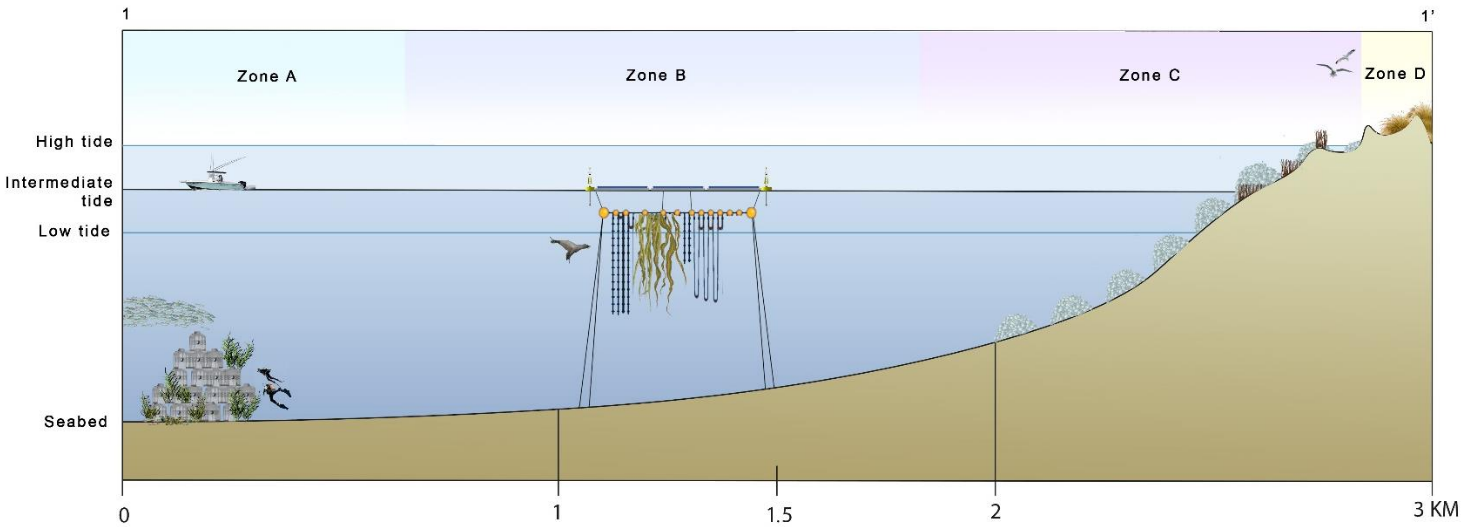

Figure 36 Cross section 1: spherical impression of the zones A, B, C & D on the west side of the Banjaard, including the artificial reef experiment, floating solar panels experiment, shellfish reef experiment and the marram grass experiment.

7.1.1. Experiment 1. Artificial reef

First, we suggest for the most seaward experiment, the creation of an artificial reef. The artificial reef will be implemented in zone A. The main reason for creating an artificial reef further away from the island at the Northwest is because these hard structures work well for wave attenuation. Furthermore, when northwestern storms arrive with high waves at the coast you need the most wave attenuation at this location. Besides that, the artificial reef also needs deeper water to function well. Water depth around this location is around 6 meters on average, which is why it is assigned as the first line of defense. Moreover, the creation of an artificial reef will create substrate for shellfish to grow on, as well as many hiding spots for several types of fish and crustaceans. Therefore, creating this reef will possibly also boost the biodiversity in the area. When juvenile lobsters, North Sea crab and other fish are released in this location, it could potentially also be used for sea ranching five years after the creation of the reef (see 5.6. Sea ranching).

To create the reef, we suggest offshore REB which each weigh up to seven tons. These blocks can be placed beside each other in a row with a meter in between the different blocks, as this is beneficial for animals to move through the artificial reef. The blocks will be placed in front of the coast on the sandy subsoil. The blocks have been tested for stability in high velocity environments and turn out to be suitable for this location. Due to their shape these blocks can attract marine life, as is mentioned before and accelerate the natural process of oyster growth together with creating an opportunity for fig sponges, cold water anemones, and coral to grow. The knowledge we would like to gain from this experiment is; 1) how long it takes to get a fully functioning reef, 2) how well the Reefy system attenuates waves in front of the Banjaard, 3) the influence of the reef on the biodiversity and 4) whether sea ranching around the reef can be profitable using traps and rod and reel fishing after five years.

7.1.2. Experiment 2. Floating solar panels

When moving closer towards the island, the second line of defense should be formed by a row of floating solar panels with vertical aquaculture on ropes underneath. This experiment is implemented in zone B. The solar panels can be used to generate renewable energy for the island and its surroundings and they will also attenuate waves. Because of the vertical aquaculture this effect is even more enhanced. Furthermore, the ropes with mussel and oyster cultures have an extra purpose as they can be harvested and sold for human consumption. Therefore, it is suggested to implement several islands of solar panels like Oceans of energy has done before near the Dutch coast in zone B (Oceans of energy, 2023). Each island will consist of multiple solar panels and will be attached to the bottom with a chain on several locations and uses buoys to stay afloat. The dimensions of a single solar panel island will be around 6 m wide and 50 m long parallel to the coastline. A single island with these dimensions will have around 176 solar panels and an example is shown on a different scale in *figure 37*. It is advised to do a costs-benefit analysis for the optimal number of islands implemented in zone B.

Moreover, appropriate space should be left between the different solar panel islands so they will not damage each other during a large storm. Underneath the panels several ropes will be hung for vertical shellfish seagriculture. For the first island just mussel culture will grow on the ropes starting at 30 cm underneath the panel all the way to the bottom of the rope. For the second island ropes with oysters will be installed, and no aquaculture will take place underneath the other solar panel islands at first. We decided to work with vertical oyster and mussel farming because these are some of the only species that can grow underneath solar panels due to the lack of natural light, even though their average MCDA analysis score is relatively low. Different harvest techniques and locations of ropes can be investigated to see which techniques work best before upscaling the shellfish aquaculture towards the other solar panel islands.

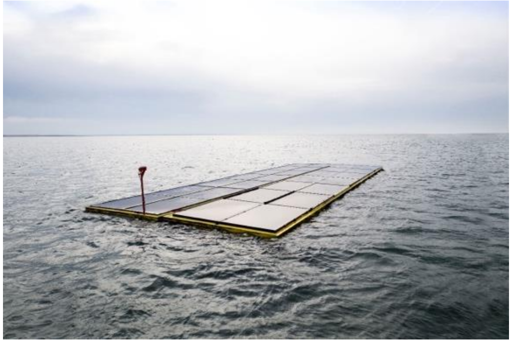

Figure 37 Floating solar panels from Oceans of energy (Oceans of energy, 2023).

The knowledge we would like to gain from this experiment is; 1) how well solar panels work at attenuating waves, 2) what the optimal amount of solar panel islands is to implement in this zone, 3) whether this renewable energy source is profitable, 4) what the best type of hanging aquaculture under solar panels is, 5) until what depth oysters and mussels grow on the ropes, and 6) what the best harvesting technique is.

7.1.3. Experiment 3. Shellfish reef

Moving further towards the island we suggest installing a reef of shellfish as this is a rough structure that can keep sediment in place and will promote sedimentation because the flow velocity of the water that moves over the reef will decrease. This experiment will be implemented in zone C. We decided to put mussels and oysters as biobuilders in this zone because they both score the highest in the biobuilder MCDA analysis and this is an area where we need most reduction of erosion during storms. For this experiment we want to create a living breakwater like what is already being done with oysters in front of Staten Island by the Billion oyster project using collected oyster shells from seafood restaurants in New York (Living Breakwaters|Billion oyster project, n.d.). For the reef at the Banjaard three different patches with a small gradient will be designed each of a least 300 x 300 m. Between the patches there will be around 100 m as a transition zone. The first patch will be filled with blue mussels (zone C1), the second one with a mix of oysters and mussels (zone C2), and the third only with Pacific oysters (zone C3). Furthermore, there will be a control area, which is in zone C4.

To enhance the development of a reef, a leeside should be created. This can be accomplished by implementing brushwood groynes perpendicular to the waves. This first line of defense will attenuate the waves giving the mussels and oysters the opportunity to attach. The brushwood groynes are approximately 2 meters high. To implement the different patches of oysters and mussels, enough leftover shells should be collected for a bed from seafood restaurants in Rotterdam. After that, the shells are first cleaned in a different location. Then they are transported to the lab where seeding of the oyster shells either occurs with just lab harvested blue mussel larvae, with just lab harvested Pacific oyster larvae or with a combination of both. The shells containing just mussel larvae are dropped in the patch in zone C1, the shells with a combination of mussel and oyster larvae are dropped in the patch in zone C2 and the shells just containing oyster larvae are dropped in the patch in zone C3. Currently, a lot of research is already done to investigate how to make the release of oyster larvae directly in open water feasible. This technique might be used in the future (New

Technique Shows Oyster Shell Seeding is Possible in Open Water, 2021). From this experiment the following information would like to be gained; 1) what type of shellfish will best survive in strong currents, 2) which patch has the highest biodiversity and 3) what patch works best as a breakwater to prevent erosion of the island.

7.1.4. Experiment 4. Marram grass

After the shellfish reef, the beach slowly turns into a dune landscape that will keep the North Sea away from the mainland behind the island. We suggest planting marram gras on the raised dunes, which will stabilize the sand and prevent it from being transported away by wind and water. We decided on marram grass as biobuilder because the average score on the MCDA analysis was okay and it is the only species we investigated that grows well in a dune landscape. This experiment will be implemented in zone D. Because of the marram gras that keeps the dunes in place a new ecosystem will arise and therefore it is important to keep monitoring this area in the future to see if new species come to live in this habitat. It is important to gain more knowledge on how many marram gras plants should be planted to stimulate dune formation and in what pattern the plants should be planted.

In front of Oostende, Belgium in the dune area, plots were created with different patterns and densities of Marram grass plants to investigate what type of planting design would work best for dune restoration. Unfortunately, results are not yet available for this research. However, if the research is finished before the sand suppletion starts, the planting pattern they recommend should be used. But if those results are not available in time, it is suggested to create three different zones within the marram grass zone or dune landscape of the island (*figure 38*). In the first zone a random pattern of nine marram grass plants per square meter should be planted, in the second zone nine plants per square meter should be planted at equal distance and in the third zone fifteen plants per square meter could be planted at equal distance from each other to investigate if location and density of the marram grass plants for dune formation on the island matters (Agentschap MDK, n.d.).

From this experiment the aim is to gain information on; 1) the influence of marram grass on dune formation, 2) the potential biodiversity increases due to marram grass, and 3) the effect of different planting patterns, if used.

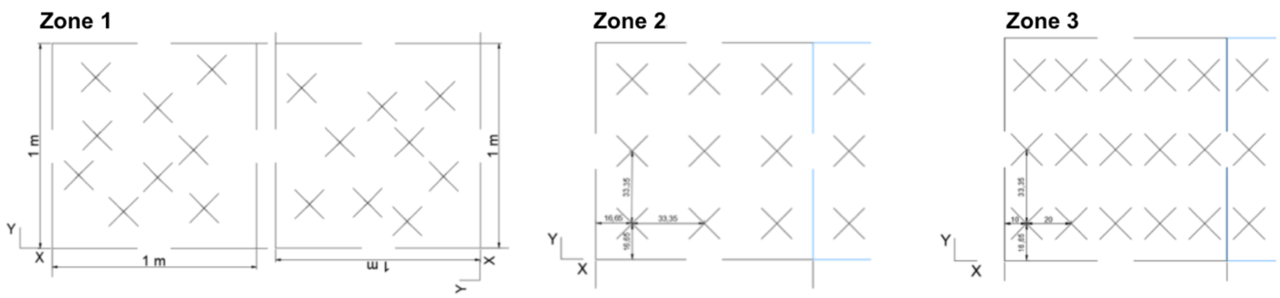

Figure 38 Overview of the marram grass planting design in topview that can be used in case previous study from Agentschap MDK has not yet generated results (Agentschap MDK, n.d.). Every cross is a seagrass plant.

7.2. Cross section 2: Erosion site

At the erosion site (*figure 39*), it is advised to start with an artificial reef by elongating experiment 1, so this is also in front of the coast at the southwest of the island and not only at the northwest (zone A). Then when moving further towards the island there is an option to also put solar panel islands here as most general waves will come from the southwest and those also need to be attenuated (zone BE). Increasing the area covered with solar panels will increase the yield and profitability of green energy production. After this zone the water depth will decrease slowly, and we suggest building a vertical seagriculture farm here and lastly creating an area with stones for intertidal pools. This cross section will be approximately 3 kilometers long. The cross section will be described from deep (south) to shallow (north).

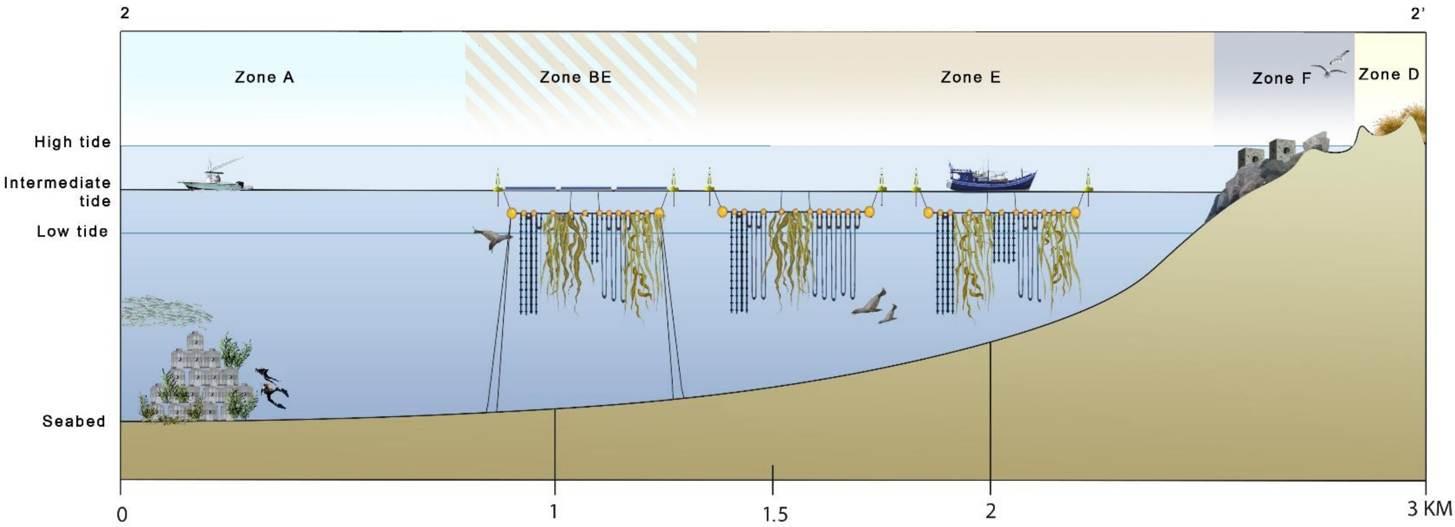

Figure 39 Cross section 2: spherical impression of the zones A, BE, E, F & D on the south side of the Banjaard, including the vertical aquaculture experiment and the rocky tidal pools experiment.

7.2.1. Experiment 5. Vertical aquaculture

We suggest starting with vertical farming in the Southwest of the island, outside of the intertidal zone at an average depth of around 4 meters, because this method scored relatively high in the MCDA analysis. This will be in zone E. The plot will be 0.5 km in width and 2 km in length. This site results in a plot of 1 km^2 which is the same area used by the North Sea Farmers for their pilot experiments (North Sea Farmers, 2023). However, the depth around the anjaard is shallower, thus resulting in a different yield. The seaweed will be attached to a vertical rope that stays afloat by attaching it to a buoy. When harvesting, the ropes can be lifted from a boat, after which the seaweed can be cut off (Seaweed Solutions, 2023). It is suggested to use sugar kelp as this is a suitable species of seaweed to use for food production. By harvesting seaweed, the chances of seaweed blooms due to nutrient washing from the mainland are limited. The option of vertical seaweed farming is chosen as it attenuates waves more than with horizontal seaweed farming. Furthermore, the profitability is higher than horizontal seaweed farming as more biomasses can grow in a relatively smaller area.

Furthermore, we advise putting cages with scallops and ropes with blue mussels between the seaweed strands as they filter the water and these species can also be harvested for human consumption. In addition, cages with clams can be put on the bottom and these can be collected after they reach maturity. Here it is advised to reach out to Green wave for more information, training, and help with the implementation of this vertical seagriculture farm (Green wave, n.d.). The aim is to gain the following information from this area; 1) the wave attenuation effectiveness on the erosion side of the island, 2) if the potential biodiversity increases due to vertical aquaculture and 3) whether the option is profitable.

7.2.2. Experiment 6. Stones for intertidal pools

After the vertical aquaculture zone, we advise to drop large rocks, boulders and ReefPools (see 4.3.2. Artificial Reef Structures) in the inter tidal area around the southern corner of the island in zone F. In the northern corner of the island (zone F), this is also advised to implement. By doing this, the island is less likely to erode, because these boulders are heavier than sand. Furthermore, it will also create a completely new habitat as pools will develop, which will stimulate biodiversity around the island. From this experiment the aim is to gain the following knowledge; 1) how this new habitat will contribute to the biodiversity around the island and 2) whether it functions as a breakwater.

7.3. Cross section 3: Tidal flat

The third cross section (*fugure* 40) discussed is the tidal flat, so the landward side of the island. This section is approximately 3 kilometers long. The cross section will be described from deep (east) to shallow (west) and consists of an off-bottom oyster culture, seagrass and *Salicornia* respectively.

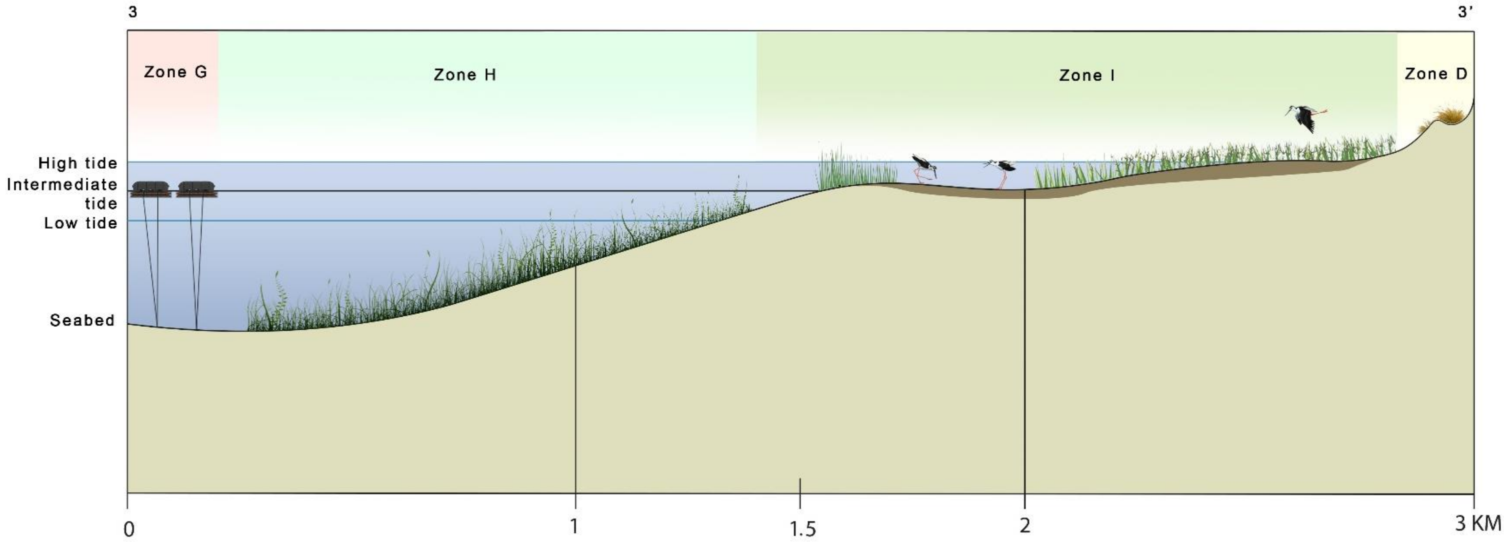

Figure 40 Cross section 3: spherical impression of the zones D, G, H & I on the east side of the Banjaard, including the off-bottom oyster farming experiment, seagrass experiment and Salicornia experiment.

7.3.1. Experiment 7. Off-bottom oyster farming

Firstly, it is suggested to make an oyster farm in zone G. As this is outside of the intertidal area it will be submerged all the time with an average depth of approximately one meter (EMODnet Map Viewer, nd). To enable accessible harvesting, it is suggested to use a floating oyster system, where the oysters can be harvested wearing wading suits. Another advantage of a floating oyster system is that the oysters will be tumbled automatically by the waves and currents, ensuring stronger shells (Pangea Shellfish Company, 2015). Oysters filter the water, which benefits the neighboring zone for seagrass growth. *C. gigas* grow well in the North Sea and is thus suggested to be used in the oyster farming. *gigas* grow well in the North Sea and is thus suggested to be used in oyster farming. It is suggested to use a patch of 30 m x 1 km, with three rows of floating oysters in there (*figure 41*). From this experiment we would like to see if; 1) this way of oyster farming is profitable, and 2) the effect on biodiversity. From this experiment, we would like to see if; 1) this way of oyster farming is profitable and 2) the effect on biodiversity.

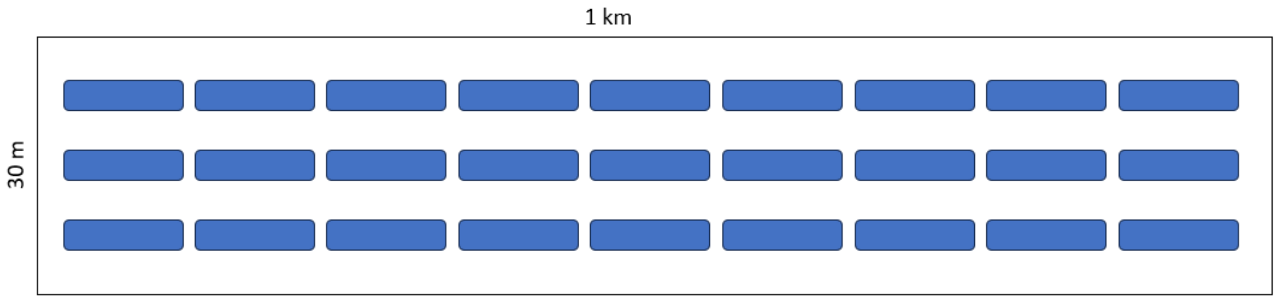

Figure 41 Suggested design in a top view for floating oyster experiment.

7.3.2. Experiment 8. Seagrass

Seagrass is limited by light and the optimal depth to grow is 20 to 40 centimeters below low tide. As seagrass has difficulty settling due to the harsh hydrodynamic conditions their MCDA score for using seagrass as a biobuilder is low. Using seagrass as a nursery however is a better option. Therefore, it is decided to plant a seagrass patch moving from the seaweed farm towards the Banjaard in zone H. *Z. marina* and *Z. noltii* can live together in the intertidal area and to support biodiversity it is suggested to include both species in the plot. For the introduction of the species, it is suggested to plant seagrass shoots in a seacrete mat as seeds will probably be washed away by the currents. In a reintroduction project in Grevelingenmeer, seagrass shoots are taken from Denmark and planted to research the possibility for large scale seagrass recovery (Rijkswaterstaat, 2023). For the Banjaard it is advised to plant the seagrass shoots in a small raster to investigate its survival rate first. Therefore, it is advised to implement two small rasters with 9 different plots of 1 m x 1 m (*figure 42*) and 4 seagrass shoots in there and monitor the survival rate of *Z. marina* and *Z. noltii.* It is suggested to implement one raster on a seacrete mat and one raster on a sinking mattress to investigate success rate of the seagrass shoots (see chapter 4). It is advised to plant the shoots between 0.5 meter and 1 meter depth (M. Van der Kamp, personal communication, June 15, 2023). With this experiment we would like to gain information on; 1) the success rate of seagrasses in the tidal flat, 2) the difference in success rate between the two rasters, 3) the effect on biodiversity and 4) the possibility of upscaling the small-scale experiment to a nursery.

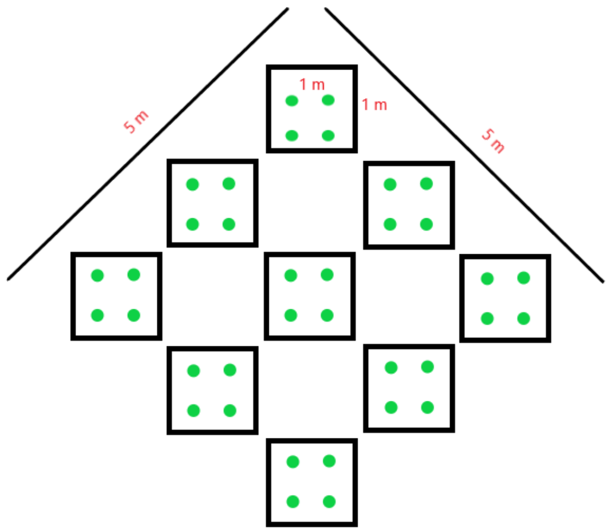

Figure 42 Suggested raster in top view for seagrass shoot planting

7.3.3. Experiment 9. *Salicornia*

Moving further towards the Banjaard, it is suggested to work with *Salicornia* in zone I. *Salicornia* is a plant that causes sediment accretion and is a good option for food supply. *Salicornia* is a pioneer species that grows in intertidal areas. According to optimal growing conditions, the highest germination rate can be reached when the seeds are planted at the beginning of the growing season in April (van Regteren et al., 2020). As they are pioneer species, they will increase the biodiversity, introducing other harvestable species such as sea lavender. The mud percentage in the upper soil is an important factor for the salt marsh vegetation development. A mud percentage of 20 – 50% is optimal and is advised to be used in this zone (de Vries et al., 2021). In the MCDA, *Salicornia* scores relatively high for both being a biobuilder and a seagriculture option. *Salicornia* will accrete sediment, but just on a low scale as the plants are small. However, the food options for *Salicornia* are promising. According to Ventura & Sagi, (2013) the yield is highest when *Salicornia* is harvested in a 3-week interval. However, this does not include the effect on biodiversity. Therefore, it is suggested to include different harvest intervals to see the effect on biodiversity. The area allocated for

Salicornia is in the intertidal area on the tidal flat side of the area as this side of the Banjaard has the highest surface area for potential *Salicornia* growth. We suggest sowing a dense patch of *Salicornia* of 100 m x 100 m in the south of the zone and investigate its colonization of the tidal flat as *Salicornia* spreads fast. According to de Vries et al., (2021) no difference in vegetation density on neighboring patches was found after the first growing season, even though one patch was sown in with *Salicornia* and the other patch was left bare. This might suggest that after the first year, *Salicornia* spreads with the currents and wind from the southern side of the tidal flat up north. To increase the success rate, it is also suggested to implement brushwood groynes in this zone. With this experiment we would like to gain the following information: do the pioneer species increase the biodiversity on the tidal flat (1), to what extent does *Salicornia* accrete sediment (2), what is the influence of the harvest interval on the biodiversity (3) and does *Salicornia* spread after the first year (4).

7.4. Cross section 4: Accretion site

The fourth cross section (*figure 43*) discussed is the accretion site, so the northern side of the island. This section is approximately 1 kilometer long. In this cross section one experiment is suggested in zone J.

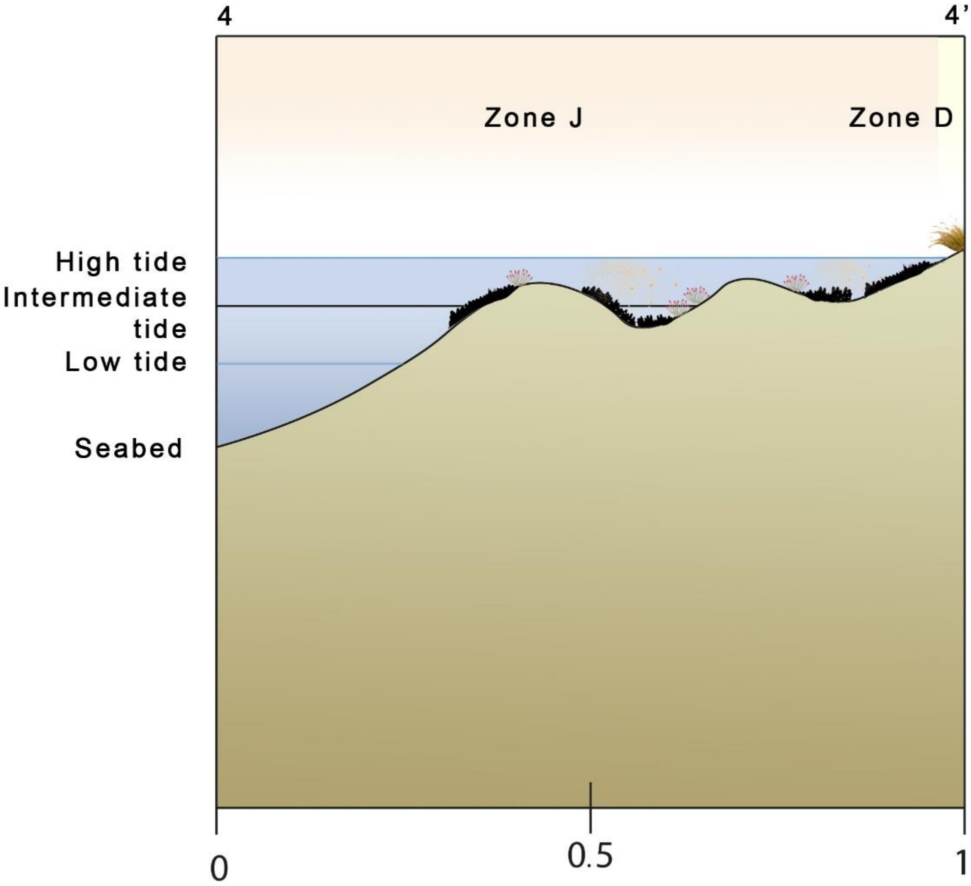

Figure 43 Cross section 4: spherical impression of the zones D & J on the north side of the Banjaard, including the sand accretion experiment.

7.4.1. Experiment 10. Effect on accretion

From west to east, the first plot will be bare (zone J1), after which a plot of mussels (zone J2), oysters (zone J3) and tubeworms (zone J4) follow. Every plot will be 300 m x 100 m. In this experiment, the main goal is to find the accretion rate within the different plots and compare them to the accretion rate that will happen in the bare plot. Furthermore, the sediment rate will change with depth and thus the mussels, oysters and tubeworms might react differently. Therefore, it is suggested to also measure the adaptation of the different species to the sedimentation rate difference over the depth gradient. The blue mussel and Pacific oyster will both be introduced in the same way as explained in experiment 3, the shellfish reef. It is difficult to introduce

L. conchilega in a new area as the juveniles normally stick to adult tubes. Coastbusters (2020) did promising experiments on the introduction of *L. conchilega* with geotextiles. Therefore, it is suggested to contact Coastbusters to gain information on the possibilities of introducing *L. conchilega* with geotextiles. The density aim should be 1000 individuals per m^2. From this experiment we would like to gain the following information: 1) are the species able to keep up with the sedimentation rate, 2) how do the species contribute to the accretion of sediment, 3) is there a difference in performance of the species over the depth gradient and 4) the effect of the different species on biodiversity.

7.5. Overview of habitat type zones

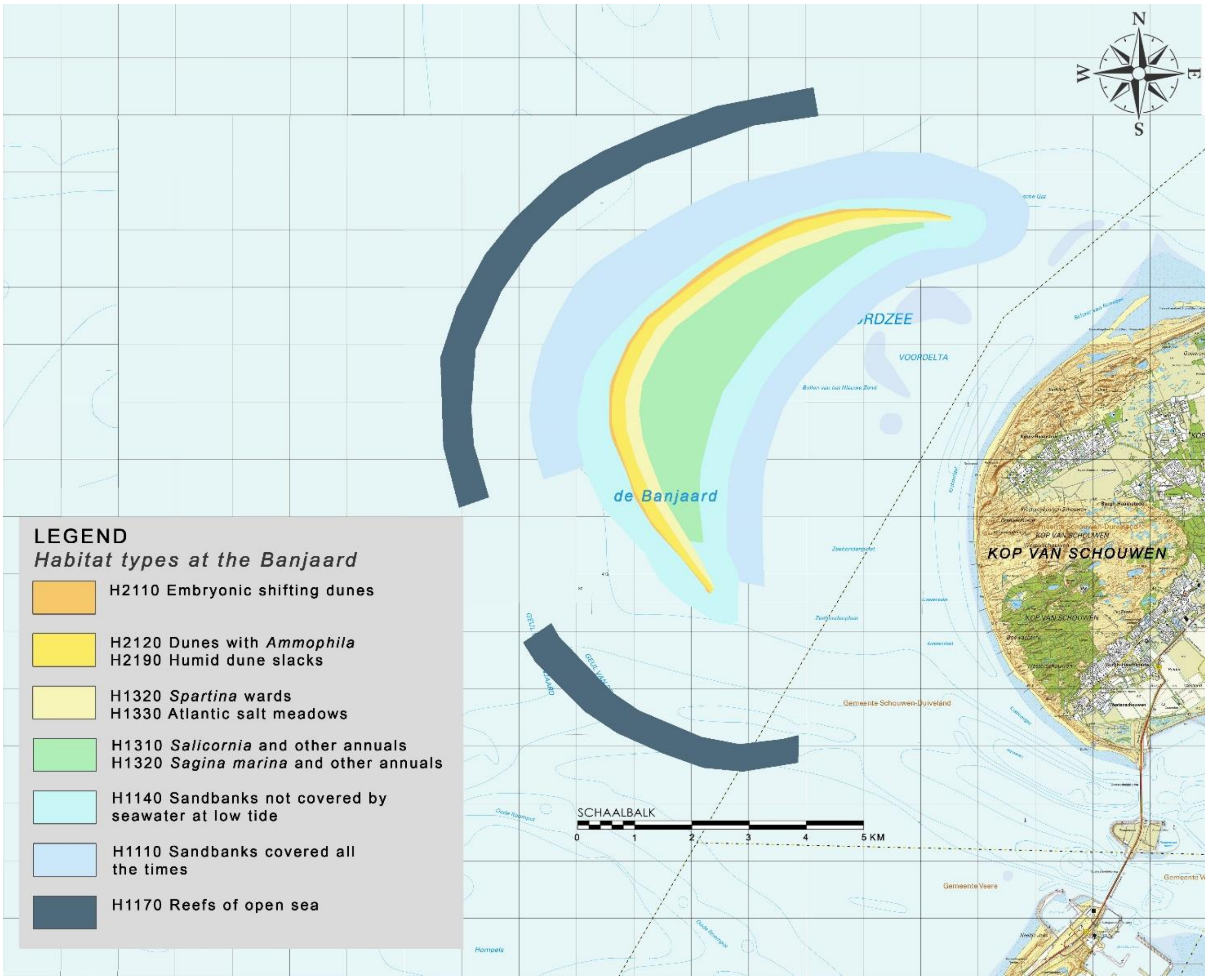

Figure 44 Potential spatial distribution of habitat types on the Banjaard.

As described in chapter 3, the Natura 2000 habitat types can be used as a guideline for designing an ecologically valuable site. *Figure 44* shows a potential spatial allocation of habitat types on the Banjaard. Although a nature area must meet strict criteria to be assigned a particular habitat type, the necessary information is not currently available to say with certainty which habitat types may actually develop. The areas that have been drawn are therefore purely suggestive.

Whether the habitat types can develop depends in part on implemented measures. For example, the habitat type H1170 Reefs of open water, which is characterized by an almost continuous substrate of large stones, can, considering the sandy seabed in the pre-delta, only develop if considerable artificial reefs are created. In addition, it is not impossible for habitat types to develop outside the zoned areas. The zones include the parts of the island where, with the information currently available, there is a realistic chance of developing the habitat types in question.

In some parts that have not been included in a habitat zone, certain habitat types could probably develop, but have been omitted due to a relatively high expected level of disturbance from other experiments. This is the case for experiment zone E, designated for vertical seaweed, mussel and oyster farming. This does not completely exclude any ecological value, but is nonetheless not ideal, making a strong ecosystem meeting the requirements of habitat type H1110 less realistic.

8. Monitoring indicators

In the zonation chapter, a spatial plan has been devised for the Banjaard based on the aim to maximize the biodiversity on the island, to increase coastal protection and to create opportunities for aquaculture. To be able to make statements about the results arising from the implementation of this plan, it is crucial to monitor the developments on and around the island over the coming decades. For this purpose, monitoring indicators must be established, on which a monitoring plan can be based. In this chapter, for such a monitoring plan, several potential indicators are listed and described, divided into the categories of coastal protection, biodiversity, aquaculture and other optional indicators.

Apart from assessing the functioning of the Banjaard as a beaker, this pilot also creates an opportunity to generate knowledge on the use of artificial reefs and biobuilders for coastal protection and biodiversity enhancement. Even though the creation of artificial reefs has become much more commonplace lately, the amount of knowledge on the effects on coastal protection and the surrounding ecosystem lags behind. The limited research that has been done has mainly focussed on small reefs created for scientific purposes (Hylkema, 2021). The Banjaard provides an ideal opportunity to properly document and evaluate these effects on a much larger scale.

To provide a structured chapter exploring the most relevant monitoring indicators these will be divided in coastal protection, biodiversity, seagriculture and others. Each monitoring indicator will aim to obtain data to fill specific knowledge gaps for the experiments detailed in chapter 7. Finally, a summary table comprised by the experiments and indicators is also available on this chapter.

8.1. List of critical indicators

In this section a list of monitoring indicators with a brief explanation will be classified according to the three main criteria of this project: coastal protection, biodiversity, seagriculture and some additional controlling indicators that allow the linking of the experiments with topics as climate change and ocean acidification.

8.1.1. Coastal protection

This subsection explores possible monitoring indication that could give relevant information about the role of the biobuilders in coastal protection and the island dynamics.

A: Coordinates. The geographical location of the Banjaard has been mapped by satellite images. The movement in comparison to the initial location can be determined by comparing geographic coordinates over time.

B: Island perimeter. The length of the coastline of the island can be calculated through several imagine methods and it gives information on the island shape. This indicator can give information on the island vulnerability to erosion.

C: Breakwater island height, surface area and volume. To assess the condition of the breakwater island, the height, surface area and volume needs to be measured. A decline of these could indicate that the breakwater is eroding away. These staying the same or increasing could point towards the Banjaard being a durable solution for coastal protection.

D: Dune height, surface area and volume above sea level. Characteristics of the sandy body above the sea level is affected by several factors in this pilot project. The general development of the surface island with time will have a major impact on its success as barrier island.

E: Biobuilder height, area and volume. Measuring height, area and volume of biobuilders in a certain area over time will give an indiation of their ability to grow and multiply, and therefore their functionality and longevity as biobuilders

F: Artificial reef height, area, and volume. The height, area and volume of the artificial reefs will be measured to assess the condition of the artificial reef. It could get smaller over time by sinking into the substrate, or through sedimentation on and around the reef, decreasing its functionality.

G: Wave energy. To assess effect or correlation between biobuilders and wave attenuation it is necessary to perform measurements before and after the introduction of the biobuilder. A measurable indicator is the wave energy, which links speed and mass of the wave.

H: Currents. The measurement of speed and route of water in dynamic environments. Insight in the route and speed of sea currents can give an indication of its influence on the growth of biobuilder organisms in different zones. Some species can't tolerate currents over a certain threshold.

I: Depth. The vertical distance from sea level to the sea floor is dynamic and can give information about several parameters relevant for erosion, sedimentation, and island movement description over time. This indicator is also of importance for the growth of species, because is one of the determining features for the success or failure in the establishment of a species in certain area.

J: Sediment height. The vertical distance between the bottom surface of a body of water and the accumulated layer of sediment on the bottom surface. This can be composed of sand, clay or organic matter. The change in sediment height gives an indication about the sedimentation rate which can influence the performance of bivalves growing on the sea floor.

K: **Biobuilder vertical movement.** When sediment height increases or decreases, some biobuilders have the ability to adjust. Mussels can climb on top of the newly deposited layers for example, while oyster reefs can grow taller. The speed at which they're able to do this could be an important factor in adapting to the rising sea levels or movement of the Banjaard.

8.1.2. Biodiversity

This subsection covers the possible monitoring indicators that could represent the success of the experiments on enhancing biodiversity. Here the macrofauna is also regarded and included in the indicators measurement.

L: Presence/absence of indicator species. Indicator species are linked to certain ecosystem conditions and are therefore widely used in research to monitor environmental changes, evaluate the effectiveness of management strategies and serve as warning signals for impending ecological shifts (Siddig et al., 2016).

M: Species composition. An overview of the different species present in an area. This could give insight into the workings of an ecosystem, as well as its health and variety.

N: Species richness. A count of the number of species in an area. A higher number of species is usually a consequence of a healthier and more stable ecosystem with more variety.

O: Abundance of individuals. The total number of individuals (per species) in an area.

P: Diversity index. The Shannon Wiener diversity index combines the abundance and the species richness, and also takes into account how well the individuals are divided between the different species (evenness). A higher abundance, species richness and evenness all lead to a higher diversity index.

Q: Biomass. The total mass of all living organisms (or of a certain group) in an area.

8.1.3. Seagriculture

To determine the success of the diverse seagriculture initiatives, monitoring indicators linked to product safety and profit are presented in this subsection.

R: TTX concentration. Tetrodotoxin accumulation in shellfish cultures in the seagriculture experiment areas. A unit of concentration that gives information on consumption safety.

S: Nutrient concentration. The concentration of nitrogen and phosphorus in the seawater. The nutrient concentration will be of direct importance for the growth of plants, and therefore for the rest of the ecosystem as well.

T: Concentration phytoplankton. To identify the status of phytoplankton concentration and map the possibility of algal blooms, the concentration of these species needs to be monitored.

U: Market price. The revenue of a company depends on their product unit price on the market, but market price is not stable and depends on fluctuations in demand and product availability in the market.

V: Production cost. To know the profit for a company, the cost to produce a unit of product must be lower than the sale price. This indicator allows to determine if the investment in the initiative is worth it.

W: Productivity. The amount of product generated per unit of time, commonly a yearly value. This indicator has a direct influence on the revenue and usually makes the production cost lower due to the economy of the scale concept.

8.1.4. Others

X: pH. The pH value indicates the acidity or proton concentration of the water. This variable is dependent on climate change and might have an impact or be altered by several organisms that are introduced in the Banjaard experiments.

Y: Energy conversion efficiency. This monitoring indicator applies to the FPV systems initiative and allows to obtain specific data on its performance compared to inland PV systems.

Z: T-sum. The accumulation of heat over a determined timespan is an indicator that can be linked to climate change and, at the same time, the ability to adapt of the species present.

8.2. Relevant indicators per experiment

In this section the monitoring indicators will be assigned to the experiments developed in chapter 7, they can provide relevant data for the three main criteria in the Banjaard pilot. The information gained by monitoring these indicators can then be used to compare zones or assess island-wide processes.

8.2.1. Island dynamics

Critical indicators: A, B, C, D, G, H, I, J.

For the Banjaard pilot to be a success the breakwater has to be flexible and stay somewhat consistent in size. To get a better understanding of the dynamics of the island the location, height, size, and shape will be monitored over time.

8.2.2. Artificial reef

Critical indicators: A, E, F, G, H, I, J, K, L, M, N, O, P, Q, S, T, U, V, W, X, Z.

Experiment 1 (see 7. Zonation, 1. Artificial reef) will have an artificial reef. It is important to monitor how it performs as a breakwater, since that is the main function of this zone. In addition, creating this habitat will attract more different species to the area as it provides shelter and food options. Therefore, monitoring the increase in biodiversity by looking at the species richness among other things is important together with investigating if it can be used for sea ranching.

8.2.3. Floating solar panels

Critical indicators: A, G, H, I, L, M, N, O, P, Q, R, S, T, U, V, W, X, Y, Z.

Experiment 2 (see 7. Zonation, 2. Floating solar panels) includes FPV solar panels combined with vertical mussel farming. It is expected that this area will have influence on the three pillars or criteria for this project, having a role in wave attenuation due to the solar panels, biodiversity enhancement due to the added surface for organisms' attachment, and seafood and energy production. Here there are included the specific monitoring indicators for shellfish cultivation and energy conversion, to calculate the FPV system on wave attenuation and, additionally, the effect of sea dynamics on the location of this experiment with time. It is necessary to check whether the anchors will resist climatic conditions, move faster, slower or at the same speed and direction as the Banjaard.

8.2.4. Shellfish reef

Critical indicators: A, E, G, H, I, J, K, L, M, N, O, P, Q, S, X, Z.

Experiment 3 (see 7. Zonation, 3. Shellfish reef), the creation of a shellfish reef is important for the functioning of the island as a breakwater. Therefore, it is important to monitor how the reef improves wave attenuation, which type of bivalve reef has the highest biodiversity and monitor if the reef is susceptible to climate change or not.

8.2.5. Marram grass

Critical indicators: A, D, E, L, M, N, O, P, Q, S, X, Z.

Experiment 4 (see 7. Zonation, 4. Marram grass) takes place in the dunes, above sea level. Data from the dune development and location of the marram grass over time gives useful insight into its role to keep the dune sediment in place, and which pattern and density has the highest impact on dune dynamics.

8.2.6. Vertical aquaculture

Critical indicators: E, G, H, I, J, K, L, M, N, O, P, R, Q, S, T, U, V, W, X, Z.

Experiment 5 (see 7. Zonation, 5. Vertical Aquaculture will generate knowledge on the profitability. Therefore, indicators related to the product safety and production were selected. The biodiversity indicators around the vertical aquaculture experiment are crucial to monitor since this directly influences the production processes. It is expected that this experiment will also impact the wave attenuation, and therefore costal protection indicators are also used for monitoring.

8.2.7. Stones for intertidal pools

Critical indicators: A, B, G, H, I, J, L, M, N, O, P, Q, X, Z.

Experiment 6 (see 7. Zonation, 6. Stones for intertidal pools), by placing stones together with Reefpools, will create a new habitats, and therefore, it is important to monitor the biodiversity change in this area, together with the ability of the habitat to prevent erosion of the island.

8.2.8. Off-bottom oyster farming

Critical indicators: A, E, G, H, I, J, K, L, M, N, O, P, Q, R, S, T, U, V, W, X, Z.

Experiment 7 (see 7. Zonation, 7. Off-bottom oyster farming) is mostly seagriculture oriented, exploring the possibilities for oyster farming in the shallow low-current lagoon zone and comparing them to other zones around the island. The oyster farm could also affect biodiversity in this area and play a role in lagoon formation trough sediment trapping and current reduction, so biodiversity and coastal protection indicators are included as well.

8.2.9. Seagrass

Critical indicators: A, E, G, H, I, J, K, L, M, N, O, P, Q, S, T, U, V, W, X, Z.

Experiment 8 (see 7. Zonation, 8. Seagrass) is based on seagrass and its prospective nursery role once the ecosystem develops. In this experiment the biodiversity enhancement plays a critical role in determining the success for aspects like the sheltering of juveniles. Seagrass is vulnerable to few several stressors measured with the indicators from the coastal protection sector such as strong currents and can produce profit if it succeeds as a nursery. Therefore, some indicators from both sectors should be monitored to obtain conclusive results from this experiment.

8.2.10. Glasswort (*Salicornia*)

Critical indicators: A, E, G, H, I, J, K, L, M, N, O, P, Q, S, T, U, V, W

Experiment 9 (see 7. Zonation, 9. *Salicornia*) incorporates the planting of *Salicornia* in the intertidal region of the Banjaard. Since *Salicornia* causes sediment accretion, coastal protection related indicators are interesting to use for monitoring. Since this plant also incorporates the seagriculture component, related indicators will be used for monitoring.

8.2.11. Effect on accretion

Critical indicators: A, B, C, E, G, H, I, J, K, L, M, N, O, P, Q, S, X, Z

Experiment 10 (see 7. Zonation, 10. Effect on accretion) aims to get results on coastal protection criteria and sediment fixation, since this location of the island is expected to get elongated with time, monitoring of indicators related to the island sedimentation, shape and location are important to determine the effect of the biobuilders in this zone. Biodiversity indicators will also provide information about the ecosystem development and if a species gradient is generated in the area of the experiment.

8.3. Summary table of the critical monitoring indicators distributed per experiment

Effect on accretion	Salicornia	Seagrass	Oyster on-bottom farming	Stones for intertidal pools	Vertical thinking	Marram grass	Breakwater role of reefs	FPV panels	Artificial reef	Island dynamics	
X	X	X	X	X			X	X	X	X	**A: Coordinates**
X				X						X	**B: Island perimeter**
X										X	**C: Breakwater island height, surface area and volume above**
						X				X	**D: Dune height, surface area and volume above sea level**
X	X	X			X	X	X		X		**E: Biobuilder reef height, area, and**
									X		**F: Artificial reef height, area, and**
X	X	X		X	X		X	X	X	X	**G: Wave energy**
X	X	X	X	X	X		X	X	X	X	**H: Currents**
X	X	X	X	X	X		X	X	X	X	**I: Depth**
X	X	X	X	X	X		X		X	X	**J: Sediment height**
X	X	X	X				X		X		**K: Biobuilder vertical movement**
X	X	X	X	X	X	X	X	X	X		**L: Presence/absence of indicator**
X	X	X	X	X	X	X	X	X	X		**M: Species composition**
X	X	X	X	X	X	X	X	X	X		**N: Species richness**
X	X	X	X	X	X	X	X	X	X		**O: Abundance of individuals**
X	X	X	X	X	X	X	X	X	X		**P: Diversity index**
X	X	X	X	X	X	X	X	X	X		**Q: Biomass**
			X		X			X			**R: TTX concentration**
X	X	X	X		X	X	X	X	X		**S: Nutrient concentration**
	X	X	X		X			X			**T: Concentration phytoplankton**
	X	X	X		X			X			**U: Market price**
	X	X	X		X			X			**V: Production cost**
	X	X	X		X			X			**W: Productivity**
X	X	X	X	X	X	X	X	X	X		**X: pH**
								X			**Y: Energy conversion efficiency**
X	X	X	X	X	X	X	X	X	X		**Z: T-sum**

9. Discussion

9.1. Result summary

For the creation of the Banjaard breakwater spatial plan, seven biobuilders were selected. These include oysters, mussels, tubeworms, seaweed, seagrass, *Salicornia* and marram grass. They were chosen because of their ability to increase coastal protection by trapping and retaining sediments, attenuating waves, and reducing current speeds. All of them are capable of a certain amount of flexibility, allowing them to grow and move with the dynamic breaker island, unlike conventional hard coastal defences. Another advantage of these biobuilders is their potential for facilitation of other species by providing many supportive effects on the ecosystem like water quality improvement, shelter, substrate for settlement, and direct and indirect food sources. This often has a positive effect on biodiversity. The added habitat diversity also has the possibility of increasing ecosystem stability. These effects on biodiversity in turn create opportunities for sustainable sea ranching and fisheries. Aquaculture options like vertical mussel, oyster and seaweed farming could contribute to coastal protection as well as biodiversity, while at the same time providing a local, renewable food source. The mussel and oyster farms can even be combined with floating solar panels, optimizing the use of space as well as increasing the Banjaards' functioning a breakwater.

These results served to develop a spatial plan with experiment proposals that could give relevant data for the correct implementation of the pilot Banjaard and similar future projects.

9.2. Critical aspects

The spatial plan presented is based on the current research for the pilot project obtained from previous student groups and was developed within a limited time. Nonetheless, it gives an assessed overview of the possibilities for biobuilders and seagriculture initiatives that have more chance to be successful when applied. In this section the critical aspects to monitor and or mitigate to increase the feasibility of the advice will be discussed.

Currently, the spatial plan is not bound to a hydromorphological model for the pilot, but instead adapted to the predefined shape and location provided. However, this shape and its location may not necessarily be a realistic or the most suitable considering the local conditions. With the output from the model, the shapes, size and depths of the zones could be improved and more detailed to ensure the best place for the species growth. It must be noted that the expected hydrodynamics differ considering a single island, like the Banjaard, compared to a second coastline consisting of several islands, an idea that could be explored further depending on the results from the Banjaard pilot. It would be necessary to monitor the evolution of local hydrodynamics and island morphology if the plan moves to the new coastline phase.

If the erosion rate of the island is larger than expected, additional suppletions every few years might be required. Should this be the case, a new variable is to be added to the monitoring program; the impact of the repletion on the biobuilders, the ecosystem diversity and sustainability. An indication of the necessity of repletions can be obtained via a hydromorphological model. Such repletions could have impact on the biobuilders, the ecosystem diversity and sustainability. Assessing this potential limitation could be relevant for the pilot success as a whole.

For the biobuilder overview from the report, a preselection was performed after researching ecosystem engineers and their most suitable conditions for growth and settlement. Coral reefs, for example, were not explored in the report, but they are ecosystem engineers used worldwide and could also provide advantages in cold water ecosystems as the North Sea (NatureScot NàdarAlba, nd.). For the assessment on which biobuilders and seagriculture initiatives were more suitable for the Banjaard, an MCDA was performed. This MCDA has a weight for the criteria to calculate a total score, therefore, the highest scores could change if other criteria were used or with different weighting or relative relevance to the project. This preselection and the use of MCDA reduced the number of options explored and added to the spatial design and recommendations.

The introduction stage of biobuilders in the Banjaard is crucial for the success of the pilot, because during the time between the sand suppletion and the implementation of the erosion-reducing measures, the island will be the most vulnerable. However, due to logistic limitations in terms of time, manpower and resources, not all the measures can be implemented simultaneously. Besides, there are species of greater importance for the structural integrity of the island than others. This means it will likely be necessary to arrange the implementations based on relative time constraints, i.e., to first carry out the measures that need to happen the soonest. Additionally, during the starting stages an intensive monitoring on the species is important, and to react to the information it provides. A timely and adequate response to unexpected developments could be key in the successful development and adaptation of the biobuilders.

Looking into the social side of the project is noticeable that these initiatives will also need investment in money, time, and effort in product monitoring, as any project needs when it is starting. When referring to aquaculture practices factors as quality and quantity of the production play a big role in determining the harvesting method and frequency which also will lead to profitability, risks and how appealing it is to investors.

Another factor that will affect the development of the pilot is the impact of seasonal change in environmental conditions on the proposed biobuilders. Since the weather conditions affect the species it would be necessary to examine and design a setup preventing the possible detrimental effects on the coastal protection function of the biobuilders. Another factor to take into account with the seasonal change is the impact on currents and storms. The design of the island is focused on protecting the coast mostly against the common southwest direction and intensity of currents and winds rather than the northwest occasional storms and large waves. It would be important to monitor the northwest oriented section of the Banjaard during stormy seasons and to ensure the biobuilders can endure them. The introduction of hard structures complementing the experiments would be needed for the biobuilders to establish, like brushwood groynes in front of the mussel and oyster reef for example.

During the report, as a tool for biodiversity assessment, the habitat types from Natura 2000 were discussed. Nonetheless, this perspective might not reflect the biodiversity completely or the best habitats for coastal protection due to its rigidness. This is also a recurring limitation when looking at for example the monitoring program. The spatial plan is divided in zones limiting the experiments, though these barriers solely exist to create an overview that's easy to grasp. The Banjaard would not have these barriers, allowing gradients of ecosystems and the possibility of experiments influencing each other. Therefore, the zones and monitoring results can be influenced by neighbouring experiments. Apart from the rigidness, the monitoring program could turn out costly, given the area, the number of variables that play a role and the number of experiments that should be performed.

During the realization of this report, there were also ethical considerations. Sediment suppletion is a disruptive event for the current ecology of the Banjaard, and it will impact the local flora and fauna in the short term. Nonetheless, the placement or expansion of a dam would impact the ecosystem too, either way there would be certain effect to the ecology derived since there is need of enhancing coastal protection in Zeeland. Although the idea for the location of the barrier island is placed on the Banjaard location, where the sea is shallow with very little nautical activity, the placement of this island will still cause unavoidable interference in the nautical activities. The degree depends on the final shape, area, and minimum distance needed for nautical routes to avoid ecosystem disturbance. Yet leaving the Voordelta unprotected is not an option either, since the Netherlands is losing land as sea level rises due to climate change.

10. Advice

To create a situation in which the Banjaard will add to existing biodiversity and increase ecological value, we recommend creating a wide variability of habitats on and around the breakwater. To do so, we advise to help steering in this habitat creation by introducing key species like biobuilders (e.g. Pacific oysters, blue mussels, seagrass) and pioneering species (e.g. *Ammophila*, *Salicornia*) which will in their turn facilitate new habitats and may attain environmental conditions for several other species as well. After the establishment of a variety of habitats on and around the Banjaard – with the help of artificial structures where necessary – we recommend letting them evolve naturally to allow these systems to move towards an equilibrium state.

To optimize the coastal protection characteristics of the Banjaard, we recommend using a combination of man-made structures, hard substrate, and a set of multiple biobuilder species which can ensure a dynamic sand bar that is resilient to the eroding forces of the North Sea. Research showed that biobuilder settlement conditions are specific and might not be provided by the physical and hydrodynamical conditions. Therefore a hybrid implementation of coastal defense would be more suitable. We recommend the implementation of several artificial reefs built with hard structures like Reef Enhancing Breakwaters (REB's) about three kilometers in front of the Banjaard coastline. This will provide a rigid first line of defense that also helps facilitating better settlement conditions for biobuilders closer to shore. Including a set of multiple biobuilder species would be very beneficial, as they 1) add to wave attenuation and sedimentation close to shore and thereby have a breakwater function, and 2) because a variety in biobuilder species facilitates habitat differentiation, ultimately adding to biodiversity of the Banjaard. These biobuilders mainly include bivalve reefs and *Lanice* reefs on the west side (seaward side) of the Banjaard, but also incorporating *Salicornia* and sea species on the east side of the Banjaard. We recommend assisting in kickstarting these biobuilder species communities by placing artificial structures like seacrete mats and brushwood groynes on the experiment sites as this might provide a better chance of survival and establishment, which positively affects their defense function.

Secondly, we recommend to place rocks and other hard substrate at the two outermost points of the Banjaard sand bar because this will form a barrier line of defense that assists in the short-term fixation of the island, while remaining dynamic enough to reshape and spatially evolve. Also, we recommend the placement of floating PV-panels between the artificial reefs and the Banjaard sand bar, about 2 kilometers off the coastline to attenuate incoming waves. This will form an extra line of defense in the breakwater and besides this add to the societal value of the Banjaard pilot by producing renewable energy. Lastly, our advice is to contact expert parties and companies (e.g., van Aalsburg B.V., Oceans of Energy, EcoShape) directly to gain extensive details about the most suitable methodology for the use and establishment of biobuilders.

To provide new options for sustainable seafood production at the Banjaard, several side effects must be considered. First and foremost, we recommend including only integrated multiculture strategies for seafood production, like for example vertical aquaculture, as these minimize the harm to the ecosystem when compared to other methods. Intensive and bottom-fixed aquaculture may seriously harm the surrounding ecosystem, for example by changing nutrient balances in the water column, monocultures that increase vulnerability and transmission of diseases, and physical damages or bycatch from harvesting. Therefore, we also recommend looking further into the options for sea ranching rather than including intensive aquaculture.

Besides this, we advise thoroughly considering the placement and location of included seafood production methods to optimize the benefits between cultivated species and other species present at the Banjaard like biobuilders. Placing certain species can provide beneficial effects for other species at the Banjaard. For example, the placement of a bivalve culture next to an area where seagrass meadows are developing might be beneficial as the shellfish will filter the water and add to wave dissipation. This facilitates better living conditions for seagrasses. In the case of sustainable seafood production, we also recommend contacting expert parties and companies (e.g. North Sea Farmers, the Seaweed Company, Green Wave, de Oesterij) to initiate seafood production initiatives directly.

10.1. Spatial implementation of recommendations

To translate all the presented recommendations into a suitable spatial configuration for the latter phases of the Banjaard development, a suggestive map was created (*figure 45*). This detailed map is not a definitive design of the landscape but rather a suggestive indication of how the habitats and experiments as describe throughout the report can be spatially distributed on the Banjaard site. The map is based on the habitats and zonation as described in chapter 8 and the recommendations as presented above. An explanation will follow to elaborate on the details presented in the map.

On the north side of the Banjaard, natural sediment accretion will be most prominent, and this may be enhanced by introducing reef building species like tubeworms or bivalves in the area. Here, the shoreline of the Banjaard naturally grows parallel to the Dutch coastline. In the foreshore of the sand bank, several levels of breakwater functions are implemented, starting with several clusters of REB's about three kilometre off the coastline. Here, the REB's used will attenuate waves and provide hard substrate and shelter for marine life to flourish. This can be combined with the sea ranching of lobsters, a very valuable product on the Dutch markets which is currently still being imported. Local and sustainable production by sea ranching could be a big chance for the lobster industry while being almost harmless to the environment.

Behind the artificial reefs (two kilometres off the Banjaard shore), a line of floating hexagonal solar panels forms the secondary line of defence in the breakwater. Simultaneously, the PV panels produce renewable energy and provide options for vertical aquaculture like vertical mussel farming. Since mussels need no direct light to thrive, placing these cultures beneath the panels can provide a multifunctional and profitable use of this breakwater line.

At the seaward coastline of the Banjaard, wooden groynes are placed to facilitate suitable living conditions for bivalve reefs (oysters and mussels) to develop as natural breakwater in the intertidal zone and submerged close to shore. Behind the intertidal reefs the emerged beach will gradually evolve into embryonic and mature dunes which are held in place by marram grass to form a prominent defence structure. At the outermost points of the sand bar, the sandy coastline is covered by natural rocks and artificial ReefPools, to create a rigid point breakwater that also provides a new habitat with intertidal pools.

On the south side of the Banjaard, space will be reserved for multispecies (mixed) vertical aquaculture, meaning a combination of hanging shellfish culture and vertical seaweed cultures can be farmed in the area. These types of seagriculture pose a low amount of environmental disruption as described in the previous section.

On the landward side (east side) of the Banjaard, a more gradual slope and decreased wave forcing combined with increased sediment accretion provide opportunities for the development of an intertidal salt marsh. By planting *Salicornia* as a pioneer species, the intertidal flat can grow out to become a salt marsh which slowly builds up a peat layer, elevating the intertidal surface. In the fully submerged area a lagune-like shallow fallows for seagrass to grow, which provide breakwater and sedimentation functions. Due to the vulnerability of seagrasses, the future meadow should be artificially kickstarted. To enhance the living conditions for seagrass even further, floating oyster cultures can be placed besides the seagrass as these will filter the water and simultaneously attenuate incoming waves, whilst also being a profitable and low impact food source.

Figure 45 Suggestive detailed map of how the proposed experiments can be spatially situated for the Banjaard, when realised as functioning breakwater landscape. The map is based on the zonation as described in chapter 7 and includes all the recommendations made in this chapter.

10.2. Advice on monitoring

Since using biobuilders and artificial reefs for the creation of a breakwater of this size is relatively uncharted territory it is vital to meticulously monitor and document its development. A list of indicators was created to base the monitoring programming on, falling into the categories of coastal protection, biodiversity and seagriculture. These range from things like the current speeds and sediment height to species richness. The monitoring section of the report contains an overview of all these indicators, as well as for which zone and experiment they are relevant. In the first place these variables will be monitored on a zone/experiment-specific basis, assessing the development and processes of these zones. Examples of this are the comparison of wave attenuating abilities of different biobuilders in a zone, or the effect these different biobuilders have on local biodiversity. Next, there's the comparison between the different zones. Most biobuilders are only present in specific zones, all with their own conditions, so making direct comparisons is difficult. An assessment of differences in wave attenuating and sediment fixation abilities between biobuilders for example could still yield valuable knowledge on their general usefulness in coastal protection. Lastly, there are multiple indicators which need to be monitored/compared island wide. Because of erosion and sediment deposition the shape, size, and location will change over time. The breaker will also have an effect on the hydro morphology of the surrounding coastal area. All of these processes and their interactions are all extremely complex and need to be meticulously monitored and researched. The knowledge gained from the Banjaard pilot can then be used to create a line of even more proficient breaker islands along the Dutch coastline.

10.3. Stepwise approach

We suggest the following stepwise approach for the development of the Banjaard artificial sand bank (*figure 46*). Before realizing the proposed sand suppletion, a baseline monitoring program should be developed and executed on the location of the former sand bank. This monitoring will give insight into the development of the area before and after the sand suppletion, as the sand suppletion itself will have a big impact on the area and its surroundings. The second phase will be the sand suppletion on the location of the former Banjaard. The third phase in the stepwise approach should then be the implementation of the different suggested experiments which follow from this consultancy report. We recommend to first implement the hard structures (e.g. REB, rocky shore and brushwood groynes), as they will create more favourable environmental and physical conditions for the aimed introduced species to settle. After the conditions have improved, the next step in the implementation phase is the introduction of the species. The last step of this phase is advised to be the implementation of the different seagriculture practices, like the harvesting process. The last phase in the stepwise approach is to develop and execute another monitoring program, like suggested in chapter 8. This monitoring program will focus on the effect of the different experiments on the development and functioning of the Banjaard. This monitoring program will be a follow up of the baseline monitoring program. It is advised to execute this monitoring program for the whole stretch of the pilot.

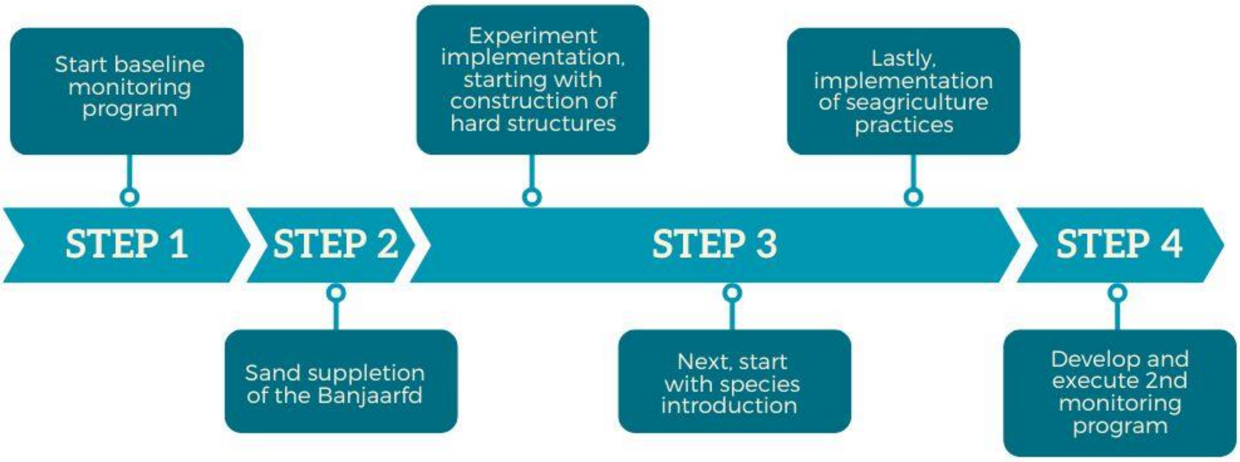

Figure 46 Suggested stepwise approach for the development of the Banjaard. Timescales are not indicated as there is uncertainty on the time each step will take in practice.

10.4. Future perspectives and advice for further research

Because of time constraints to work in the project and field of expertise in the team there are several aspects that still require further research in order to make a complete plan for the recreation of the Banjaard.

Firstly, a detailed hydromorphological model should be established for the Dutch coast in order to predict its morphological behaviour in general and on the area (Taal et al., 2023). Additionally, another model should be developed for the hydromorphology of the future Banjaard to determine the exact conditions the biobuilders should withstand. With the combination of these two models a calculation of sediment resources necessary could be performed. This would give a more definitive answer on if hard structures should be implemented in the design. It could go against the original idea of having a flexible island protecting

Schouwen-Duiveland, but the possibility of movable hard structures could be also explored in the case they were necessary. After the mentioned model is developed, a more detailed and accurate spatial plan can be created. It is important to mention that a new hydromorphological model of the future Banjaard should be made in the case of extending the pilot to a new coastline.

This consultancy assessment focused mostly on the biobuilders zonation and monitoring once they are developed enough to fulfil its role for coastal protection. However, kick-start strategies and methods for the successful implementation of biobuilders to the environment should be intensively researched, for this is a bottleneck for the project. This is most likely the stage when the ecosystem engineers will be more vulnerable, and it is advisable to research of the best way to integrate them for their survival.

A study on the chemical components and its concentration on the water in the area would give relevant data for several of the proposed experiments. Factors as concentration of nutrients and contaminants will impact the formation of the ecosystem and reefs, especially during the kick-start stage. Furthermore, an analysis of toxins and other contaminants would be necessary to warranty the safety of the seagriculture products to be commercialized.

Biodiversity and ecology and intrinsically complex, for a biobuilder leads to a higher species biodiversity and richness plus different species composition. There is not a linear or direct link between the biobuilders and how the ecosystem will develop due to the how diverse is the web of interactions in an ecosystem, a perfect prediction is not possible. But a more detailed and accurate prediction on how the different ecosystems will develop in the area is possible by digging further into the interspecies interactions.

A market analysis of the proposed products will be necessary to determine the unit cost, unit price and scale of the initiative to make it profitable from an empirical perspective. On the social perspective, an extensive analysis of stakeholders including interviews is recommendable because it might undisclosed other opportunities not explored and the willingness to invest on the explored ones.

There are few parts of the current legislation, such as Natura 2000 or the removal of man-made structures for reef facilitation after few years, that could affect, delay, or hinder the success of the pilot. An extensive literature research on procedures for the authorities to accept the proposal, for example by exploring successful case studies that set a precedent on the field and that could be as an argument for the pilot development.

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Appendix 1: MCDA Assessments

MCDA Assessment of Biobuilder options

Seagrass

Seagrass scores an 8 for climate change as the species can both mitigate and adapt to climate change. They can sequester CO_2 from the water (mitigation) and they grow well under high CO_2 concentrations (adaptation). Biodiversity scores a 9, as seagrass is an important key habitat which has a nursery function. Furthermore, it provides shelter and is a food source for other species. It scores a 6 for sustainability, as it is a self-sustaining plant once it is planted. However, the implementation of seagrasses can be a challenge as they settle under harsh hydrodynamic conditions. Furthermore, they are susceptible to diseases. The coastal protection of seagrass scores a 3 as it is hard to grow on the ocean side of the island, where coastal protection is most necessary. However, on the hindside of the island seagrass can assist in sedimentation. The profitability gets a 4, as the seagrass itself is not harvestable but it can have a nursery function.

Kelp

Kelp can sequester carbon and counteract ocean acidification, thereby scoring a 7 on climate change. Kelp can increase the biodiversity by providing a substrate for settlement. However, seaweeds might also grow extensively and overshadow for example seagrass patches resulting in a decrease of biodiversity. Thus, kelp scores a 7 on biodiversity. On sustainability kelp scores a 7, as it needs to be introduced in the area after which it is able to adapt to strong flow velocities due to its flexibility. Kelp scores an 8 on coastal protection as it is effective on the foreshore location when the conditions are right. Then it will strongly contribute to wave attenuation and fixing the substrate. Kelp is edible and thus could be harvested. However, kelp optimally should contribute to coastal protection, harvesting should be limited. Therefore, it scores a 6 on profitability.

Salicornia

Salicornia scores a 6 for climate change, because *Salicornia* does not primarily add to carbon sequestration in a very significant way. However, the species are very climate resilient, making it a valuable species for climate adaptation still. Furthermore, *Salicornia* is a key pioneer species and thereby facilitates a new habitat formation which is good for the biodiversity, thus scoring an 8. It gets a 9 for sustainability, as it has a high tolerance for saline conditions and can settle under those harsh conditions as pioneer species. For coastal protection *Salicornia* scores a 6 as it does trap sediment, but in a low amount because of the size of the plants. Lastly, it gets a 7 for profitability as *Salicornia* is edible and can be harvested quite easily as it grows in the intertidal area.

Marram Grass

Marram grass scores a 7 for climate change, as it can grow quite easily but does not have any special implications for climate change mitigation or adaptation. Marram grass is a pioneer species, thus creating the dune landscape and its belonging habitat. However, the potential for biodiversity in a marram grass habitat is lower than in an intertidal habitat. Therefore, it gets a 5 on biodiversity. Marram grass scores a 9 on sustainability. It has a high resilience and can grow in newly created sand areas to create dunes as it is a pioneer species. For coastal protection, marram grass scores a 9 as well. Those species are good in creating a fixed dune landscape, which is what we desire at the Banjaard. Marram grass is not edible and thus not harvestable, scoring a 0 on food provisioning.

Mussel and oyster reefs

Mussel and oyster reefs score a 6 for climate change as they do not specifically contribute to for example sequestering CO_2, but are able to grow under changing climate. Mussels and oysters are filter feeders, so they purify the water by removing nutrients and toxins. This is good for the water quality and might increase biodiversity. Besides, they provide substrate and shelter for other organisms. Therefore, mussels and oysters both score a 9 on biodiversity. Mussels are able to rise with sedimentation, but this process also makes them vulnerable. Oysters on the other hand glue themselves to other hard substrates and thus being less flexible. However, oysters do need hard structures to grow, while mussels can use their byssal threads to grow in sediments. Thus, the settlement of oysters can be harder. As the mussels are vulnerable when they grow with the sediment for high velocity currents they score a bit less on sustainability than oysters. Mussels score an 8 and oysters score a 9. Both mussel and oyster reefs are good for coastal protection. They clearly attenuate waves and also trap some sediment. For coastal protection, both reefs score an 8. For profitability they score a 6. Mussels and oyster can be eaten, but they are difficult to harvest from a reef as this diminishes the coastal protection function. Therefore, they both score a 6 on profitability.

Tubeworm reef

Tubeworm reefs score a 3 for climate change, as the impact of tubeworms on climate change mitigation like CO2 sequestration is so small it is almost neglectable. For biodiversity they score an 8, as they provide shelter for amongst other benthic species. It is quite hard to introduce tubeworms in a new area, as the juveniles stick on the adult tubes. Therefore, tubeworm reefs score a 6 on sustainability. They also score a 6 on coastal protection, as tubeworm reefs are small and just trap sediment and attenuate waves on a small scale. Tubeworms are not edible and thus not harvestable, scoring a 0 on food provisioning.

MCDA Assessment of Seafood initiatives

Sea ranching

The assessment on sea ranching points out that the climate change adaptation and mitigation scores a 7, since the system can adapt to climate change effects. Other species can be introduced to cope with changing environmental conditions. The same score is seen for the profitability of this option since it will provide economic opportunities for the local population. New jobs are expected to be created around this practice however it does require a significant investment in technology and maintenance. In comparison to other practices the revenue will also be lower since it is a less intensive farming practice. On coastal protection this option does not contribute to any protection values, so it scores a 2. It is however a good solution to the local biodiversity since the principle on sea ranching is based on farming with biodiversity on the first priority. The farming practice is also self-sustainable since the ecological balance is the key to the farming practice. Both scoring an 8.

IMTA

Integrated Multitrophic Aquaculture (IMTA) was assessed with a score of 7 on the climate change and adaptation, since the risk on algal blooms is being lowered. Harmful Algal Blooms (HABS) are the result of warmer waters and nutrients in the water. By incorporating an IMTA system, bivalves will filter the water from these algae. On local biodiversity IMTA scores a 6, since will be attractive to wildlife and forming habitats withing the system. Also, it uses native species as much as possible, however it is an artificial created ecosystem. For self-sustainability it scores a 4 since the system balances itself due to a circular stream of nutrients. Nonetheless, the system needs to be maintained, since the open cage system is prone to damage, ropes need to be replaced and often checked. In a way the bivalves and seaweed constructions add to coastal protection, since they form physical barriers and break the waves. However, this will not be year-round and is dependent on the growing and farming frequency, resulting in a 4. The profitability for this system scores a 9, since the insurance of having an income of this farm is spread through different sources; namely seaweeds, sea cucumbers, fish and oysters. However, growing cycles can involve multiple years, a good planning and keeping sea livestock in multiple ages, will ensure a good income.

Vertical mussel and oyster farming

Vertical mussel and vertical oyster farming is very similar in this assessment. However, the profitability of oysters has one point higher since the market value of oysters is higher than for mussels, respectively 8 and 7. In coastal protection, ropes hanging vertically with oysters and mussels will have a positive effect on the breaking of waves, scoring both a 6. This is lower than seaweeds since the wave attenuation is lower. For sustainability this system scores a 6 for both, because the ropes or cages which are used needs maintenance. Also, it is not a circular system in the way that oysters and mussels are only grown and harvested and will not be in the farming practice for a longer time then their growth cycle. The local biodiversity is not enriched since a monoculture is placed, therefore scoring both a 4. The temperature range of mussels and oysters are acceptable in waters warming up by climate change, however they are prone to ocean acidification, therefore scoring a 6.

Vertical and horizontal seaweed farming

Vertical and horizontal seaweed farming is adaptable to climate change and is graded with a 7, because some species also grow with higher water temperatures, so in case water temperatures rise new species can be grown. The biodiversity of a seaweed farm gets a 5, as this is mostly monoculture that might attract some algae or birds but overall does not increase biodiversity much. As for sustainability, both horizontal and vertical seaweed production get a 6, because plants need to be introduced into the area, they grow, and after reaching the desired size they get harvested and new plants are introduced. So, by itself this type of agriculture needs maintenance to make it profitable. Coastal protection scores an 8 for vertical culture and a 4 for horizontal production respectively. In a vertical hanging culture, the waves will be broken more since the leaf surface is bigger resulting in a higher wave attenuation compared to the horizontal seaweed production. Vertical seaweed farming is considered more profitable with an 8 than horizontal seaweed farming with a 7. Because more biomass of seaweed can be grown with vertical strands in a small area compared to horizontal strands, so profit will also be higher for vertical production.

Seagrass

Seagrass species that currently occur in the North Sea can tolerate a wide variety of temperatures up to 30 ^{o}C for certain species. They are also good at sequestering CO2 and therefore, they score an 8 for climate change adaptation and mitigation because restoring this habitat would both be adaptable to global warming and help prevent it by sequestering CO2. However, part of the plant dies off in winter which is why it does not score higher than an 8. Seagrass also creates food and shelter for many different animals and is a habitat which is not very common in the Netherlands. That is why for biodiversity it gets a 9. However, long term successful experiments where seagrass fields in the North Sea were restored have not yet been performed. Therefore, it is hard to estimate for the future if the habitat will be able to sustain itself and it is scored with a 6 for sustainability. Seagrass is good for wave attenuation and can hold sediments in place, however it is not very stiff plant which is why it gets a 3 for coastal protection. If juveniles can be produced and released in the seagrass field and matured animals can be easily caught, this type of sea ranching could be very profitable, but it has not been done before so therefore it now only gets a 6.

Salicornia

Salicornia functions as a pioneer species in salt marches and other barren alkaline flats. Because of this characteristic, they facilitate good conditions for other species to grow and contribute to biodiversity development. In that way an 8 can be given for adding to biodiversity. With that *Salicornia* is sustainable in terms of longevity, maintenance, and self-sustainability. Only the shoots will be harvested, and after the cutting, they will grow back. The plant can be used for multiple times during the year. A 9 is given as score for sustainability. In coastal protection, they can serve by trapping sediment, however this is not what the emphasis is on in seagriculture, scoring a 6. Whether it is adding to climate adaptation or mitigation, it gives an insurance on good crop growth, since it is saline adaptive, scoring a 6. This last reason also gives an insurance on the profitability, since less maintenance is needed, and the crop can be harvested multiple times a year, that is why it gets a 7.

Biobuilders

Criteria	Climate change		Biodiversity		Sustainability		Coastal protection		Profitable		
Description	Is the solution adding to climate change adaptation or mitigation		Does the solution add to (local) biodiversity and ecological value?		Is the solution sustainable in terms of longevity, maintenance and self-sustainability?		Is the solution adding to coastal protection and functioning as a breakwater?		Is the solution profitable for sea food harvest?		
Weighting factor (%)	2		2		2		3.5		0.5		>adds up to 10
Options	Ass.	Score	Ass.	Score	Ass.	Score	Ass.	Score	Ass.	Score	**Total**
Seagrass	8	16	9	18	6	12	3	10.5	4	2	58.5
Kelp	7	14	7	14	7	14	8	28	6	3	73
Salicornia	6	12	8	16	9	18	6	21	7	3.5	70.5
Marram grass	7	14	5	10	9	18	9	31.5	0	0	73.5
Mussel reef	6	12	9	18	8	16	8	28	6	3	77
Oyster reef	6	12	9	18	9	18	8	28	6	3	79
Tubeworm reef	3	6	8	16	6	12	6	21	0	0	55

Seagriculture

Criteria	Climate change		Biodiversity		Sustainable		Coastal protection		Profitable		
Description	Is the solution adding to climate change adaptation or mitigation		Does the solution add to (local) biodiversity and ecological value?		Is the solution sustainable in terms of longevity, maintenance and self-sustainability?		Is the solution adding to coastal protection and functioning as a breakwater?		Is the solution profitable for sea food harvest?		
Weighting factor (%)	2		2		2		1		3		>adds up to 10
Options	Ass.	Score	Ass.	Score	Ass.	Score	Ass.	Score	Ass.	Score	**Total**
Sea ranging	7	14	8	16	8	16	2	2	7	21	69
IMTA/ Vertical thinking	7	14	6	12	4	8	4	4	9	27	65
Vertical oyster farming	6	12	4	8	6	12	6	6	8	24	62
Vertical mussel farming	6	12	4	8	6	12	6	6	7	21	59
Vertical seaweed farming	7	14	5	10	6	12	8	8	8	24	68
Horizontal seaweed farming	7	14	5	10	6	12	4	4	7	21	61
Seagrass (nursery)	8	16	9	18	6	12	3	3	6	18	67
Salicornia	6	12	8	16	9	18	6	6	7	21	73

Appendix 2: Ideation session

The time frame in which this project was conducted did not allow for discussions with stakeholders. However, because stakeholder input is useful, both in terms of adding valuable content for the project, adjusting the course of action if necessary, and to gain support for the implementation of the plan, it was decided to hold an ideation session with the present stakeholders after the presentation of the report. Based on this, several ideas and comments emerged. These have been divided into five categories and included below.

Coastal protection

- At the points of the island, wooden poles may be used instead of rocks.
- Think on a larger scale, for example by using a line of several islands instead of just one.
- For breakwater constructions, use with materials that are from the surrounding areas.
- Hard structures might not be placed due to Natura 2000 legislation.
- The project 'Vlaamse Baaien' in Flanders, Belgium, is a very similar project. This may be used as a guideline.

Biodiversity

- Legislation is a very important aspect. A next group could do an entire project about the possibilities within the Natura 2000 guidelines. Nonetheless, the existence Natura 2000 doesn't necessarily mean there's nothing to do. Engaging in a conversation and demonstrating the urgency of the problem and looking at ways in which biodiversity can also be improved could lead to an exception for the Banjaard. It must be considered what will happen if Natura 2000 is influenced or adjusted.
- Research 'Vlaamse Baaien' in order to create the right conditions for species to flourish without directly introducing the species in the area.
- Keep the natural habitat that was already there.
- *Elytrigia juncea* could be researched further as a pioneer species in dunes.
- There are several challenges and questions to consider. How flexible is the nature conservation law? How much biodiversity increases if you introduce hard structures? Convincing stakeholders that the field of biodiversity improves with hard structures.
- A similar project is the 'Marker Wadden', the investigation and development on this pilot could help designing the Banjaard by learning how it was done, if there was a loss in biodiversity, etc.
- It must be demonstrated that implementing the Banjaard would do more for biodiversity than doing nothing.

Aquaculture

- Before initiating any aquaculture practice is necessary to assess the nutrients stream trend surrounding the area to check whether it is enough. A combination with IMTA could make a difference in terms of components, for example by adding more nutrients trough fish farms.
- Research companies as OSS who works with platforms and big ships specialized in placing oysters and mussels on hanging cultures near windmill parks in the ocean.
- PO Mosselcultuur specializes in mussels, could be useful to investigate the options for mussel aquaculture too.
- The Banjaard could be a change to investigate more innovative aquaculture options.

Tourism

- Tourism should not be mentioned as a first starting point. Including it in the initial plan, will lead to rejection or resistance by the government, since it's against the regulations from Nature 2000.
- Tourism could happen at a small scale eventually, focused on education about the project. Raising awareness is the most important aspect.

- One option for walking routes on the island without damaging the environment, is by using an elevated wooden pathway. Might be subsidized by the European Union, as is done in some nature areas in Portugal.
- Boat excursions to find seals or wading birds, or other water sports might be less impactful to island itself, as tourists cannot roam the island freely.
- Diving could also be part of tourism. However, this might cause damage the artificial reefs.

Other options

- Tidal or wave energy hasn't been incorporated into the project, though this might be a profitable source of energy. Some of the stakeholders were sceptical about the feasibility, considering the extreme forces in the water of the open sea.

Appendix 3: Introduction of the consultancy team

To formulate a fitting and concise consult for Shared Concepts, our consultancy team consists of seven MSc students with different, complementary backgrounds and interests. Our expertise mainly lies in the natural- and environmental sciences and as a team our qualities lie in clear communication, structured and detailed work, large brainstorming capacity and the ability to produce a wide variety of high-quality end products. Our consultancy team's expertise is shaped by the individual skills and interests of the members, who will be shortly introduced:

- *Marit Schapendonk*: Current MSc student Earth and Environment with a specialisation in Hydrology and water resources. Knowledge of different hydrological processes, delta geology and sustainable delta management. Her interest lies in projects that work with nature-based solutions. She will be the manager of the consultancy team.

- *Sebastiaan 't Hoen*: Current MSc student in Greenhouse Horticulture and graduated in Plant Sciences with a specialisation in Seaweed Agriculture. His role will be the secretary of the consultancy team and will be the contact person during the upcoming weeks. His interest lies in the appliance of sea-based plants for food production but is also curious how this can contribute to coastal protection.

- *Alba Rodríguez Boltes*: Current MSc student Biobased Sciences and graduated as BSc Biotechnology. She focuses on biorefinery and environmental engineering. The use of science to heal nature is one of her goals. She will be the controller of the consultancy team and be responsible for reaching deadlines and the budget.

- *Vivien Vos*: Current MSc student in Earth and Environment with a focus on hydrology and environmental hydraulics. She graduated her BSc Soil, Water, Atmosphere. Knowledge on different hydrological processes, delta geology and sustainable delta management. Her interest lies on combining environmental hydraulics with nature-based solutions.

- *Rijn van Kampen*: Current MSc student Aquaculture & Marine Resource Management, focusing mainly on marine systems ecology and Building with Nature in coastal projects. He graduated his bachelor's in landscape architecture. His interests lie in integrating spatial design and marine ecology in coastal projects.

- *Thom Verreijt*: Current MSc student Biology, specializing aquatic ecology. He graduated his BSc in Biology with a specialization in ecology and a minor in marine resource management. His main interest lies in aquatic ecosystem restoration.

- *Evert Sprockel*: Current MSc student Biology with a focus on ecology. He is interested in biodiversity and the resilience of natural ecosystems, and how this can be improved. Because humanity depends on nature, this will also work to our benefit eventually.

Appendix 4: Personal communications

During the project different people have been contacted to gain more information about different subjects. The following people were contacted:

Met with the following contacts:

1. About building with biobuilders
    a. Van Aalsburg BV with Robert Willem Pol: robert.w.pol@vanaalsburg.com
2. About Seagrass
    a. Witteveen en bos with Marloes van der Kamp: marloes.van.der.kamp@witteveenbos.com
3. About hydromorphological map and hydrodynamics
    a. J. (Joris) G.W. Beemster: joris.beemster@wur.nl
4. About marine animal ecology
    a. prof.dr. AJ (Tinka) Murk: tinka.murk@wur.nl

Contacted, but no answer:

1. About biobuilding for coastal protection
    a. Coastbusters with Tomas Sterckx: sterckx.tomas@deme-group.com
2. About seaweed farming
    a. North Sea Farmers: info@northseafarmers.org
    b. Dutch Seaweed Company: mail@dutchseaweedgroup.com
3. About Oyster reefs
    a. Oyster Heaven: info@oysterheaven.org
4. About offshore solar panels
    a. Oceans of Energy: offshore.solar@oceansofenergy.blue

Appendix 5: Colophon

Copyright information

Programs used for this report

For this report several different programs were used to create the content. Firstly, the report was written in Microsoft Word, furthermore, various programs within Adobe creative cloud were used to create the imaging. In addition to that, ChatGPT is used for this report as a search engine, source of inspiration, and chatPDF was used to analyse literature and elaborate on valuable sources.