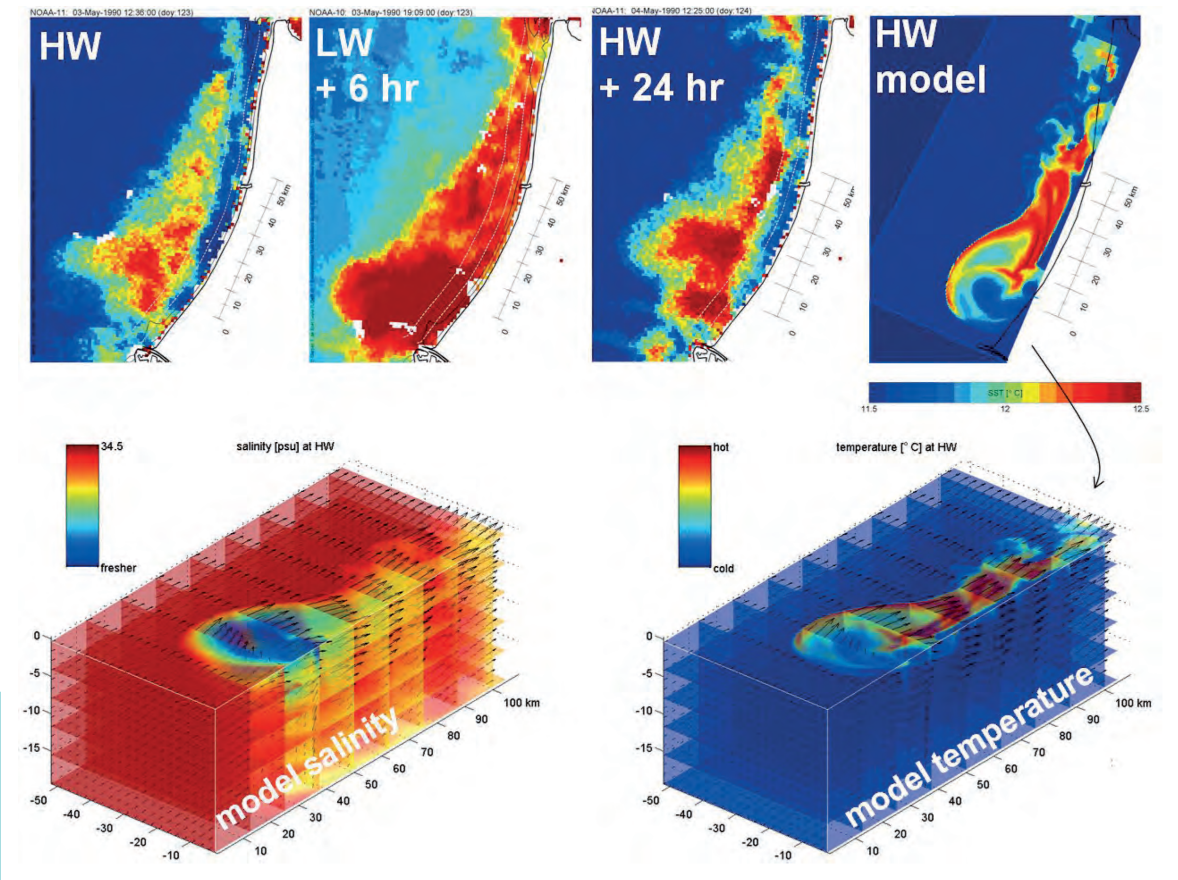
LAND-OCEAN INTERACTIONS IN THE COASTAL ZONE (LOICZ)

Core Project of the International Geosphere-Biosphere Programme (IGBP) and
the International Human Dimensions Programme on Global Environmental Change (IHDP)



Aspects of coastal research in contribution to LOICZ in the Netherlands and Flanders (2002-2010)

Carlo Heip and Remi Laane

LOICZ Research and Studies No. 38

Aspects of coastal research in contribution to LOICZ in the Netherlands and Flanders (2002-2010)

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Cover: The cover shows three subsequent KNMI NOAA SST satellites image of water surface temperature on May 3rd 1990 (blue=10°C, red=14°C). The 1st is high water, the 2nd is low water and the 3rd is the next high water, the 4th panel is the surface temperature calculated with an idealized numerical model at high water. The modelled temperature is shown again in the 3D plot underneath it (lower right panel). The blue cold band along the Dutch coast is caused by upwelling induced by tidal straining. In the lower left panel the modelled 3D salinity field is shown at the time time as the modelled temprature field. The newly discovered upwelling induced by tidal straining is caused by the dominant salinity stratification during neap tides as represented by the blue and yellow shades in the lower left panel.

The LOICZ Research and Studies Series is published and distributed free of charge to scientists involved in global change research in coastal areas.

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Preface by Prof. Alice Newton

The Netherlands has made a very large and historic contribution to the science and knowledge of Land-Ocean Interactions in the coastal zone. The very existence of this tiny, densely populated country, squeezed between a large river delta and the North Sea and fringed by a delicate string of islands, has depended on human ingenuity at balancing their activities within this complex setting. It is on Texel, one of these lovely islands, that the fledging LOICZ project of the IGBP - International Geosphere-Biosphere Programme was nurtured, in the NIOZ nest, during 13 years.

The coast of the Netherlands is dominated by the multiple river- mouth systems of the Rhine, Scheldt and Ems (see section A-Rivers). Understanding the importance of the biogeomorphology of this deltaic coastline is fundamental to understand the ecological functioning (see section B-Biogeomorphology). These biogeochemical cycles in shallow coastal areas support highly productive ecosystems, (see section D-Cycle of Carbon and related compounds).

The landscape that results from human intervention along the coast of the Netherlands is unique, and one of the most highly engineered coastlines in the world. Much of the land has been reclaimed from the sea and is defended by the impressive Delta works. As the LOICZ project matured, it was also adopted as a core project of IHDP - the International Human Dimension Programme on Global Environmental Change with the challenge to integrate the social sciences, economics and natural sciences in the coastal zone and context of global change. This was in response to the increasing socio-economic influences (see section E) in the coastal zone and transboundary issues (see section F- Flemish Dutch collaboration).

After 13 years, LOICZ was fully fledged as a global dimension project and held an international conference at Egmond, in the Netherlands. This major open science Meeting in 2005 reflected the broad spectrum of scientific coverage and the continental evolution of methodologies developed in LOICZ.

Hosting the International Project Office and in parallel addressing the variety of LOICZ science in a national Dutch and Flemish LOICZ were major pillars for this development.

The forward looking perspective in these national efforts can be seen in the fact that the Dutch LOICZ Programme already in its early stages had a special work package on the social sciences and this was also reflected in the composition of the Dutch LOICZ committee. In a LOICZ context this report though being based on research of the last 10 years clearly points to the future LOICZ global scale, in a currently fast changing Earth system science landscape.

LOICZ then moved to the GKSS Research Centre (now Helmholtz-Zentrum Geesthacht, HZG) in Germany, where it continues to work in collaboration with many scientists from the Netherlands, both on its Scientific Steering Committee and through affiliated projects, to support sustainability and adaptation to global change in the coastal zone.

Prof. Alice Newton

LOICZ Chairperson

Acknowledgements

The board members of NWO (NWO/ALW and NWO/MaGW) and the former Dutch Ministry of Agriculture, Nature and Food quality (nowadays: Ministry of Economic Affairs, Agriculture and Innovation (EL&I)) are acknowledged for their financial support for the LOICZ-NL programme. The members of the steering group were: Prof. Dr. W. van Vierssen (chairman, WUR), Drs. A. Bijlsma (secr., NWO/ALW), Prof. Dr. J. Dronkers (Deltares), Dr. J.K. Koppen (NWO) and Dr. J. van Baalen (EL&I). The members of the programme committee were: Prof. Dr. E. van Beek (chairman, TUD), Drs. A. Bijlsma (secr., NWO/ALW), Prof. Dr. P.G.E.F. Augustinus, Ir. G. Blom (EL&I, Deltares), Prof. Dr. P. Glasbergen (UU), Prof. Dr. H.J.M. Goverde (RU) and Prof. Dr. W. Admiraal (UvA).

The Dutch Ministry of Education, Culture and Science and the former Flemish Ministry of Science, Innovation and Media (nowadays: Ministry of Economy, Science and Innovation (EWI)) are acknowledged for their financial support for the VLANEZO programme (Flemish-Dutch Cooperation in Coastal Research).

NWO
Nederlandse Organisatie voor Wetenschappelijk Onderzoek

Ministry of Economic Affairs, Agriculture and Innovation

Ministry of Education, Culture and Science

Ministry of Education, Culture and Science

EWI

Interviews by Dr. R. Hisgen – Direct Dutch, The Hague, the Netherlands.

They were translated by D. Thomas – Native Speaker Translation, Kampen, the Netherlands

Introduction

The Netherlands is a small deltaic country nearly completely situated in the coastal zone of the North Sea and at the mouth of two medium sized rivers: the Rhine and the Meuse and a third smaller river, the Scheldt. The geography of the Netherlands originates from the long term interaction between land, rivers and the sea over thousands of years and has been highly impacted by human activities. Over time, people have reclaimed land and reduced the risk against fresh and seawater flooding by damming and diking. The interaction between land and water is still of major importance for the Dutch economy, safety, welfare and ecology.

A large part of the Dutch land is now below sea level and is protected against flooding, not only by dikes and dams, but also by continuously pumping out excess water. This has required a complex socio-economic organization and involves a huge cost to society. Dutch society has started to realize that the enormous efforts and costs to provide safety may become insufficient as global climate change threatens to increase the risk of flooding, from the sea through sea level rise and from the land through changing precipitation and freshwater runoff. These changes require innovative adaptations and solutions. To assure sustainable and cost-effective solutions on the short and long term, knowledge of the coastal (eco)system is essential.

From the beginning of the LOICZ office, that was hosted for 13 years at the NIOZ (Royal Netherlands Institute for Sea Research) on the island of Texel in the Netherlands, there was an interaction with the Dutch research community and ministries. LOICZ-NL is a subsidized program of the Netherlands Organization for Scientific Research (NWO), and the former Ministry of Agriculture, Nature & Food quality. In the beginning of the twenty-first century, NWO launched a call that addresses the LOICZ objectives. Specific subjects of interest in this call were:

- Rivers
- Biogeomorphology
- Element cycles (carbon and nitrogen)
- Socio-economical aspects

A second important initiative relevant to LOICZ was launched by the Ministry of Science, Culture and Education in the Netherlands and the Flemish ministry of Education in Belgium in the framework of cooperation between bordering EU countries. This VLANEZO project (Flemish-Dutch Cooperation in Coastal Research) concentrated on the Westerschelde estuary in the southern part of the Netherlands and its river, the Scheldt in Flanders. It was jointly managed by NWO and the Research Foundation – Flanders FWO. More specifically joint Flemish-Dutch research was performed on the microbial food web, including diatoms and meiobenthos, the carbon and nitrogen cycles, and biodiversity in relation to estuarine productivity.

Within the LOICZ-NL and the VLANEZO initiatives, a relatively large number of projects on the above-mentioned subjects were funded and a relatively large international and multidisciplinary community of scientists was supported and active for a number of years. In this report an overview of the results of these studies is presented.

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Remi Laane (Deltares)

Auke Bijlsma (NWO)

Kirsten Spoorendonk (NWO)

Frans Martens (NWO)

Hans de Boois

Spoorendonk (NWO)

Recommendations

The program on coastal research in the Netherlands and Belgium started in 2002 and finished in 2010.

In LOICZ-NL and VLANEZO an enormous amount of scientific information has been gathered on the various topics described above and published in many theses and many scientific publications in well established international journals. In this way, the two programs were very successful. The scientific community involved has worked together for a number of years and in some cases continues to cooperate today. Many PhD students starting in LOICZ or VLANEZO continued their careers in an institute or university. In the Netherlands, the Program on Marine and Coastal Research ZKO as well as the Netherlands Centers for Coastal Research NCK and for River Studies NCR continue to provide platforms. On the other hand, several efforts to continue a Flemish-Dutch cooperation in coastal research were unsuccessful, despite the fact that coastal research was recognized as a priority area in Dutch-Flemish cooperation. One reason may have been that not enough attention was given to present the impressive results of both programs to a wider audience.

Even the scientists involved never got a complete overview. The results of both programs have never been synthesized or brought together in a single overview and there has never been a concluding scientific conference to obtain this overview. For these reasons, to commemorate the efforts of so many scientists and to inform policy makers on what has been done and how relevant it is for policies in coastal zone management and protection, the idea was to write a short but complete report on the achievements of the programs.

Impression of the writers' day in The Hague

To obtain this report the project leaders and senior scientists of both LOICZ-NL and VLANEZO were asked to write an extended scientific summary of a few pages and to incorporate references to all their publications, reports and theses. To make a quick start they were invited to join one day in The Hague and to write their contributions together. In addition, the coordinators of the groups were interviewed and they were asked to present the scope and the outcome of a specific subject. During this writers' day the participating scientists were asked to indicate what they consider to be the future research topics that need more attention in coastal zone research and management.

Their recommendations are:

- To study the behavior of coastal (eco)systems under extreme meteorological conditions. It is more and more recognized that most of our information and knowledge that is based on data from ships has been gathered below wind speed 7. However, it is well recognized that the behavior and transport of, for instance, suspended particulate matter and sand is completely different under stormy conditions than during quiet weather.
- Technological developments make it possible nowadays to make measurements in the field during extreme conditions. Another advantage of these Coastal Observatories with automatic sensors is that the sampling frequency for some parameters is shortened from biweekly to every 30 seconds. In this way, the short term variability of for instance suspended particulate matter can be studied in detail.
- To study the predictability and resilience of coastal (eco)systems. Like the weather, it is recognized that the predictability of various parameters in coastal ecosystems is limited. The structure within an ecosystem can change quickly from one steady state to another and returning to the previous state can be very difficult. What is causing these changes (the so-called tipping points) and what the impact will be on the stability and functioning of the ecosystem and the ecosystem services is still largely unknown.
- To integrate physical activities, for instance, for protection against flooding, with ecosystem and socio-economic research and knowledge. Many coastal countries are planning or have already developed projects to protect their coastal zones against flooding and the rising sea level. Making dikes higher and higher is not possible and often very costly, especially the maintenance. In other words, not only hard stones and fixed defense structures but also where possible soft defense structures (e.g. sand) in such a way that it moves with the forces of nature and takes into account the local ecology. This concept is called Building with Nature: integrating the knowledge of biology, ecology, morphology socio-eonomic developments and eco-technology to come up with tailor-made solutions for specific areas, makes it possible to develop sustainable solutions.

Carlo Heip

Remi Laane

A. Rivers

1. Interview with Prof. Dr. J. Middelkoop

Research into flood plains: finding a balance between nature and safety

Professor Hans Middelkoop has been involved with the LOICZ research programme right from the start and as a researcher at the Netherlands Center for River Research he wrote the proposal for the rivers theme and supervised this. The project mainly focussed on the flood plains along the Waal and IJssel rivers. Flood plains are interesting for a delta area: besides serving as an emergency containment area during high water, they also act as a filter that traps many contaminants. Middelkoop, who gained his doctorate for research into the behaviour of flood plains, rose to the challenge of combining the abiotic research that "his" Utrecht University specialises in with the ecological research of Radboud University Nijmegen.

Middelkoop: At Utrecht University, we were already doing research on alluvial deposition on flood plains and investigating the quantity of metals found in the sediment. We were curious about the effect of rough vegetation on alluvial deposition. Moreover, we wanted to know how the entire system worked and the effect of climate change on this. How much water will there be in the future, how will the river discharge change and what will the high-water peaks be? How will preventative measures from the Space for the River project affect the flood plains? And what would be the effect of combining these two changes in the flood plains?

How did you start the research?

We first of all reviewed the existing literature and tested Rijkswaterstaat's river model. We soon realised the effect of rough vegetation on water movement had scarcely been investigated. At high water these shrubs impede the flow of the river, thereby retaining the water. That makes the river area unsafe. It was hard to determine how the height and density of the vegetation affected this process, as these factors scarcely played a role in the then prevailing model. We have now significantly improved the models in this area. However, we still had to come up with a method for measuring the vegetation in the field. In the end, we used the recently introduced technique of laser altimetry to make very detailed recordings from a helicopter. With this data, we then built models for the biotic aspect which clearly showed the effects of the vegetation density on water retention.

But didn't you investigate more than just vegetation density?

Vegetation patterns reveal more than just the flow at high water. They also say something about the density of heavy metals in the subsoil. Our colleagues of the RU Nijmegen examined the arthropods in the flood plains, such as spiders, as well as mice. Where exactly are the animals found in the flood plain? And what quantities of metals do they take up? A model was built to clarify where the animals were located and took up metals. We also examined the predators that eat the mice. Which metals did they contain and in what quantities?

So a lot of instruments have been developed to gain an understanding of how the system works from both a biotic and abiotic perspective.

We used these instruments to examine the effects of climate change in relation to a range of interventions, such as those from the Space for the River project. We worked with the spiral dynamics model that functions at a range of levels (from primitive to integrated thinking) without value judgements. Using this model we sketched three future scenarios for the year 2050. The first scenario is based on business as usual, simply carrying on as we are doing now. The second has a stronger focus on safety and a future of concrete flood defences. The third is the most integral with nature taking centre stage. We examined climate change, physical processes, metal pollution, biodiversity and species distribution. We discovered that climate change has less impact on the flood plains than the effects of human interventions.

Is that good news?

The ecological patterns become increasingly more favourable if the interventions focus more on constructing secondary channels and wildlife-friendly banks. This increases the habitat diversity for the animals. However, a disadvantage is that such interventions result in twice as much sediment being trapped by the flood plain than is the case now with a concomitant increase in pollutants. Consequently, the filtering function of the large delta changes. It becomes ecologically richer and it captures more heavy metals. This means that we will need to manage the flood plains in a more dynamic manner. Monitoring will become very important. What is happening to the ecology of the flood plains and to the alluvial deposition? We now have models that provide insight into the processes. However, follow-up research must lead to models that show what the flood plains will look like in fifty years' time.

Looking back at the research then, what advice would you give future researchers?

Don't lose sight of the large spatial relationships. Do not limit yourself to individual flood plains. All of the flood plains jointly form the large filter of the delta. Keep monitoring. Make sure that you understand what is happening. Learn from the experiments and interventions that we are carrying out now. Space for the River is an example of a fantastic experiment and the Netherlands forms a superb laboratory for this. Lots of people can learn from this, including researchers in other countries. Fundamental knowledge of the system often leads to practical knowledge.

And the policy makers?

Formulate your questions to the researchers in clear and accurate language. That does not always happen at present. When it comes to decisions the Netherlands prefers the consensus model. Yet it does mean that governing authorities have become masters at negotiating with all parties with the risk that knowledge is trickling away from the organisations. As a result of this, knowledge increasingly has to be outsourced. And I find that disturbing because knowledge is needed to pose good questions and to thoroughly assess plans. An organisation that lacks such knowledge is very vulnerable.

2. Biogeomorphological interactions within floodplains and their role in sediment transport and ecological transformation processes in the lower Rhine delta

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General introduction

Lowland floodplains (Fig. 2.1) play an important role as sinks of suspended sediments and pollutants, and have a key-role in ecological transformation processes along the river continuum from the upstream basin towards the estuary. Sediment accumulation rates on floodplains are spatially highly variable, associated with differences in flooding frequency, flood pattern and distance to the river channel (Walling and Owens, 2003).

Fig. A-2.1: *Field photograph of a floodplain with a side channel.*

After deposition, sediment-associated pollutants, such as metals, are incorporated in the ecological food-chain (Torres and Johnson, 2001). Floodplain characteristics and inundation frequency also influence ecological habitat ('ecotope') distributions, which in turn determine the potential biodiversity (De Nooij et al., 2004). Over the past centuries, the natural bio-geomorphology of many flood plain has been dramatically affected by humans, which has caused considerable degradation of their ecological status (Tockner and Stanford, 2002). In recent years, therefore, ecological restoration projects have been carried out in many countries (Buijse et al., 2002). At the same time, however, flood protection has remained a primary objective for river management.
The study was part of the LOICZ-project "Biogeomorphological interactions within floodplains and their role in sediment transport and ecological transformation processes in the lower Rhine delta". It consisted of three components. Firstly, a study was performed into the parameterization of floodplain vegetation for hydrodynamic models (Straatsma, 2007). Secondly, influences of multiple stressors on floodplain biota were studied (Schipper, forthcoming). The results of these two projects were integrated into a value-based scenario study of the biogeomorphological interactions under climate change (Straatsma et al., 2009).

2.1 Hydrodynamic roughness of floodplain vegetation: Airborne parameterization and field validation

Menno W. Straatsma, Hans Middelkoop, Steven de Jong

i. Problem

Hydrodynamic modeling is a central tool for flood risk management and lies at the base for the determination of deposition of sediment and heavy metals. In recent years, considerable effort has been made on the development of 2D and 3D hydrodynamic models that accurately simulate overbank flow patterns and predict extreme flood water levels in rivers and floodplains (e.g., Baptist et al., (2007) and Stoesser et al. (2003). In addition to surface topography (Marks and Bates, 2000), hydrodynamic roughness of the floodplain surface is the key input parameter of these models. Currently, no accurate, spatially distributed and quantitative method exists to parameterize hydrodynamic roughness of the floodplains as input for models, leading to uncertainty in flood water levels as well as deposition patterns.

Vegetation roughness is dependent on vegetation structural characteristics like vegetation height and density, rigidity of the stems and the presence of leaves (Kouwen and Li, 1980) . To provide hydrodynamic modelers with reliable input, the spatial and temporal distribution of surface characteristics is needed. This requires accurate and fast monitoring methods that can cover large floodplain areas. Various remote sensing data may provide information on vegetation type, structure and dynamics, using vegetation classification. While the spatial resolution and the level of detail of the classification vary with the type of remote sensing data, in all cases vegetation classes are converted to vegetation structure, which leads to undesirable loss of within-class variation. In contrast, Airborne Laser Scanning (ALS) enables direct extraction of vegetation structural characteristics such as vegetation height, biomass, basal area, and leaf area index (Cobby et al., 2001; Lim et al., 2003). However, ALS was never tested for floodplain vegetation under leaf-off conditions representative for winter floods, which has specific problems of inundated ground surface and small herbaceous vegetation elements which cannot be detected.

Any mapping strategy requires accurate field reference data for validation of remote sensing information products. Vegetation density is a difficult parameter to measure in the field, due to the presence of side branches, complex stem shapes and leaves (Dudley et al., 1998; Zehm et al., 2003). In addition, none of the current field methods generates information on the three-dimensional distribution of vegetation density. Especially for herbaceous vegetation, no accurate method exists to determine density in the field. Therefore a large uncertainty remains in the input to hydrodynamic models. On the other hand, the output of roughness models is mostly calibrated in flume facilities, where high flow velocities are used, combined with steep water surface slopes and low water depths. These circumstances are not representative for flow conditions on lowland floodplains. Current in situ measurements of vegetation roughness using fixed current meters and water level meters are inadequate to measure the relevant hydrodynamic parameters such as water depth, water surface slope and the 3D flow field. This lack of calibration data further increases the uncertainty in the hydrodynamic modeling.

ii. Aims

Based on the problems described above, the research objectives were summarized as to:

Parameterize floodplain vegetation structure accurately, quantitatively and spatially distributed using ALS to derive vegetation roughness, and assess the effects on floodplain flow patterns

Develop a method that provides accurate estimates of hydrodynamic vegetation density using terrestrial laser scanning and field photographs.

Determine floodplain roughness from in situ measurements.

The study was carried out in different floodplain sections along the lower Rhine distributaries, including the Gameren and Afferden floodplains along the Waal, and the Duursche Waarden along the IJssel branch.

iii. Results

Floodplain vegetation characterization

In this research we developed a novel method for automated roughness parameterization. It delivers a spatially distributed roughness parameterization for an entire floodplain by fusion of airborne multispectral data with laser scanning data (Straatsma and Baptist, 2008). The method consists of three stages: (1) pre-processing of the raw data, (2) image segmentation of the fused dataset and classification into the dominant land cover classes, (3) determination of hydrodynamic roughness characteristics for each land cover class separately. In stage three, we assigned roughness values to the classes' water, sand, paved surfaces (e.g., roads, parking lots), meadows and built-up area. For forest and herbaceous vegetation, ALS data were used for spatially detailed analysis of vegetation height and density. The vegetation density of forest and height and density of non-woody herbaceous vegetation were mapped using calibrated regression models (Straatsma and Middelkoop, 2007). Herbaceous vegetation cover was further subdivided in single trees and non-woody vegetation. Single trees were delineated using a novel iterative cluster merging method, and their height is predicted. The vegetation density of single trees was determined in an identical way as for forest (Straatsma, 2008). Fig. A-2.2 shows the different input maps for the hydrodynamic model. A 2D hydrodynamic model was applied with the results of this method, and compared with a traditional roughness parameterization approach. The modeling results showed that the new method is well able to provide accurate output data, it provides an easier and quantitative way of obtaining floodplain roughness and it yields a high spatial detail.

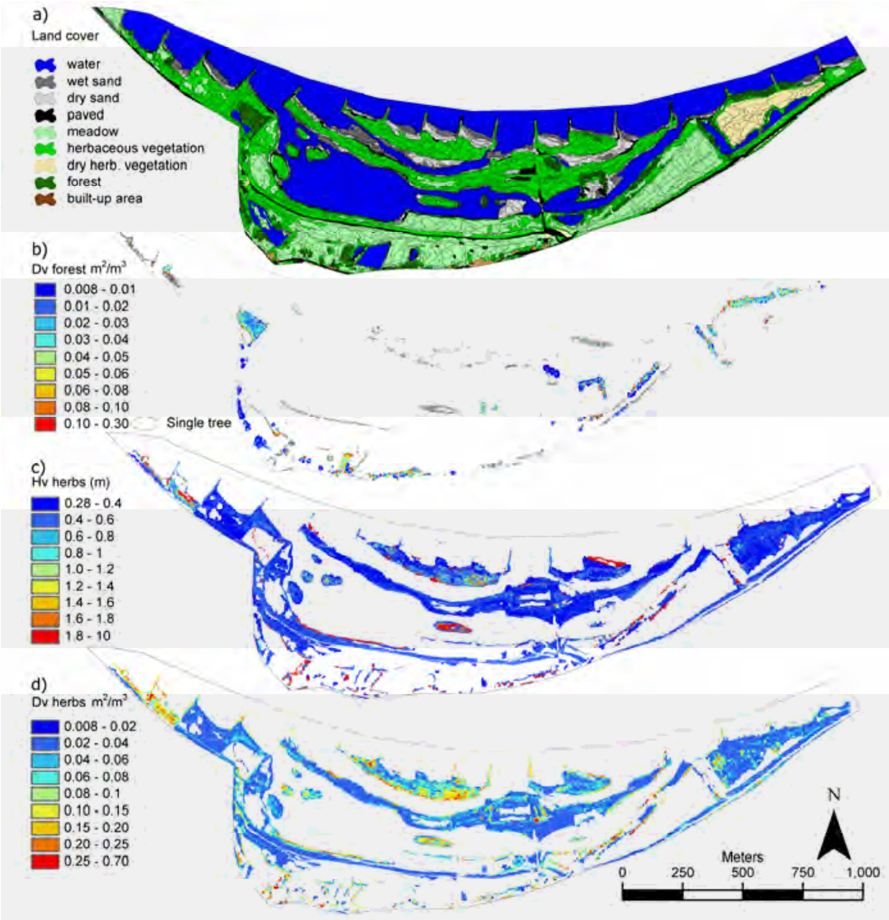

Fig. A-2.2: *Map stack describing the surface properties of the Gameren floodplain (Waal river). a) classified land cover map, b) vegetation density of forest (m^2/m^3), c) vegetation height of herbaceous vegetation (m), d) vegetation density of herbaceous vegetation (m^2/m^3).*

Field validation of hydrodynamic vegetation density

To measure vegetation density in the field, two new methods were developed (Straatsma et al., 2008). In Parallel Photography (PP) we used a large number of parallel photographs that were taken in a horizontal direction through the vegetation against a contrasting background (Fig. A-2.3).

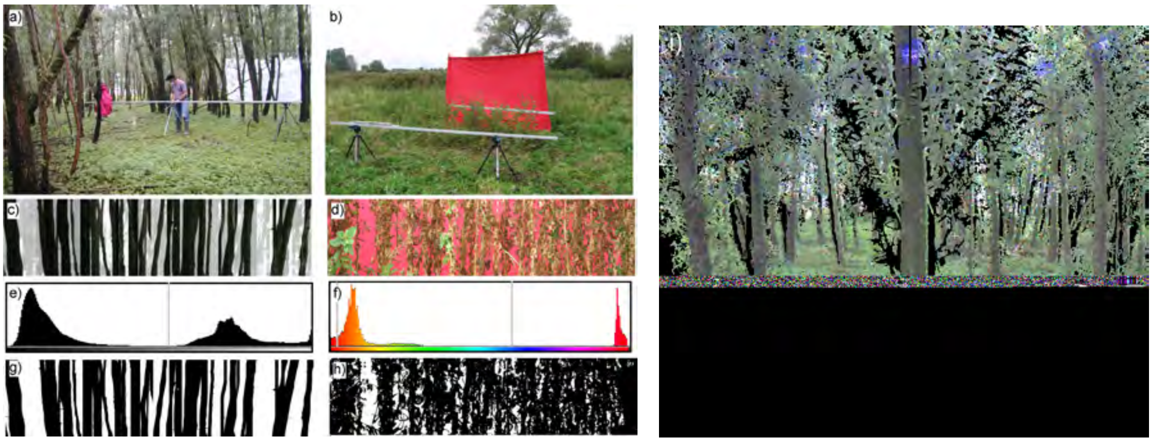

Fig. A-2.3: Parallel Photography (PP) methods: a,b) setup of the guide rail for the camera and background for forest and herbaceous vegetation, c,d) derived parallel photo-mosaics, e) histogram of intensity values (0 to) with threshold, f) histogram of hue values (0 to 360) with thresholds, g,h) thresholded images, i) TLS point cloud, with the points colored using the built-in camera.

From these we created a photo-mosaic of the central vertical slices of these adjacent images. This solves the problem of overestimating the size of vegetation elements that are close to the camera). Using the inverse gap fraction method (Jonckheere et al., 2004) the density was computed. PP proved extremely accurate in predicting the hydrodynamic vegetation density at plot level. The regression model was linear and did not deviate from the line of identity, which indicates that this method does not have to be calibrated and generally applicable. In addition, the support of this method is variable as the distance between the digital camera and the background screen is easily varied. The second method that was tested was based on Terrestrial Laser Scanning (TLS), which generates a 3D point cloud based on distance measurements (Fig. A-2.3i). TLS provided a 2D distribution of the forest vegetation density with a high accuracy. This method is easily extended to 3D. PP and TLS are complementary techniques as they combine high plot level accuracy and spatially distributed estimates of vegetation density. More detailed analyses of the composite image and laser data might enable the distinction between stems, twigs, and leaves. Such a method should include the classification of different vegetation elements and an estimate of their size. In this way, average stem spacing or flexural rigidity might be derived from the same methods.

Floodplain roughness determination

For in-situ quantification of hydrodynamic roughness of submerged floodplain vegetation, a novel method called ´3D float tracking´ was developed and tested (Straatsma, 2009). A platform floating over an inundated floodplain (Fig. A-2.4) was tracked using a shore–based laser positioning instrument (total station), while a current meter measured the flow profile.

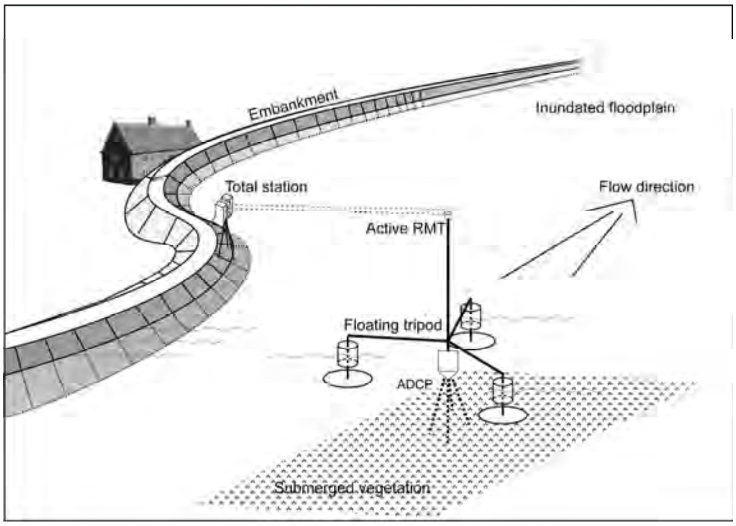

Fig. A-2.4: *Sketch of 3D float tracking, in situ roughness parameterization.*

This method is easily applied at various locations with different submerged vegetation types. The main achievement of this method is its high accuracy of the local water surface height determination (residual standard deviation of 0.7 mm) in the absence of waves. Combined with the depth averaged flow velocities and the water depth this enables solving the 1D equation for free surface flow locally, leading to the hydrodynamic roughness. 3D float tracking proved very suitable for inundated floodplains with high water depth and modest flow velocities. A clear spatial pattern in roughness could be detected using this method. In addition, 3D float tracking generates the detailed hydrodynamic data that are needed to verify the output of high-resolution hydrodynamic models, which will provide a substantial improvement of the calibration of these models. The effective roughness estimates, obtained using this device, are well within the range of suggested values from previous studies. The real achievement of this study is that it shows the spatial patterns in roughness, which points at the underlying processes.

iv. Conclusions and recommendations

Flood risk reduction and ecological restoration will remain important objectives of integral river management in the future. Within this project we developed methods to create building blocks for accurate parameterization of the input of hydrodynamic models and to validate the output of these models. We conclude that:

Vegetation height and density of herbaceous vegetation can be determined using airborne Lidar with high accuracy. However, the conversion of laser measurements to vegetation density still requires calibration for new flight campaigns. In the future, full waveform laser data analyses could improve the characterization the roughness of low vegetation.

Airborne laser scanning is able to provide maps of vegetation density of floodplain forest at high spatial resolution.

Field reference data of vegetation density can be acquired using parallel photography for plot level estimates and terrestrial laser scanning for 2D and 3D mapping. Detailed analysis of the PP photo-mosaics and TLS point clouds are required to estimate leaf coverage and flexural rigidity of the vegetation.

3D float tracking can be used to estimate the vegetation roughness under field conditions. At the same time it provides additional calibration data for hydrodynamic models to constrain parameter setting to realistic values. 3D float tracking could be further expanded using horizontal ADCP and small-footprint echo sounders to map the horizontal flow field and the vegetation structure of inundated floodplains.

The fusion of airborne spectral imagery with ALS data provides an effective source for mapping vegetation structural characteristics required to determine floodplain roughness. The method that was developed in this project provides more accurate determination of 3D floodplain vegetation structure than the current method of manual delineation and classification of floodplain ecotopes and, hence, of hydraulic roughness. Multi-temporal data analyses seems a promising way to optimize discriminate between herbaceous vegetation and meadows.

2.2 Influences of land use, flooding and metal contamination on biota in lowland Rhine River floodplains

Aafke M. Schipper, Rob S.E.W. Leuven, Ad M.J. Ragas, A. Jan Hendriks

i. Problem

Floodplains of large rivers are among the most dynamic and diverse natural systems on earth. The large spatial diversity of site conditions, combined with the flooding-induced dynamics, yields a constantly changing habitat mosaic, which favors a high diversity of both aquatic and terrestrial plants and animals (Sparks, 1995; Tockner and Stanford, 2002; Ward et al., 2002). Apart from their biological richness, floodplains provide important resources to mankind, for example through the supply of fresh water, food and fertile soils (Costanza et al., 1997). Particularly in densely populated regions, large areas of natural floodplain have been reclaimed for agricultural, industrial and urban activities, thus modifying or simply eradicating natural floodplain habitats (Nienhuis and Leuven, 2001; Tockner and Stanford, 2002). Due to the profound human influences, floodplains are ranked among the most altered ecosystems worldwide (Millennium Ecosystem Assessment, 2005; Tockner and Stanford , 2002). The lowland floodplains of the Rhine River represent a clear example of such man-dominated and deteriorated systems (Nienhuis et al., 2002). These floodplains have a long history of reclamation and land use and received large loads of persistent contaminants, notably metals, during the past century (Lenders, 2003; Middelkoop, 2000; Nienhuis et al., 2002; Thonon, 2006).

Triggered by the extreme floods of 1993 and 1995, major reconstruction measures are to be performed in many floodplain sections along the Rhine River in The Netherlands, in order to enlarge the discharge capacity of the river corridor (Nienhuis et al., 2002; Van Stokkom et al., 2005). Possible measures include the creation of side channels, removal of minor embankments and lowering of the floodplain surface (Straatsma et al., 2009). These reconstruction measures provide opportunities for ecological rehabilitation, as floodplain areas may be taken out of agricultural production and left to spontaneous vegetation succession (Nienhuis et al,. 2002). In order to be successful, however, floodplain management and rehabilitation should be based on a solid scientific foundation, as insufficient consideration of floodplain natural dynamics and ecological processes may result in further loss rather than rehabilitation of biological integrity (Lake et al., 2007; Sparks, 1995; Stanford et al., 1996; Ward, 1998). Hence, a thorough understanding of floodplain properties and processes is needed, not only in pristine situations but also under anthropogenic influences (Arthington et al., 2010; Stanford et al., 1996; Ward, 1998; Wassen et al., 2002).

ii. Aim

To increase insight in lowland floodplain properties and processes, the present study aimed to assess the influences of flooding, land use and metal contamination on biota in the lowland floodplains of the Rhine River in The Netherlands. The influences of the three stressors were studied separately or concomitantly in various case studies comprising different groups of organisms, including plants, terrestrial arthropods and vertebrates (birds and mammals). The research took place from 2005 to 2010; field data were collected in 2005 and 2007-2008.

iii. Results

Plants and arthropods in relation to land use, flooding and soil metal contamination

Plant communities and terrestrial arthropod assemblages were investigated in relation to land use, flooding and metal contamination (As, Cd, Cr, Cu, Ni, Pb and Zn) in the "Ewijkse Plaat" floodplain and the "Wolfswaard" floodplain (Fig. A-2.5). This was done with multivariate statistical techniques designed to relate variation in taxonomic composition to multiple explaining variables. Plant species composition showed stronger relationships to flooding characteristics and land use (grazing) than to metal contamination levels (Schipper et al., 2010c; Fig. A-2.6). Nevertheless, the relationship to metal contamination was also significant, whereby plant species richness significantly decreased with increasing contamination levels. To check whether the soil metal concentrations in the study area were high enough to indeed induce toxic effects in plants, a tentative comparison was made with reference values for phytotoxicity reported in the literature (Schipper et al., 2010c). As these reference values are commonly expressed as plant tissue concentrations, soil metal concentrations (Cd, Cu, Ni, Pb and Zn) were translated to plant tissue metal concentrations using floodplain- and species-specific bioaccumulation factors (Schröder, 2005). Estimated plant tissue concentrations were generally well below levels critical for phytotoxic effects. Therefore, it was suggested that the negative relationship between plant species richness and soil metal concentrations might reflect additive effects of multiple stressors rather than impacts of single metals. Multiple stressors may include multiple contaminants or contamination combined with non-chemical stressors like flooding.

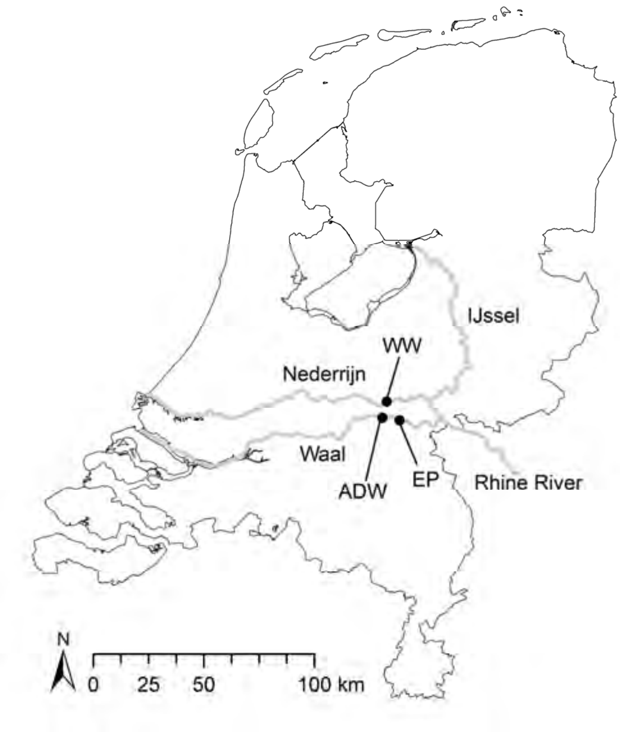

Fig. A-2.5: *Main Rhine River distributaries in The Netherlands and study area locations. ADW = "Afferdensche en Deestsche Waarden"; EP = "Ewijkse Plaat"; WW = "Wolfswaard".*

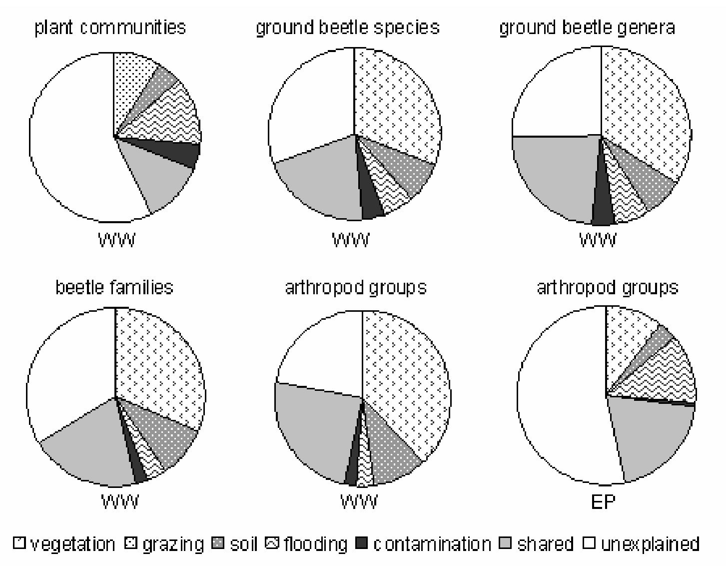

Fig. A-2.6: *Relative importance of different environmental factors for explaining variation in plant communities or arthropod assemblages. Percentages were derived from variance partitioning analyses using canonical correspondence analysis (CCA; for plants) or redundancy analysis (RDA; for arthropods). WW = "Wolfswaard"; EP = "Ewijkse Plaat".*

Terrestrial arthropods showed stronger relationships to flooding and vegetation characteristics than to soil properties and metal contamination (Schipper et al., 2010b; Schipper et al., 2008b; Fig. A-2.6). These results were similar for four arthropod datasets of different taxonomic detail: ground beetle species, ground beetle genera, beetle families and arthropod groups at class-order level (Fig. A-2.6). This suggests that in strongly heterogeneous environments like floodplains relatively coarse taxonomic data can be used to assess the relative importance of different environmental factors for structuring biotic communities. Yet, the ground beetles showed a higher specificity for different vegetation types and a more distinct relation to soil contamination levels than the coarser arthropod taxa. This indicates that a higher level of taxonomic detail might be beneficial for detecting and quantifying more subtle effects of land use and contamination.

Exposure of wildlife to metal contamination

Potential health effects of metal contamination in floodplain soils were investigated for various vertebrate species, including six small mammals and four top predators. This was done by developing a spatially explicit wildlife exposure model that simulates dietary exposure to soil metal contamination via species-specific food chains. The model was parameterized for cadmium contamination in a floodplain area along the Waal River, the "Afferdensche en Deestsche Waarden" (Fig. A-2.5). Simulations were performed for 1000 individuals per species and revealed that the exposure concentrations were generally highest for worm-eating species: common shrew (Sorex araneus), European mole (Talpa europaea), little owl (Athene noctua) and badger (Meles meles). To check whether the predicted exposure concentrations might lead to potential adverse health effects, a comparison was made with dietary no-observed effect concentrations (NOECs) obtained from the literature (Schipper et al., 2008a). Because these NOECs typically originate from laboratory tests, they were corrected for differences in for example metabolic rate and food caloric content between laboratory and field conditions (Traas et al., 1996). Although toxicological hazards were difficult to assess because NOECs were not species-specific, tentative hazard estimates indicated that negative effects of floodplain metal contamination cannot be excluded for the four worm-eating species investigated (Fig. A-2.7).

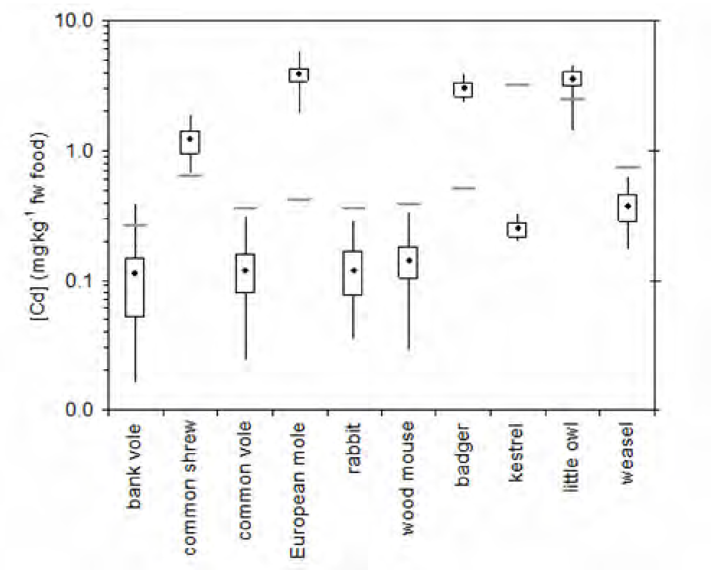

Fig. A-2.7: *Predicted exposure concentrations (mg·kg^{-1} fresh wt food) of cadmium for 10 vertebrate species in the study area "Afferdensche en Deestsche Waarden". Mean values are indicated by black diamonds; total range (minimum and maximum) are indicated by vertical lines; 10th and 90th percentiles are indicated by boxes; predicted no-effect concentrations (mg·kg^{-1} fresh wt food) are represented by grey horizontal line marks.*

Corncrake occurrence in relation to land use

Breeding site locations of the corncrake (Crex crex), a floodplain-specific bird species, were related to land use characteristics in the floodplains along the three main Rhine River distributaries in the Netherlands: the IJssel River, the Nederrijn River and the Waal River (Fig. A-2.5). Records of corncrake breeding sites obtained in 2001-2007 were related to landscape characteristics pertaining to area, shape, texture and diversity with logistic regression models. Landscape characteristics were determined at three spatial scales: distinct floodplain units ("floodplain scale"), circular zones around individual observations ("home range scale"), and individual patches ("patch scale"). The probability of corncrake occurrence showed a significant increase with patch area and with the area of potential habitat, i.e., herbaceous vegetation and grasslands, at the home range scale (Fig. A-2.8). In addition, significant positive relationships were found with the area of nature reserves (i.e., areas where mowing is delayed). The median potential habitat patch size associated with corncrake occurrence was 11.3 ha; 90 % of the corncrakes were associated with patches of at least 2.2 ha. These results indicate that the corncrake is an area-sensitive species, possibly governed by the males' tendency to reside near other males while maintaining distinct territories (Schipper et al., 2010a).

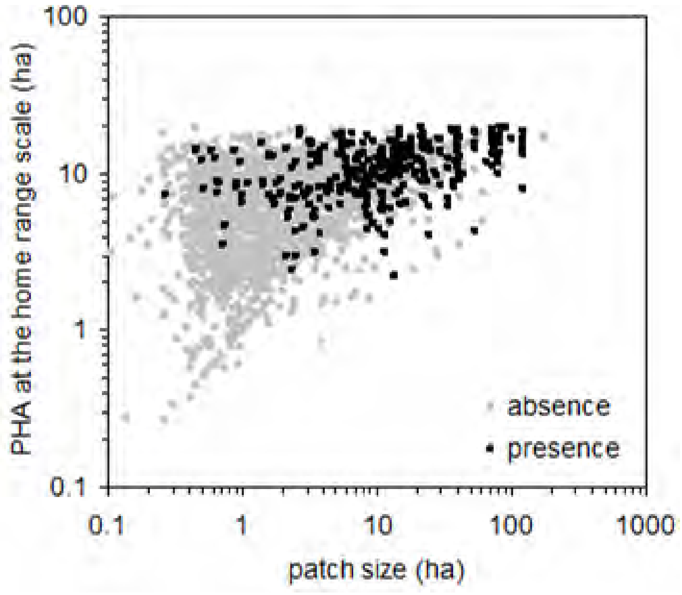

Fig. A-2.8: *Corncrake presence and absence in relation to patch area and potential habitat area (PHA) at the home range scale.*

iv. Conclusions and recommendations

The results from this research project give rise to some conclusions and recommendations which may be useful to consider in present and future floodplain management:

For plant communities, terrestrial arthropod assemblages and various vertebrate species in the present-day lowland Rhine River floodplains, effects of metal contamination are likely limited or subordinate to influences of other environmental factors. However, species with specific traits (e.g., feeding on earthworms, relatively long generation time, permanent residence) may be more susceptible to adverse impacts of metal contamination. This may warrant attention particularly in case of endangered, protected or key-stone species like the little owl.

Results of the case study on floodplain vegetation communities indicated that the concomitant influence of other stressors, notably flooding, may increase the vulnerability of biota to adverse effects of metal contamination. This implies that an integral approach is required to assess multiple stressor impacts in floodplain ecosystems.

In strongly heterogeneous environments like floodplains, the relative importance of different environmental factors for structuring biotic communities can be assessed based on relatively coarse taxonomic data. However, more taxonomic detail will be beneficial for detecting more subtle effects of, for instance, land use and contamination.

A floodplain-specific bird species like the corncrake, which relies on present-day land use and management practices, is unlikely to benefit from reconstruction and rehabilitation measures that yield wetter habitats and much denser vegetation.

Habitat conservation schemes for the corncrake should focus on the preservation of sufficient potential habitat area. Existing corncrake habitat management measures, like delayed mowing, should be implemented in relatively large, preferably contiguous areas.

2.3 Impact of value-driven scenarios on the geomorphology and ecology of lower Rhine floodplains under a changing climate

Menno W. Straatsma, Aafke Schippe, Marcel Van Der Perk, Claus G. Van Den Brink, Rob S.E.W. Leuven, Hans Middelkoop

i. Problem

In the future, the bio-geomorphological functioning of lowland floodplains is likely to be altered at an increasing pace. Together with increasing socio-economic demands, climatic changes are expected to increase the pressures on lowland rivers in developed countries. To cope with these pressures, integrated management plans have been developed for riverine areas across Australia, North America, and Europe (Brierley and Freyirs, 2008; Klijn et al., 2008). The choice and design of the measures proposed in these plans depends on the choices made in the decision making process, which in turn is strongly influenced by the value systems of the stakeholders. Planning of landscaping measures requires a long time horizon - decades to centuries - as the implementation is time-consuming and costly. Planning, therefore, involves scenario analysis to determine the feasibility and effects of potential landscaping measures.

ii. Aim

Our main objective was to explore the potential changes in future bio-morphological functioning of lowland rivers. In this project we adopted Spiral Dynamics (SD; Beck and Cowan, 1996; Graves, 2006) as a basis for scenario development. The advantage of this concept when compared to traditional methods is that it makes the role of human values explicit (Grumbine, 1997), and gives a framework of value systems that is hierarchic in nature, thereby limiting transitions to steps up or down the hierarchy. This makes that SD has an excellent potential for application in scenario development. We combined SD-based scenario development for river management with a quantification of the effects of the scenarios on floodplain bio-geomorphology. We firstly developed scenarios for 2050 based on shifts in the dominant value system in river management. For each scenario, we quantified the spatially distributed effects on the bio-geomorphology using existing spatially distributed simulation models. We exemplified these objectives for the lower Rhine River floodplain in The Netherlands.

iii. Results

Spiral Dynamics and Scenario Development

Spiral Dynamics (SD) structures the evolution of human value systems in a color-coded double helix (Graves, 2006; Fig. A-2.9). Each stage of development on the spiral represents a value system, which is a container for methods, beliefs and opinions. The hierarchy in value systems represents increasing inclusiveness and complexity. The spiral dynamics describe transitions up or down along the spiral. The current dominant value system in the Netherlands, with its consensual attitude and attention for ecology and landscape diversity, can be considered 'green' (Straatsma and De Nooij, 2010). Hence, starting from the green value system, we established three different scenarios that are plausible given the possible dynamics in value systems in relation to the time horizon of 2050 (Tab. A-2.1). This means that shifts from green to e.g. blue or turquoise are not considered realistic based on SD.

Fig. A-2.9: *The color-coded spiralling double helix of the biopsychosocial human development in Spiral Dynamics. One spiral represents the life conditions, the other the mind/coping capacities required for dealing with these life conditions. See Table A-2.1 for details.*

Tab. A-2.1: *Overview of the scenarios based on green, orange and yellow river management*

Value system	River management	Implementation
GREEN		
• Living with the human element • Getting along with others • Consensual	• Consensus mentality, local communities have a say • Focus on ecology • Dike raising is no option	• Space for the river combined with ecological restoration • Solutions for individual floodplain sections • Groyne lowering • Cyclic floodplain rejuvenation
ORANGE		
• Conquering the physical universe as to overcome needs • Oriented at technology and competition • Pragmatic	• Centralized authority • Cost-benefit analyses • Dike raising is a cheap option	• Dike raising • Groyne lowering • Removal of hydraulic bottlenecks • Removal of vegetation that obstructs flow • Removal of minor embankments • Retention areas
YELLOW		
• Restoring vision in a disordered world • Integrative	• Spatially coherent plan for the whole river section • Interactive • Local communities participate from the design phase • Water as the guiding principle • Dike raising is an option when needed	• Side channels follow the historic swale channels • Cyclic floodplain rejuvenation • Local initiatives in line with the overall direction • Multi-purpose groyne lowering

Using the SD value systems framework, we established three fundamentally different color-coded sets of landscaping measures (Fig. A-2.10):

The green relativistic scenario incorporated measures in three regions where consensus was found. Measures comprised side channels with naturally vegetated banks, 32 floodplain lowering projects, three dike section relocations, minor embankment removal, and natural management of ecotopes.

The orange multiplistic scenario was characterized by a productive-efficient layout applied to the entire study area. Measures comprised deep side channels with unvegetated banks, 51 floodplain lowering projects, minor embankment removal, and emphasized agricultural production.

The yellow systemic scenario showed a diverse pattern of city expansion, nature development, agricultural production and innovative groyne lowering. It comprised 52 floodplain height change projects, minor embankment removal outside the production regions, and seven dike repositioning projects.

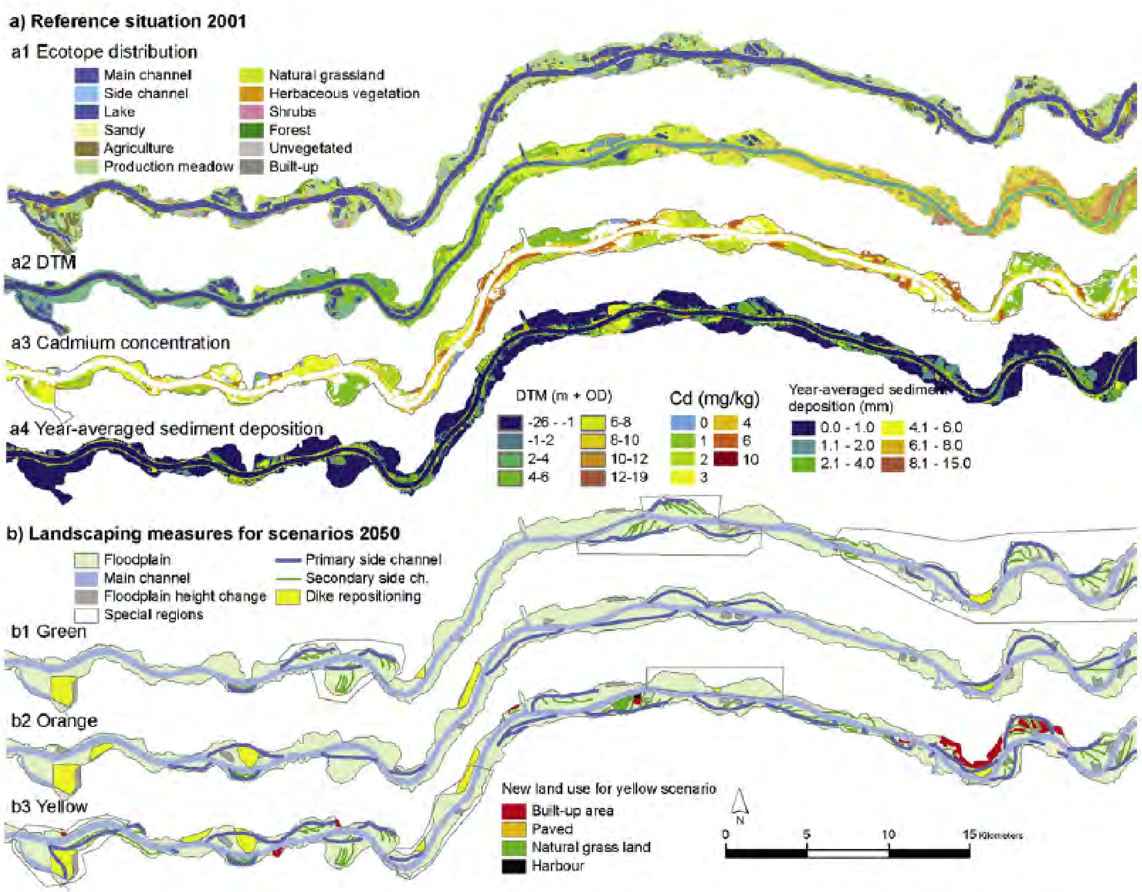

Fig. A-2.10: *a) Reference situation of the study area: ecotope distribution, terrain heights, soil cadmium concentrations, and year-averaged deposition of suspended sediment. b) Landscaping measures (floodplain height change, dike repositioning and side channels) for the scenarios: green, orange and yellow.*

Climate and river discharge scenarios

To determine the river discharge regime for 2050, we selected the KNMI-W scenario (Van den Hurk et al., 2006). This scenario assumes a 2ºC increase in temperature and a change in precipitation of +6 % in winter and -5 % in summer, and an 8 % increase in summer evaporation from 1990 to 2050. Hydrological simulations based on climate change scenarios indicate an increase in flooding probability for the Rhine as its regime will shift from a combined rain-fed/meltwater river into a mainly rain-fed river (Shabalova et al, 2003). Accordingly, for our scenario study, we adopted an increase design discharge for flood protection structures from 15,000 $m^3.s^{-1}$ to 17,000 $m^3.s^{-1}$ at Lobith for 2050. To facilitate comparison, we assumed equal input of heavy metals and suspended sediment between the three scenarios.

Floodplain biogeomorphology models

To quantify the effects of the three scenarios on the bio-geomorphology of the River Rhine floodplains and to compare these to the reference situation, we used a suite of spatially explicit simulation models, which were all calibrated and validated in earlier studies. We broke down the assessment into the following stepwise approach:

- Computation of the hydrodynamics using the 2D WAQUA model (RWS, 2007).
- Computation of the year-average deposition of sediment and metals using the SEDIFLUX model (Middelkoop and Van der Perk, 1998).
- Assessment of the potential ecotoxicological risk of heavy metal contamination (Cd) using a simplified version of the SpaCE model (Schipper et al., 2008a).
- Evaluation of the potential values for protected and endangered flora and fauna species using BIO-SAFE (De Nooij et al., 2004; Lenders et al., 2001).

We evaluated the impacts by comparing results for the reference situation with the current discharge regime (REF2001), the reference situation with the KNMI-W discharge regime for 2050 (REF2050), and the value-based scenarios with the KNMI-W discharge regime for 2050 (Tab. A-2.2).

Ecotope distribution and biodiversity

The ecotope distributions resulting over time from the landscaping measures for the scenarios are shown in Figure A-2.3a. Considerable differences in land use show up between the scenarios. Potential biodiversity values of the river landscape increase for the yellow and green river management strategies in comparison with the reference situation (Fig. A-2.12). This is due to the increasing areas of side channels, natural grassland and herbaceous vegetation at the expense of production meadows and agriculture. The orange strategy reduces potential biodiversity, due to a decrease in surface area of natural grassland, herbaceous vegetation, shrubs and forest and strong expansion of production grassland. Thus, based on potential values of the riverine landscape for protected and endangered species, the ranks of the management strategies show the following order: yellow > green > orange (Tab. A-2.2, Fig. A-2.11, A-2.12).

Tab. A-2.2: *Summary of modeling results*

	REF2001	REF2050	Green	Orange	Yellow
Average lowering of peak water level at 17000 $m^3.s^{-1}$ (m)	NA	NA	0.11	0.65	0.37
River length requiring additional lowering of water level or dike raising (km)	85	85	85	41	84
High water free surface area (km^2)	12.4	8.7	8.2	9.8	9.7
Sediment deposition in groyne area (mm)	3.61	5.06	3.56	4.33	3.68
Year-averaged sedimentation on floodplain (mm)	1.15	1.81 (+58 %)	2.44 (+112 %)	2.85 (+148 %)	2.80 (+ 143%)
Total deposition of sediment (10^6kg/y)	199	306	358	422	406
Total deposition of Cd ($kg.y^{-1}$)	655	989	1157	1372	1329
Sediment trapping during floodplain inundation (%)	26	27	31	37	35
Average cadmium concentration in floodplain soil ($mg.kg^{-1}$)	2.74	2.74	2.95	3.01	3.04
No. of species for which PEC_{Cd} > $PNEC_{Cd}$ (cumulative affected fraction of habitat)	5 (39 %)	5 (39 %)	4 (37 %)	5 (40 %)	4 (37 %)
Relative BIO-SAFE scores	1	1	1.23	0.96	1.39

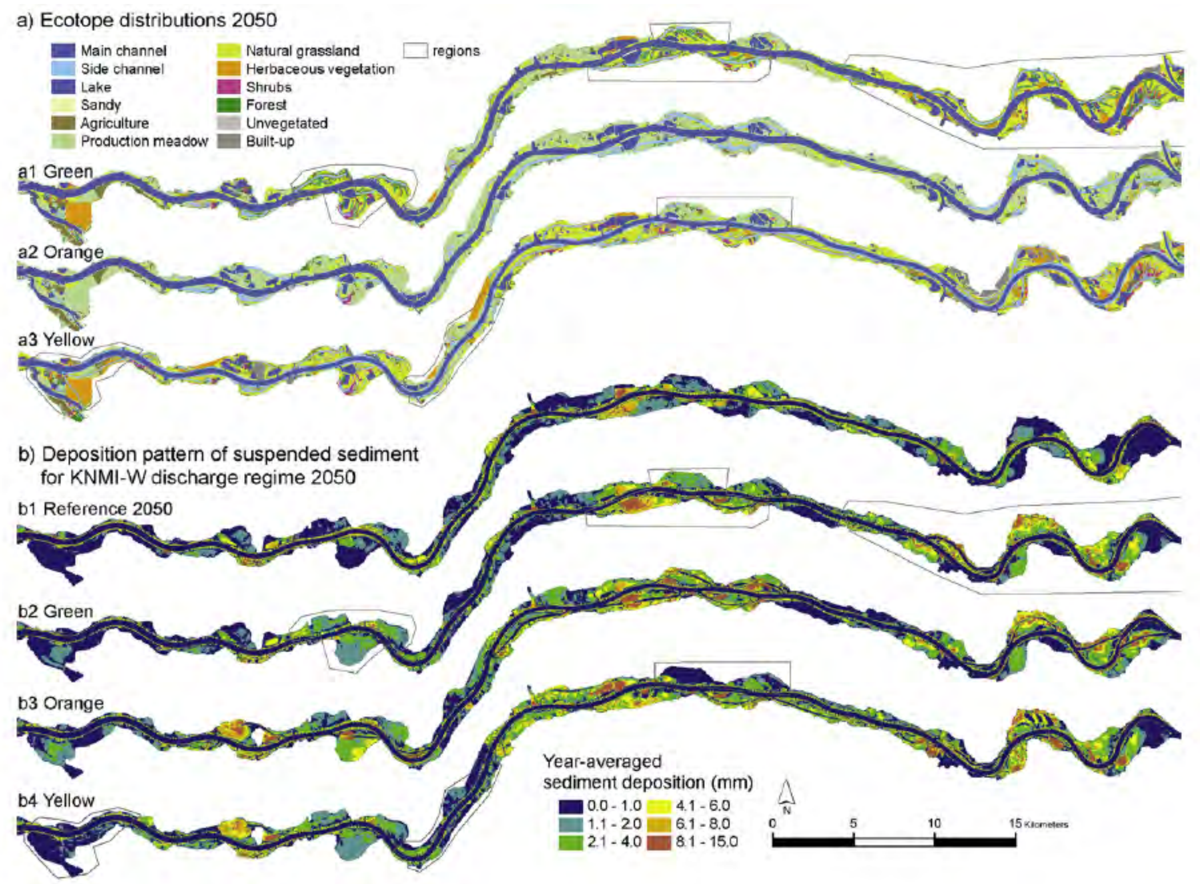

Fig. A-2.11: *a) Ecotope distribution for the scenarios, b) pattern of suspended sediment deposition in the Waal for the KNMI-W discharge regime.*

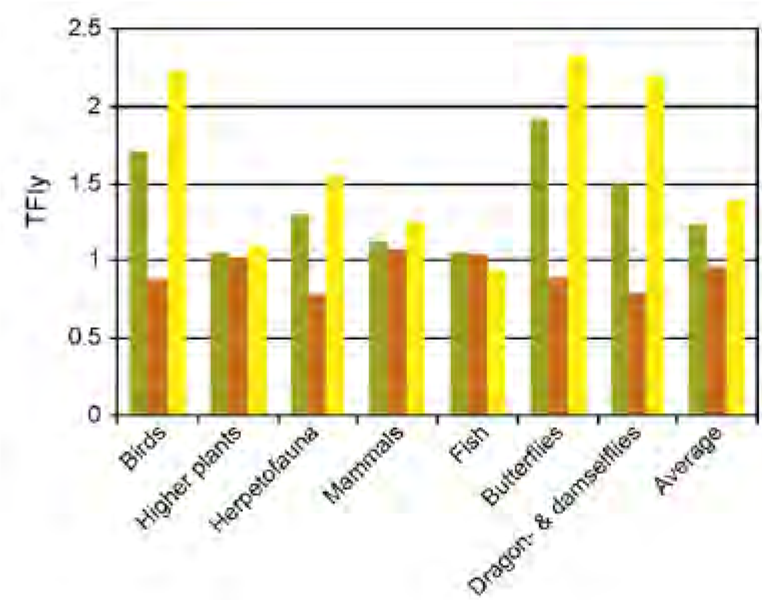

Fig. A-2.12: *Taxonomic group Floodplain Importance (TFI) scores for various taxonomic groups. Values are relative to the scores in the reference situation, hence all TFI scores for the reference situation would be one. Colors refer to scenarios.*

Hydrodynamics

The landscaping measures strongly affect the flow patterns and peak water levels. The average water level reductions along the river axis at a 17,000 $m^3.s^{-1}$ discharge are 0.11 m in the green, 0.37 m in the yellow, and 0.65 m in the orange scenario. Still, the strategies do not compensate for the expected increase in water level, due to the introduction of hydraulically rough ecotopes, such as floodplain forest.

Sediment and heavy metal deposition

Climate change leads to more frequent inundation of the floodplains, increasing average sediment deposition over the floodplain area from 1.15 to 1.81 $mm.y^{-1}$ (+58 %), with considerable spatial variation. However, landscaping measures more than double the floodplain sedimentation (+112 % to +148 %). Spatial differentiation between the scenarios is large, depending on the design of side channels (Fig. A-10b). Changes in deposition pattern of Cd largely follow the pattern in sediment deposition. The reference situation has the lowest Cd deposition rate (655 $kg.y^{-1}$), the orange scenario the highest (1372 $kg.y^{-1}$; Tab. A-2.2). Little difference (<10 %) was present for the resulting Cd concentrations.

The filter function of the river Waal within the coastal zone is expressed as the total trapping efficiency of the river for suspended sediment, calculated for Rhine discharges >3500 $m^3.s^{-1}$ that cause floodplain inundation. The reference situation with the current discharge regime shows a 26 % trapping efficiency and a total annual deposition of 0.2 $Mton.y^{-1}$. The reference situation in 2050 has a similar trapping efficiency of 27 %, with 0.3 $Mton.y^{-1}$ deposition. The orange scenario shows the highest trapping efficiency of 37 % (Tab. A-2.2).

Ecotoxicological risks

Predicted exposure concentrations (PECs) of cadmium for 10 terrestrial vertebrate species show no substantial differences between the scenarios (Tab. A-2.2). Irrespective of scenario, for four species (i.e. common shrew, European mole, badger and little owl) the largest part of the habitat area remains characterized by PECs that are higher than the corresponding toxicity reference values (predicted no-effect concentrations (PNECs); Tab. A-2.2). For the weasel, the PNEC is exceeded in a small fraction (< 1 %) of the habitat area for three out of five scenarios. For the remaining five species, the entire habitat area is characterized by exposure concentrations lower than the corresponding PNECs.

iv. Conclusions

The present study illustrates the great potential for the application of SD in the design of floodplain management scenarios, as the shifts in value systems provide a guide for selecting and positioning specific landscaping measures. In addition, the value systems analysis promotes the internal coherence of the scenarios, as measures are chosen within a storyline rather than individually. This first attempt to develop scenarios for floodplain management based on Spiral Dynamics (SD) demonstrates that the value systems analysis provides a broad interpretive framework for development of scenarios that are internally coherent and plausible.

The river floodplain bio-geomorphology is influenced by the combined effects of a climate-induced change in discharge regime and local landscaping measures. Climate-induced changes in river discharge regime may increase the year-average floodplain sedimentation by the order of 50 % but this is overshadowed by the increase of more than 100 % due to human landscaping measures. Thus, the filter function of this lowland river is more sensitive to local measures than changes in discharge regime. The trapping efficiency is positively correlated to floodplain discharge capacity. The orange scenario provided the extreme case of high discharge and high deposition.

Natural vegetation should be compensated for by sufficiently large side channels to increase discharge capacity and prevent driving up the water levels. The ecotoxicological risks of cadmium contamination remain similar as to date. The scenarios also point to the human influence on future potential biodiversity values ranging from -4 % to +39 %. None of the scenarios shows the ideal combination of a high flood peak reduction, low sedimentation, low ecotoxicological risks, and high biodiversity potential.

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3. Circulation, sediment concentration and oxygen depletion in the tidal Ems River

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Abstract

We present measurements which show that the tidal Ems River in Germany is extremely muddy over a 30 km + turbid zone, with fluid mud of 1-2 m thickness covering the bed with suspended sediment concentrations (SSC) of greater than 50 kg.m^{-3}. Moreover, we show that these elevated SSC contain large quantities of organic material which deplete dissolved oxygen (DO) and produce summertime hypoxic zones. Using mathematical modeling, we develop simplified representations of the estuary physics that reproduce the tidally-averaged circulation, SSC distribution, and oxygen depletion. These models show that SSC and oxygen concentrations are extremely sensitive to factors such as the mean depth, the mixing due to bottom friction (turbulence), and river flow. The observed increase in SSC and decrease in DO over the past 25 years is linked to the progressive deepening of the tidal Ems from 4-5 m to 7 m between 1985-1994, which moved the turbid zone upstream and decreased mixing. A review of scientific literature and data from the Ems suggests that human intervention (dyking,channel modification) combines with more gradual natural changes (sea level rise, climate variation) to continually modify sediment transport.

i. Overview

The tidal Ems River is part of the Ems-Dollard estuary, which is located at the border of Germany and the Netherlands (Fig. A-3.1). The estuary extends approximately 100 km from the barrier island of Borkum (km 0) to a tidal weir (gate) in Herbrum (km 100). Tidal forcing is significant, and the mean tidal range of up to 3.5 m produces currents of 1-2 m.s^{-1} during peak flood, with smaller currents occurring during the ebb.

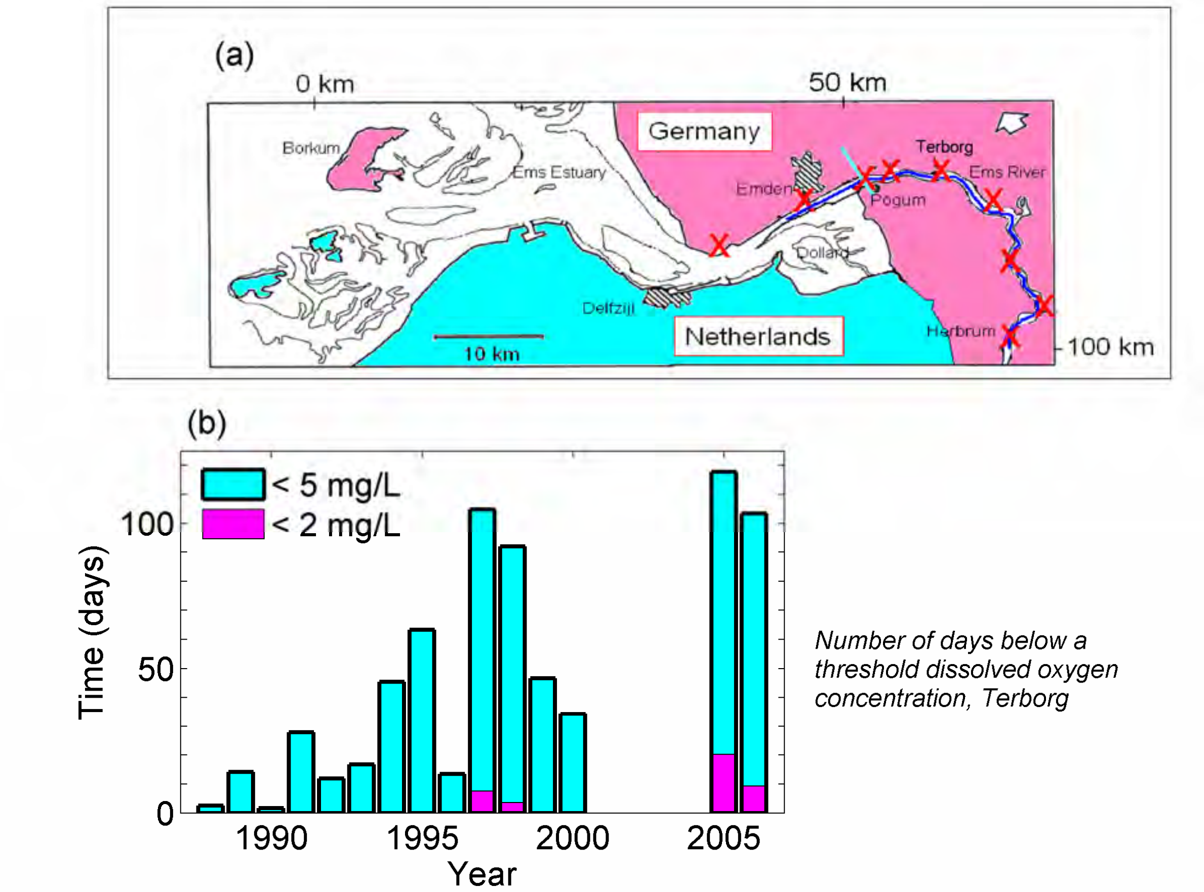

Fig. A-3.1: *Location of Ems Estuary (a), and increasing oxygen depletion over time (b); the crosses (X) denote location of monitoring stations, solid line denotes location of experimental transects.*

A gradual transition between salt water (S =30) and freshwater (S < 1) occurs in the middle of the estuary, with a peak gradient on the order of S = 1 km^{-1}. Channel depths are maintained at a depth of 8 m in the outer estuary (maximum is 30 m), and are approximately 7 m from Emden (km 47) to Papenburg (km 87). River discharge is primarily from the Ems River, and varies from an average of 35 $m^3.s^{-1}$ during the warm summer months to peak flows of up to 600 m3.s^{-1} during winter months. The yearly average flow is 80 $m^3.s^{-1}$, with a median flow of ~65 $m^3.s^{-1}$. Over the past 25 years, the number of days with severe oxygen depletion has greatly increased (Fig. A-3.1). During the same period, the river between Emden and Papenburg was deepened from 4-5 m to 7 m (1985-1994), and an increase in tidal range of up to 1.5 m was observed near the tidal weir (Talke & de Swart, 2006).

We undertook extensive hydrodynamic and water quality measurements in monthly increments from Feb. 2005 to Dec. 2007 along the longitudinal axis of the Ems estuary. Selected cross-sectional and fixed channel measurements occurred over a tidal period in March 2005, February 2006, and September 2006 in the area near Pogum (km 53) and Terborg (km 63). As explained in more detail in Talke et al. (2009a), all these experiments included measurements of water quality parameters such as nutrient concentrations, SSC, and chlorophyll. Additionally, many of these field experiments included measurements of flow velocity, salinity, temperature, dissolved oxygen (DO) concentration, and optical backscatter (for turbidity and SSC). We focus here on these latter measurements.

ii. Field Measurements

During low river discharge conditions during the summer, salinity is well mixed vertically and transitions from marine conditions (S > 20) to freshwater conditions (S < 1) over nearly 30 km (Fig. A-3.2a). As occurs in many estuaries, SSCs vary spatially and collect in the so-called estuary turbidity maximum (ETM; Fig. A-3.2b). Unlike most other estuaries, this ETM extends outside of the brackish water region (S= 1-2) and covers the entire freshwater zone up to the tidal weir at km 100. SSCs in the ETM are enormous and form a fluid mud layer (SSC > 10 $kg.m^{-3}$) of 1-2 m depth over a 35 km region. The density gradient in the vertical suppresses mixing. The SSC varies sharply in the brackish water region, and produces a longitudinal density gradient that is up to an order of magnitude larger than the longitudinal salinity gradient (on the order of 10 $kg.m^{-3}$ near the bed).

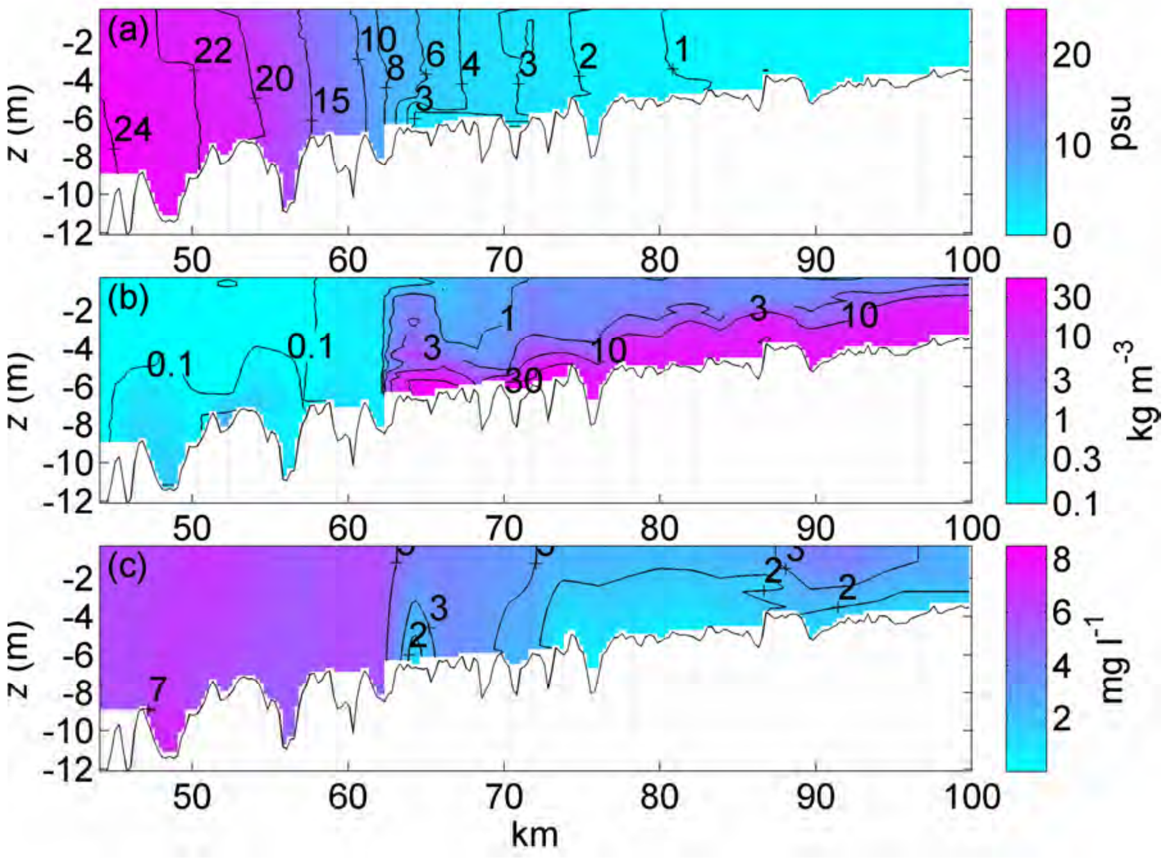

Fig. A-3.2: Measurements of salinity (a), suspended sediment concentration (b), and dissolved oxygen concentration (c) along the axis of the Ems River Estuary on August 2nd, 2006 (Reprinted from Talke et al., 2009b)..

At the water surface, turbidity at S = 4 salinity attenuates light intensity by 3 orders of magnitude within the first 15 cm of the water column (not shown). Under these conditions, phytoplankton cannot grow. The effect of turbidity on the onset of phytoplankton blooms was theoretically investigated by De Swart et al. (2009), and shows that much lower SSC concentrations than measured in the Ems ETM either move the phytoplankton bloom seaward or prevent one from occurring.

The oxygen demand from organic material (approximately 10 % of SSC os organic carbon) in the ETM is sufficient to produce a large zone of hypoxia (< 2 $mg.l^{-1}$) over much of the freshwater/brackish water region (Fig. A-3.2c; see Talke et al., 2009b). To first order, we find that oxygen demand is proportional to SSC, with the smallest Dissolved Oxygen (DO) occurring in the region of largest SSC (Talke et al., 2009b). Fish populations are stressed and cannot live at DO < 5 $mg.l^{-1}$ and DO < 2 $mg.l^{-1}$, respectively. Hence, understanding the physical conditions and processes that produce large SSC, fluid mud, and low DO are essential to devising solutions for the stressed ecology of the Ems.

iii. Modelling

To understand why SSC is elevated and oxygen is depleted, we developed mathematical (analytical) models that identify important controlling parameters in a simplified, idealized domain. While such models neccessarily exclude detail such as complex bathymetry, its simplicity allows for parameter sensitivity studies that provide insight into the effect of changing conditions. The equations can be found in Talke et al. (2008, 2009a,b); here, we qualitatively describe our methodology.

As a first step, we assume that the distribution of SSC and depleted oxygen is determined primarily by tidally averaged circulation and by mixing, which can be captured by constant vertical and horizontal mixing coefficients. Moreover, we assume a constant depth and an exponentially decreasing width (funnel shape), with an e-folding scale that is based on the natural environment. We assume a rigid lid and make the Boussinesq assumption, following standard practice. River discharge is assumed to be constant. Salinity is observed to be well mixed vertically and varies like a hyperbolic tangent in the longitudinal direction (see Fig. A-3.2).

The assumptions listed above were classically applied by Hansen & Rattray (1965) to the tidally averaged shallow water equations, which describe how pressure—either from a surface slope or from a horizontal density gradient-produces circulation. We modify the classical relationship by recognizing that dynamically significant density gradients occur not only due to salinity, but also due to the longitudinal distribution of SSC (Fig. A-3.2). Moreover, we note that SSC is distributed approximately exponentially in the vertical, with the largest concentrations near the bed (Talke et al., 2009a). This is modelled by assuming a balance vertically between diffusion and a constant settling velocity. These insights are then mathematically incorporated into the shallow water equations. The resulting novel expression describes circulation patterns that arise due the salt field, river discharge, and the distribution of SSC. As shown in Figure A-3.3a and A-3.3b, surface flow is seaward everywhere. Near the bed, a cell of upstream circulation occurs due the salinity gradient. Turbidity induced circulation downstream of the ETM opposes, but does not reverse, this upstream flow. A large dependence on depth is observed; increasing the depth from 5 m to 7 m, which occurred in the Ems between 1985 and 1994, results in a factor of nearly 3x greater circulation.

The distribution of SSC presented in Figure A-3.3c and A-3.3d is solved for by assuming equilibrium conditions. Mathematically, we assume that the local deposition of sediment equals local erosion and that the quantity of suspended sediment in the model domain is fixed. Consequently, the total sediment flux through a cross-section vanishes, i.e., the area-integrated sediment fluxes due to a combination of advection and diffusion are zero.

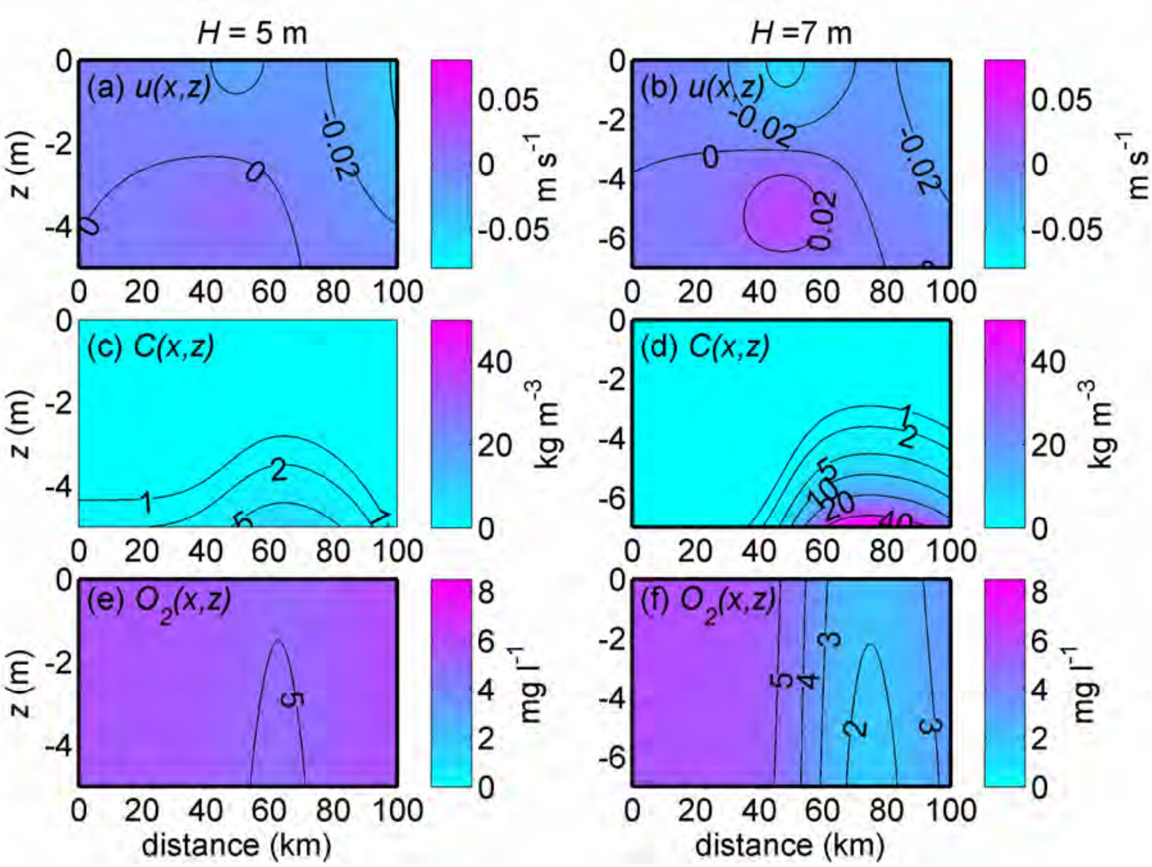

Fig. A-3.3: *Modeled circulation, SSC, and dissolved oxygen for different depths (Reprinted from Talke et al., 2009b).*

The result is an analytical expression for SSC that depends on the salinity field, the freshwater discharge, depth, the horizontal and vertical mixing coefficient, the settling velocity of sediment, and the prescribed total amount of suspended sediment in the system. Comparing Figures A-3.2b and A-3.3d, we observe that the modelled turbidity zone (Fig. A-3.3d) qualitatively captures the features of the measured distribution of SSC (Fig. A-3.2b). Elevated SSC of greater than 10 $kg.m^{-3}$ extends over the freshwater and brackish water zone and covers the bed by 1-2 m in both the measurement and model. Moreover, the SSC gradient in the brackish water transition zone is steep in both cases.

Interestingly, increasing the depth from 5 m (Fig. A-3.3c) to 7 m (Fig. A-3.3d) results in a larger turbidity zone with nearly an order of magnitude greater SSC that is centered farther upstream. Similar changes have been observed in the Ems River, in which channel deepening from 4-5 m to 7 m between 1985 and 1994 resulted in an upstream movement of the ETM and greatly increased SSC (e.g., Talke & de Swart, 2006). Our model suggests that contributors to the historically observed variation include: (1) decreased river flow (because of greater cross-sectional area), (2) increased gravitational circulation (cubic dependence on depth), and (3) a changed vertical distribution of SSC (which is now proportionally lower in the water column). Other factors include decreased mixing and increased sediment supply (not shown). More recent models also point out the importance of tidal asymmetries, increased tidal range, settling lag effects, reduced bottom friction, and flocculation processes in producing an upstream movement of SSC (Chernetsky et al., 2010; Winterwerp 2010).

The distribution of circulation and SSC is next used to model oxygen depletion. A mass-balance approach to dissolved oxygen (DO) yields an advection-diffusion equation with a sink term that is proportional to organic material, and hence SSC. Reaeration at the surface is held proportional to the local oxygen deficit, while sediment oxygen demand at the bed produces an additional source of oxygen depletion. Additional details and model verification are given in Talke et al. (2009b). As shown in Figure A-3.3e and A-3.3f, the modeled oxygen depletion is closely related to the distribution of SSC. The changes described earlier for SSC between the H=5 m case and the H=7 m case cause a switch from well aerated conditions (DO > 5 mg.l-1) to conditions that are hypoxic (DO < 2 $mg.l^{-1}$) over a large section of the estuary. From these simulations we conclude that it is the dynamics of turbidity maxima—rather than the residence time of water or the input of nutrients—that determines the depletion of oxygen in highly turbid estuaries such as the Ems.

A review of scientific literature and data from the Ems suggests that human intervention and natural variation continually modify sediment transport (Talke & de Swart, 2006). Until approximately 1950, the largest change to estuarine physics (as measured for example by tidal range) occurred due to land reclamation. Since 1950, channel modification and deepening has amplified tidal range, increased the tidal asymmetry in currents, magnified SSC and turbidity, and produced hypoxia. Other sources of variation include rising sea level and increasing tidal range in the North Sea, as well as variations to wind, waves, and river discharge caused by the Northern Atlantic Oscillation cycle (Talke & de Swart, 2006). Although natural changes are occurring more gradually than anthropogenic modifications, both factors alter depth, flow and mixing characteristics (Talke & de Swart, 2006). The models and measurements presented here suggest how these factors affect estuarine sediment transport patterns and water quality.

iv. Conclusions

In this paper we summarize recent measurements and models which show that the Ems estuary is a highly stressed environment marked by extremely turbid conditions, fluid mud, and hypoxia. A tidally-averaged circulation model is used to solve for the distribution of suspended sediment concentrations and dissolved oxygen. The model results suggest that deepening of the Ems River is responsible for the increased SSC and degraded water quality over the past 25 years.

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B. Biogeomorphology

1. Interview with Dr. M.M. van Katwijk
2. Measurements of suspended sediment concentration from ADCP backscatter in strong currents
3. Tidal stratification interaction in the Rhine ROFI Coast Zone
4. Mechanisms involved in salt-marsh rejuvenation
5. Macrophytes in estuarine gradient

1. Interview with Dr. M.M. van Katwijk

Coastal river, sediment transport, salt marshes and plants

Dr Marieke van Katwijk tells us about six different studies that fall under the LOICZ theme Biogeomorphology of coastal zones. These are innovative studies because different disciplines are collaborating together and new equipment is being used.

Two of the LOICZ studies focus on geomorphology, but their studies have biological implications. These concern the coastal river that determines how the sediment and nutrients are transported along the coast and how much sediment enters the Wadden Sea. The other studies focus more on the biological aspects in interaction with geomorphology. They mainly concern the accretion and erosion of salt marshes and seagrasses.

Coastal river and sediment transport

Van Katwijk: The first study by Gerben de Boer (Deltares) is about sediment transport and the nutrient flows just off the North Sea coast. Between Hook of Holland and Den Helder a "river" flows at a speed of 20,000 m3 per second, which is comparable in size to the Mississippi. This river is a continuation of the Rhine. The water in the coastal river is frequently stratified: the surface is often fresh but the floor salty. At the Marsdiep, the water and sediment enter the Wadden Sea. A model of this has now been developed by Lucas Merckelbach (NIOZ) that gives us an understanding of sediment transport along the coast and in the Wadden Sea.

How exactly can we measure sediment transport into the Wadden Sea?

A device was attached on the Texel ferry, a so-called Acoustic Doppler Current Provider. This is a cheap technique that allows us to measure the suspended sediment in the Marsdiep. Merckelbach calculated that about 7 million tonnes of sediment enters the Wadden Sea, a figure 5 to 10 times higher than previous models had calculated.

Salt marsh rejuvenation

Salt marshes are important for the Dutch coastal defences. When a large salt marsh is located in front of a dike, the dike needs less enforcement, which is cheaper. Wherever possible water management policies look for natural solutions in addition to elevating and strengthening dikes. Salt marshes provide a very subtle piece of coastal defence.

Due to a range of interventions and changes in water management, these marshes are disappearing. And once they have gone, re-establishing them is anything but easy. Erosion often starts that the edge of the marsh, and cliffs may form. Once a cliff has formed, the erosion accelerates. To prevent cliff erosion, it is important that the foreland is relatively high, so that wave energy has already attenuated substantially when it reaches the marsh edge. Therefore this foreland, the intertidal flat, is of importance. If sediment accretes in the intertidal flat, and this zone can keep up with sea level rise, the risk of cliff erosion reduces. In the intertidal flats, seagrasses, oyster and mussel beds are typical 'ecosystem engineers' that can stabilise and accrete sediments. The LOICZ-programme had two projects on salt marsh dynamics (van Wesenbeeck NIOO and de Groot RUG) and two on seagrass dynamics (Van der Heide RUN and Dijkstra TUD), all four focussing on interactions with sediment and hydrodynamics. The results of the projects have, amongst others, been used for further research that is funded by the innovation fund Building with Nature, which supports solutions in water management that work with nature rather than against it. In this research

That sounds fantastic. Building with nature seems to be a natural, sustainable and above all cheap form of coastal defence.

That's right, but remember that these processes are all very subtle, and we will remain depending on the hard engineering solutions for our coastal protection. All ecosystem engineers in coastal zones, like saltmarshes, seagrass beds, mussel and oyster reefs can come and go, they are typically dynamic. The restoration of Zostera fields is a thing of the future, as these fields are still disappearing and do not seem to recover by themselves.

Why does Zostera fail to re-establish itself in the Netherlands?

There is no simple answer to that question. Zostera is continuing to decline in The Netherlands. At some locations it might be due to the activities of lugworm diggers, and at other places it might be the consequence of successive cold winters. Because the causes differ per occasion, we suspect that there is some underlying cause that reduces Zostera's ability to recover. It undermines its health, so to say. We suspect that one possible underlying cause of this is eutrophication and the other a changed salt concentration due to a range of interventions in the water management. The changes are taking place so fast that Zostera can no longer adapt to these. In some parts of the Wadden Sea the salt concentration is too high, whereas at other locations it is too low. In the Oosterschelde and Lake Grevelingen, the salt concentration has increased during the 1980s and 1990s.

What can be done about this?

Re-establishing the Zostera could be the first step towards restoring the salt marshes. Perhaps we ought to consider introducing Zostera races from neighbouring countries that are more salt tolerant. Yet that would meet countless objections due to the import of foreign material. It would not be a realistic option under the current nature policy. However, in the Oosterschelde we must act soon as the sand is disappearing into the channels and there is a constant demand for sand. As Zostera re-establishment is not feasible in the short term, there are presently experiments with the creation of oyster banks in the Oosterschelde. For experimental purposes we will also try to replant local Zostera species there. This is a follow-up study that does not fall under the LOICZ. Nevertheless, the LOICZ studies were highly inspiring for the different research groups. Indeed the effect was so great that six follow-up studies are now in progress, largely funded by the Building with Nature programme: not only the oyster bed creation and seagrass mitigation in the Eastern Scheldt, but also mangroves in Singapore, coral reefs and seagrass fields in Thailand and so forth.

Now we are jumping too far ahead. Back to the studies about salt marsh rejuvenation carried out for LOICZ.

One study focussed on determining the sedimentation patterns and spatial processes in salt marshes and tidal flats. Sedimentation patterns are complex and change with the age of the salt marsh. A method has been developed to map the salt marshes using natural gamma radioactivity. Now these accurate measurements can be used to assess the impact of shell fishing and seabed subsidence on the tidal flats. Furthermore, the results serve as a reference point for the natural dynamic processes that occur there and this information is extremely useful for the Water Framework Directive, Natura 2000 and Dynamic coastal management.

And then there are also the studies into the interaction of various plant species with the sediment.

On a small scale, positive interactions can take place in the pioneer zone of the salt marsh and on a larger scale negative interactions. Plants support each other on a small scale but if such a tussock becomes too large, a channel develops around it which leads to erosion. The tussocks then become a sort of wall that the waves crash against. This results in negative feedback. The larger a tussock of Spartina becomes, the greater the negative feedback. That is sometimes referred to as mechanical warfare. Scale-dependent feedbacks give rise to certain patterns. Interestingly, the same complex feedbacks and mechanical warfare that were found for salt marshes were also discovered for seagrass in the LOICZ studies. Now we know how those processes occur, we can do more to facilitate the rejuvenation of salt marshes. And by doing this we indirectly contribute to the natural strengthening of dikes

And so we have come full circle back to dike strengthening and coastal vegetation…

Indeed.

2. Measurements of suspended sediment concentrations from ADCP backscatter in strong currents

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Abstract

Acoustic Doppler Current profilers (ADCP's) have been used to measure currents for over twenty years. Although ADCP's are origianlly not designed to measure acoustic backscatter intensity accurately, several researchers have (successfully) related the backscatter intensity to suspended sediment concentrations (SSC) using a random phase acoustic backscatter model. However, this paper shows experimental evidence that in a tidal inlet during high tidal current velocities, a random phase acoustic backscatter model overestimates the SSC by one or two orders of magnitude, which cannot be explained by a time-varying particle size distribution. An acoustic backscatter model is developed that includes the effect of acoustic backscatter enhanced by coherence in the particles' spatial distribution as a result of turbulence-induced sediment fluctuations. The model results are compared with field measurements, showing a good correspondence between measured and modeled SSC, including the strong high current conditions for which the random phase acoustic backscatter model was shown to fail.

i. Introduction

The Marsdiep is the most southwestern tidal inlet of the Dutch Wadden Sea, a shallow tidal area that is connected to the North Sea (see Fig. B-2.1).

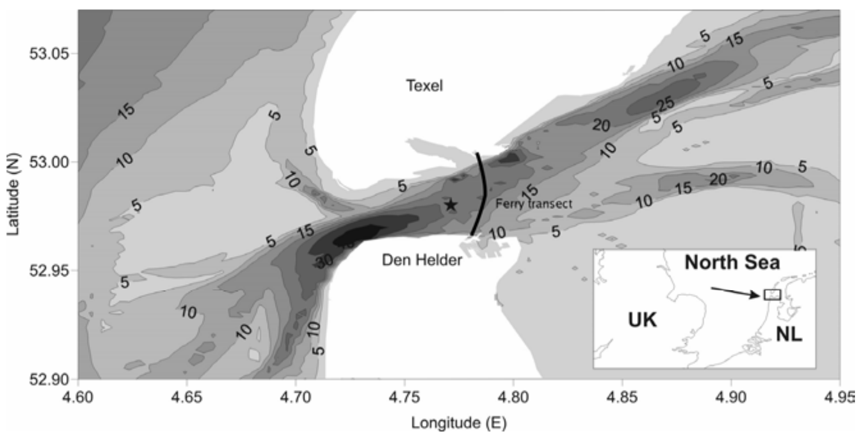

Fig. B-2.1: Map of the western part of the Wadden Sea. The numbers indicate depth in meters with respect to mean sea level.

Since 1998 ferry observations have been carried out in this tidal inlet, starting with the ferry *Schulpengat*, which was in service until 2004 and subsequently with the successor ferry *Dr Wagenmaker*. The ferries service the link between the mainland and the island of Texel, making 32 crossings of about 4.5 km each day. A suite of sensors installed in a through-flow system measures water temperature, salinity, fluorescence. For importance of this study is the hull-mounted downward-looking acoustic Doppler current profiler, henceforth referred to as ADCP, which measures three-dimensional velocity profiles. The instrumentation and dataprocessing is described in detail in Ridderinkhof et al. (2002).

The measurement principle of the ADCP is based on acoustic reflection by suspended particles. Therefore, in principle, it should be possible to relate the intensity of the acoustic backscatter to the concentration of the suspended particles. In combination with current velocities, this would provide a unique data set on suspended sediment transport through a tidal inlet. Several researches have tried to exploit the ADCP backscatter intensity to infer suspended sediment concentrations with varying degrees of success (Holdaway et al., 1999). A good review discussing the methodology is given by Thorne and Hanes (2002). Observational data presented in this paper show that the theory as described by Thorne and Hanes overestimates the suspended sediment concentration by orders of magnitude if the current is sufficiently turbulent. A physical explanation for this observation is given and the theoretical model is extended to include this effect.

ii. Field observations

For calibrating the method outlined by Thorne and Hanes, we carried out several 13-h measurement campaigns near the ferry transect, indicated by the star in Figure B-2.1. Each campaign consisted of measuring suspended sediment concentration profiles with 20-minute intervals using an optical backscatter (OBS) mounted to a CTD frame. The OBS was calibrated with water samples taken from three different depth levels concurrently with the CTD casts. Concurrently, a downward-looking Nortek 1 MHz ADCP collected velocity profiles with a vertical resolution (bin size) of 1 m. The ADCP recorded profiles of velocity vectors in three dimensions as well as acoustic backscatter intensities. Due to the divergence of the acoustic beams and the attenuation of acoustic energy due to water (and to some extent sediment), the acoustic backscatter intensity for a given bin depends on the distance from the ADCP device. Herein, the acoustic backscatter intensity, when corrected for these effects, is referred to as echo intensity, *EI*. For the mathematical formulation of this correction procedure, the reader is referred to Thorne and Hanes (2002) or Merckelbach (2006).

The model described by Thorne and Hanes (2002) assumes the backscattered signal to be an ensemble of backscattered signals with random phases. The mathematical formulation of the random phase backscatter model boils down to

$$EI = K_i \cdot 10\log_{10}\left(c/\rho_s\right), \tag{1}$$

where *EI* is the echo intensity (in dB), c the sediment concentration, ϱ_s the density of solids, and K_i a coefficient of proportionality. Figure B-2.2 shows a scatter plot of the logarithm of the suspended sediment concentration, derived from OBS, and the echo intensity, expressed in dB. According to (1) this should result in a (more or less) linear relation. It is seen that *i)* only a part of the data conforms to this linear relationship, and *ii)* the deviating data are consistently biased towards high echo intensities.

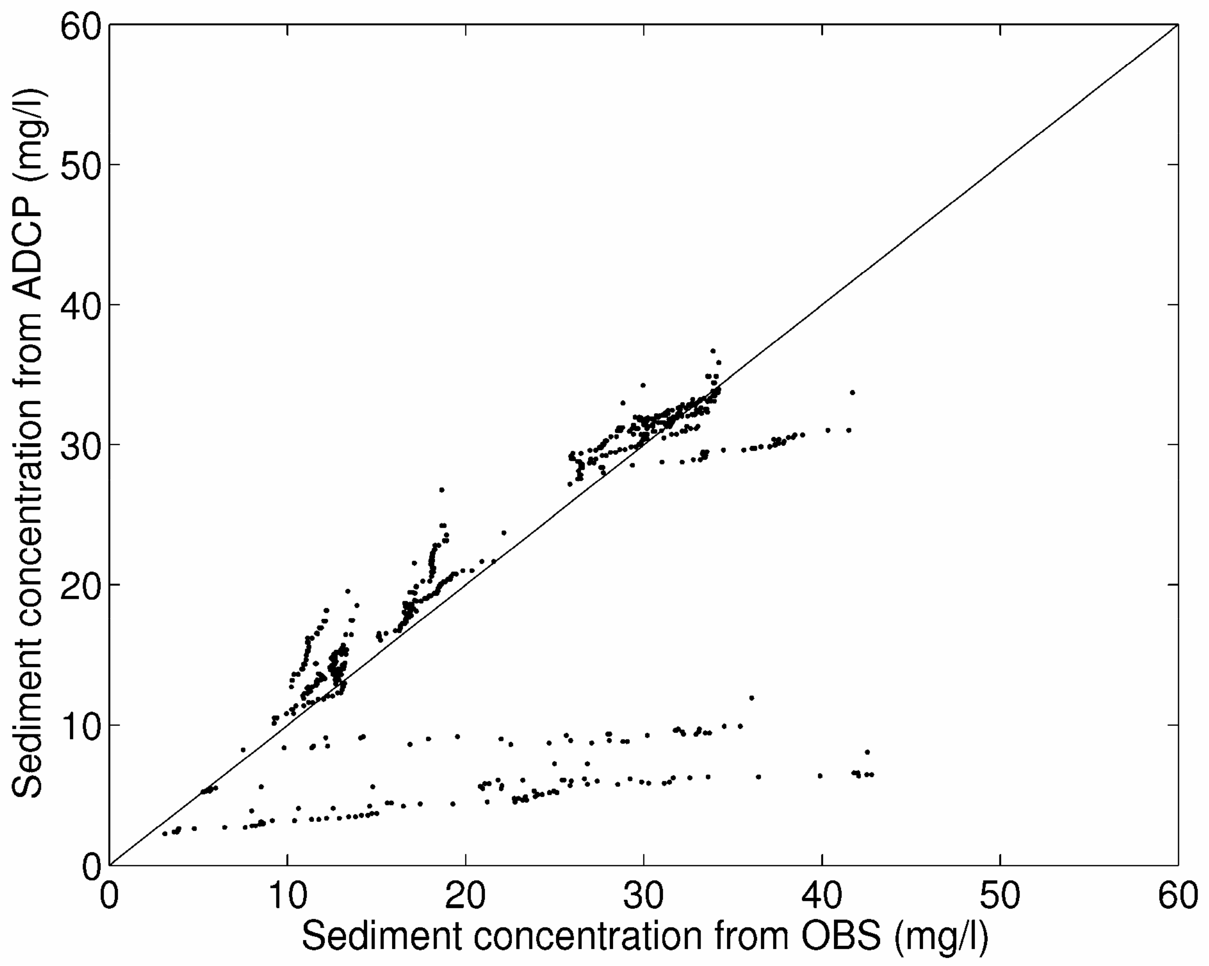

Fig. B-2.2: *OBS derived suspended sediment concentration against echo intensity.*

This means that if echo intensities were to be used to infer suspended sediment concentration, a significant part of the suspended sediment concentration data would be overestimated by at least one or two orders of magnitude. Figure B-2.3 shows measured and modelled suspended sediment concentrations using (1), at 17 m below the water level for data from the measurement campaign AS27 (5 November, 2003).

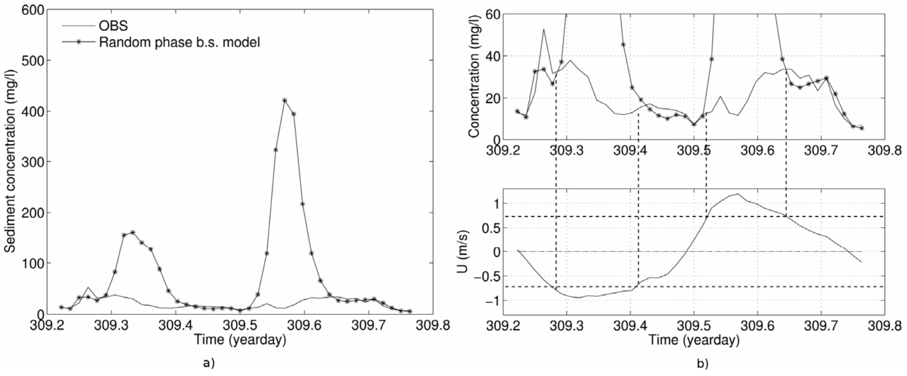

Fig. B-2.3: *Panel (a) shows measured and modeled suspended sediment concentration based on random phase backscatter at 17 m below sea level. Panel b) shows the modeled and measured concentrations clipped at 50 mg/l and the corresponding depth-averaged current velocity.*

The model is seen to overestimate during two phases of the (semidiurnal) tide (panel a), namely where the depth averaged velocity U exceeds 0.7 $m.s^{-1}$ (panel b). This observation is consistent with the observations from other measurement campaigns.

Acoustic backscatter due to turbulence

The mechanism that is proposed to explain this discrepancy accounts for enhanced acoustic backscatter intensity due to the ensemble of backscattered signals to be composed of signals with phases that are not entirely random. Figure B-2.4 explains this schematically. Incoming acoustic waves, represented by the dashed horizontal lines, travel from top to bottom. Particles within a bin, indicated by dots inside gray trapeziums cause the incoming waves to be reflected. Backscatter waves, resulting from the incoming wave drawn by the solid line, travel bottom to top.

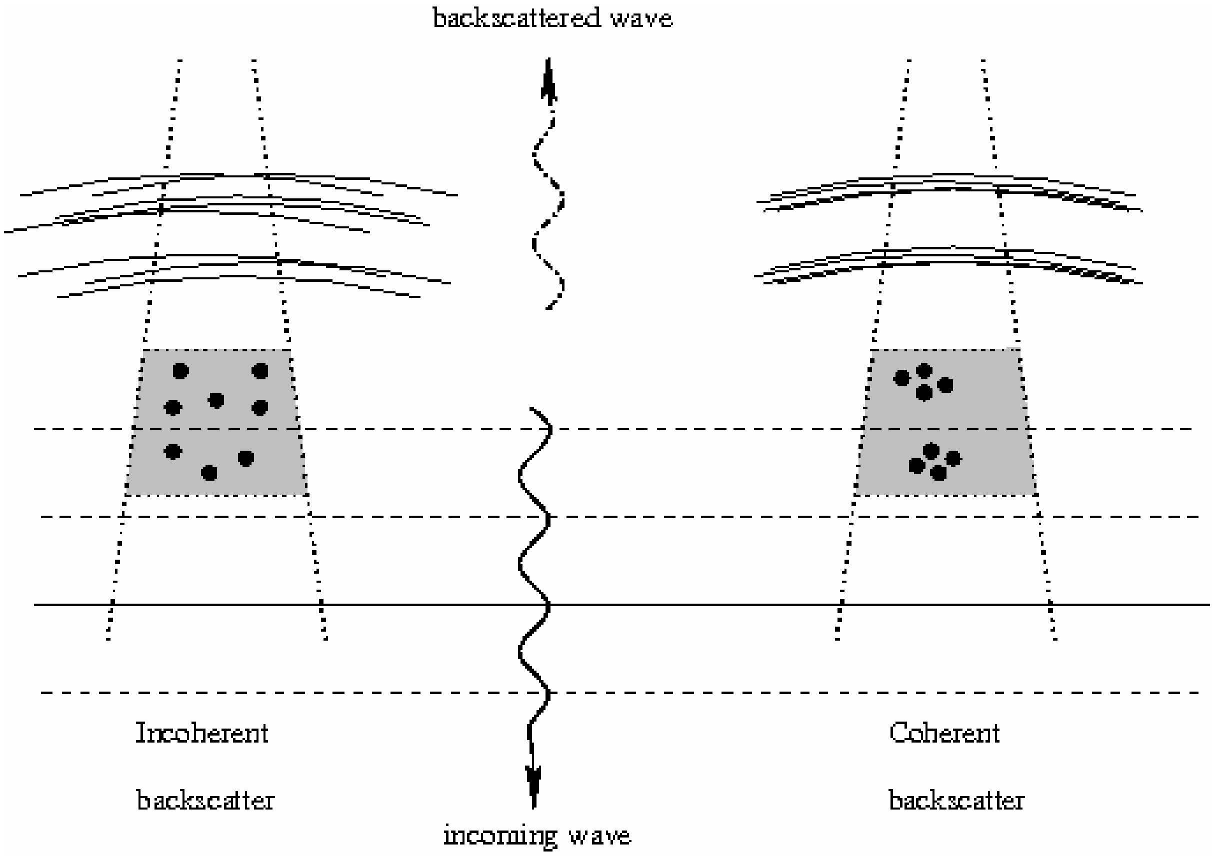

Fig. B-2.4: Schematic representation of incoherent and coherent backscatter. See text for explanation.

On the left, the scattering particles randomly positioned, causing backscattered signals to have random phases, or to be incoherent. On the right, particles are grouped in space. The resulting backscattered signals are not random any more and have (to some extent) coherent phases. In the case of incoherent signals, some signals are counter-phased and cancel each other, but not so in the case of coherent backscatter. Therefore the ensemble intensity of a given number of scatterers in a bin is stronger if the backscatter is coherent. This effect is most efficient for particles that are equally spaced (in the direction of the acoustic wave) at a distance of half the acoustic wavelength, the Bragg wavelength λ_B. For a 1 MHz ADCP the Bragg wavelength is about 0.8 mm.

Turbulence provides a mechanism to cause scattering particles (sediment) to be non-randomly distributed within a bin. Consider a constant sediment concentration gradient. A turbulent eddy of a given scale will mix water parcels with different concentration, resulting in a fluctuation in sediment concentration, superimposed on the original constant gradient. The scale of the sediment fluctuation is then the same as the scale of the mixing eddy. Turbulent eddies can appear over a broad range of scales, as large as the dimensions of the flow (water depth, for example) down to centimeter or even millimeter scale, the Kolmogorov scale at which the energy is dissipated by viscosity. The stronger the flow, the smaller the Kolmogorov scale must be to be effective enough to dissipate the turbulent energy. Can the current in the Marsdiep be that strong that the Kolmogorov scale is smaller than the Bragg wavelength, so that turbulence causes sediment fluctuations at a scale equal to the Bragg wavelength? To answer that question, we can estimate the Kolmogorov length scale η by (Tennekes & Lumley, 1972)

$$\eta=\left(\frac{\nu^3}{\varepsilon}\right)^{1/4}, \tag{2}$$

where ν is the kinematic viscosity and ε the dissipation rate. The kinematic viscosity for water is about $1*10^{-6}$ m^2/s and the dissipation rate can be estimated from

$$\varepsilon=\frac{u_*^3}{h\kappa}, \tag{3}$$

where $u_* \approx 1/20U$, h the water depth (about 22 m) and $\kappa = 0.4$ (von Karman constant). From (2) and (3), and $U = 0.7$ $m.s^{-1}$ (see Fig. B-2.3) it follows that the Kolmogorov length scale is 0.7 mm, which is close to the Bragg wavelength of 0.8 mm. It is indeed plausible that in the Mardiep the Kolmogorov length scale becomes smaller than the Bragg wavelength if the depth-averaged current velocity exceeds 0.7 m/s.

iii. Model formulation and results

A rigorous mathematical derivation of an acoustic backscatter model for (sediment) particles to cause coherent backscatter is beyond the scope of this paper. Instead, the reader is referred to Merckelbach (2006). Here we suffice by sketching the line of thoughts.

In Merckelbach (2006) it is explained in detail how the echo intensity can be formulated in terms of the fluctuation spectrum of the scatterers (sediment particles), evaluated for the Bragg wavelength. This formulation allows for particles to be randomly distributed (white noise) as well as the distribution of particles to have fluctuations at particular wavelengths. Furthermore, as argued above, the turbulent range, or more precisely, the inertial subrange may extend to scales smaller than the Bragg wavelength for currents exceeding 0.7 $m.s^{-1}$. Drawing upon the analogy with salinity or temperature, we can formulate a theoretical spectrum of sediment concentration fluctuations. Assuming the theoretical spectrum is representative for the real spectrum, we arrive at a formulation for the coherent backscatter regime that is expressed in terms of the suspended sedimentation concentration gradient

$$EI=K_c\cdot 10\log_{10}\left(\rho_s^{-2}\left(\kappa z\frac{h-z}{h}\right)^{2/3}\left(\frac{dc}{dz}\right)^2\right), \tag{4}$$

where z is the vertical ordinate, taken positive in upward direction with the origin at the sea bed and K_c is a bulk coefficient accounting for all parameters not discussed herein. (see Merckelbach, 2006) for a break-down of Kc)

Summarizing the results so far, we have the incoherent backscatter regime (random phase) for $\eta < \lambda_B$, for which the suspended sediment concentration can be solved for directly from (1), and a coherent backscatter regime for $\eta \geq \lambda_B$, for which the suspended sediment concentration is given by the (first-order) differential equation (4). Solving for the sediment concentration from (4) requires exactly one boundary condition or integration constant.

In order to verify the model extension for the coherent backscatter regime with measurements, the boundary condition is provided by an independent OBS measurement near the surface (about 3 m below sea level, corresponding to the first usable acoustic bin). In this way, (4) defines the shape of the profile, whereas the OBS measurement pinpoints the profile. Fig. B-2.5 shows a scatter plot of OBS versus ADCP inferred suspended sediment concentration, limited to data of the coherent backscatter regime. The solid line represents the line of perfect agreement. Profiles are discernible as “strings” of points.

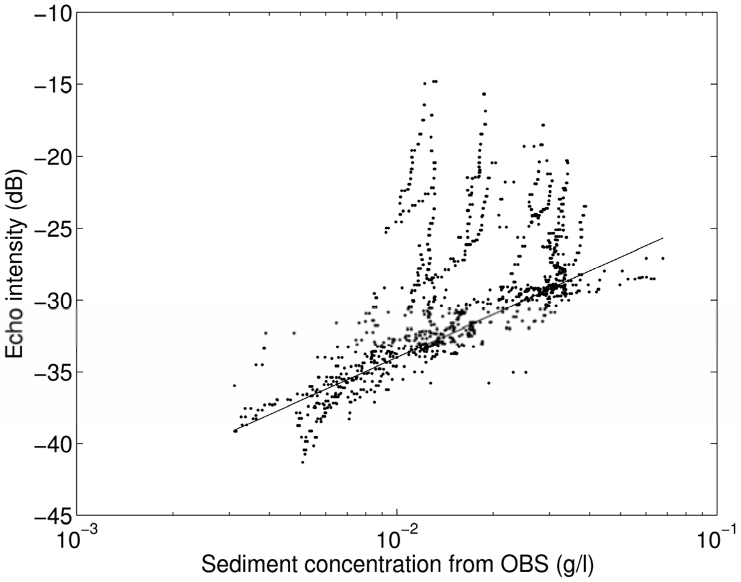

Fig. B-2.5: *ADCP estimated versus OBS derived sediment concentrations for the coherent backscatter regime only.*

As an OBS value is used as boundary condition, all profiles have their origin close to the solid line. The criterion is, however, to what extent the strings remain close or parallel to the line of perfect agreement. The results show that indeed most profiles remain within ± 5 mg.l^{-1} from the line of perfect agreement. Four profiles, appearing as two, clearly stick out by concentrations inferred from acoustic backscatter that are too low. In Merckelbach (2006) it is shown that these profiles are measured at the onset of the coherent backscatter regime, but would match well with OBS data if treated as incoherent backscatter. The most likely explanation for this is that turbulence needs time to develop when the current is quickly accelerating, but the estimate of the Kolmogorov length scale assumes steady-state conditions, or instant adjustment. Therefore the Kolmogorov length scale estimated for the onset of the coherent backscatter regime would be too small, resulting in the regime to be incorrectly identified as coherent backscatter.

iv. Disscusion and conclusions

Observational data presented herein clearly shows that if the depth-averaged current velocity exceeds a certain threshold value, the classical acoustic backscatter model as described by Thorne and Hanes (2002) fails to yield a reasonable estimate for the suspended sediment concentration. We have argued that this is caused by particles being rearranged in more organised distribution by the effects of turbulent stirring, so that the phases of the backscattered signals are not entirely random anymore, but show some degree of coherence. This in turn yields stronger backscatter intensity, in accordance with the observations.

Particle size may also play a role as for a given concentration, fewer, but larger particles cause stronger backscatter. Although we have not considered this hererin, it is conceivable that during stronger currents larger particles can be kept in suspension. However, evidence shown and analysed in Merckelbach (2006) shows no support for changing particle size distributions as explanation of the results observed. In fact, measured particle size distributions support the method described herein, if used to break down the fitting coefficients K_i and K_c (see Merckelbach, 2006) for details).

Nevertheless, unsolved issues remain. As argued before, solving (4) requires a boundary condition. Ideally this extra information is provided by an independent measurement, such as an OBS measurement somewhere in the water column, however, in practice such measurements are not always possible or available, as is the case with the ferry based measurements. Merckelbach (2006) proposes two methods as workarounds if no independent measurement is available. The first method assumes that the concentration profile can be represented by a Rouse profile. The second method is semi-empirical, in which the effect of coherent backscatter is included in (1) by a term proportional to $\log(c^2)$. Results show that the semi-empirical method outperforms the method based on the Rouse profile, but still falls short if a OBS measurement is used as boundary condition. To improve the applicability of the proposed model, and, indeed of ADCP derived suspended sediment concentration estimates in general, the boundary condition problem requires more investigation.

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3. Tide-Stratification Interaction in the Rhine ROFI Coastal Zone

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Abstract

The interaction between the semi-diurnal tide and the stratification field under the influence of the rotation of the Earth is investigated in the Dutch coastal zone. Our objective is achieved by adding powerful concepts to the Rhine region of freshwater influence (ROFI) body of literature.

First, upwelling, induced by tidal straining, was identified as a new key mechanism operating in the Rhine ROFI. The upwelling mechanism is detected using a 6-day unclouded series of KNMI NOAA-SST-imagery in May 1990 with about 2 images per tide. The ROFI is much warmer than the surrounding water, exhibits a distinct diurnal solar heating response and is clearly delineated by large spatial temperature gradients at the edges. This indicates that the whole ROFI area is stratified, an essential requirement for upwelling to occur. On three consecutive midday's a marked 5-10 km wide and 100 km alongshore band of cold upwelling water is visible along the coastline, while in the morning and afternoon this upwelling band is not present. The timing of this upwelling indicates that it is caused by tidal straining.

The existence of the upwelling mechanism was supported by simulations with the 3D numerical model of the idealized river plume. After adding temperature effects, the numerical model shows the same semi-diurnal band of cold upwelling water. We believe the presence of the 100 km long band shows for the first time the large spatial scale involved with the tidal straining mechanism of Simpson and Souza (1995) which was hitherto only observed in point observations.

In addition to the cross-shore tidal straining mechanism and the associated upwelling, the SST images also display a bulge of warmer water moving alongshore, independent of the cross shore straining. The movement of this bulge of warm water does not fit the cross-shore tidal straining paradigm. Therefore, a framework was subsequently developed that combines the observed tidal straining paradigm with the observed alongshore movements.

The well-known potential energy anomaly concept was for the first time applied with all terms. This forms the second simple, yet powerful contribution to meet our objectives.

i. Introduction

Artificial islands, harbor extensions and deepening of navigation channels, offshore sand mining, windmill parks, offshore gas extraction, disposal of dredged materials, illegal hull cleaning, marine nature reserves, fish quota and biodiversity. An almost endless list that shows that the seemingly wide and open North Sea is in fact a very versatile place. And fine sediments are right in the middle of it. Both physically – particles suspended by turbulence - and in terms of politics – by suspending laws. Sand extraction hoppers release small fractions fine sediments into the water causing unknown increases in turbidity levels. This potentially alters the light climate, impedes filter feeders, thereby possibly affecting the entire food chain. Furthermore, various pollutants are keen to attach to fine sediments, being released as harmful toxics into the water only decades later. The many unknowns concerning fine sediments made the Dutch Council of State delayed the mega-extension of the port of Rotterdam until more research was carried out.

Despite the large importance of fine sediments for the marine policy of the Dutch shelf and coast, there are still many unknowns. Even an essential figure as the net flux of fine sediments along the Dutch coast into the Wadden Sea is largely unknown today. The current estimates range from 1 to as much as 20 Megatons per year, with 1 Megaton being about a football stadium filled with mud.

The objective of this study is to gain a further understanding of the complex interactions governed by both tidal mixing and tidal straining on suspended particulate matter in the Dutch coastal zone.

Europe's largest river is in the coast

Unknown to many, Western Europe has a river carrying more water than the Mississippi. Official figures report the Rhine (2,500 $m^3.s^{-1}$) to be the biggest riverine flux of Western Europe. But, as soon as it debouches into the North Sea, it dilutes with 90 % seawater, yielding an increased volume flux of order 25,000 $m^3.s^{-1}$, ten times the Rhine flux and more then the Mississippi flux. This coastal river, river plume or Region Of Freshwater Influence (ROFI) in jargon, turns right after leaving the Dutch estuaries due to Earth rotation (Coriolis force) (Fig. B-3.1). The fresh water from the river is lighter than ambient North Sea water. This fresh water spreads pancake-like over the more salty ambient water, whereby all radial outward velocities are directed to the right and form half a cyclone structure. Where the cyclone hits the coast, the water is forced northwards, constituting a 10 to 30 km wide causeway for fine sediments northward. This flows along the European continent towards the tip of Denmark and beyond. The prevailing southwesterly winds and tidal asymmetry only add bit to this coastal river flux.

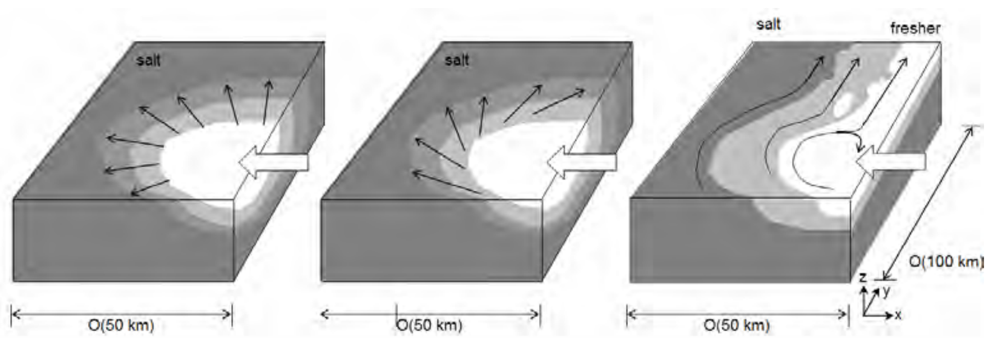

Fig. B-3.1: *Schematic of how a river flow (the Rhine) generates a large coastal river with the coast 'at its right hand' under the influence of Earth rotation. This coastal flow is the dominant mechanism for the transport of fine sediments, pollutants, algae, nutrients etc.*

The area between Hook of Holland and Texel was examined using an idealized numerical model, remote sensing images and theoretical models. Assessing fine sediment fluxes in this area requires knowledge of supply of sediments, of upstream sources, of availability on the bed, and of transport capacity of the flow. This study focused on investigating the coastal river, a main source of uncertainty.

The Rhine ROFI exhibits a bi-model state

Previous studies in the early nineties by by Simpson and co-workers in the EU projects PROFILE (http://www.pol.ac.uk/coin/profile1.html) and PROVESS http://www.pol.ac.uk/provess/) identified that the Rhine ROFI is governed by two time scales in the stratification signal. First, the dominant cross shore density gradients in the Rhine ROFI compete with tidal/wind mixing to establish stratification. During spring tide and/or storms the whole area is well-mixed, i.e. there are only horizontal differences in salinity and no vertical differences. In contrast, during neap tide and in absence of storms a 30 x 100 km^2 area is stratified, i.e. there are strong vertical differences in salinity. During the well-mixed conditions the tidal currents are rectilinear alongshore, whereas under the stratified conditions the tidal currents exhibit ellipses that rotate anti-cyclonically at the surface and cyclonically at the bottom, resulting in strong cross shore exchange flows. These interact with the dominant cross-shore density gradients through differential advection, a process referred to as tidal straining by Simpson et al. (1990), to generate a semi-diurnal cycle of stratification. This is the second time scale.

Stratification has a profound effect on vertical distribution of fines, algae, nutrients, temperature and velocity structure. Nevertheless, the onset of stratification at neap, as well as the behavior of the ROFI during such a neap tide is very complex and is not fully understood yet today, despite neap tides occurring nearly half the time.

ii. New: tidal up and downwelling during neap tide

The dominant physics during neap tides was discovered by Visser et al. (1994) and Simpson & Souza (1995) as a special case of Prandle's (1984) classic theory on the vertical profile of tidal flows. During periods of stratification the surface layer is physically decoupled from the bottom layer, allowing different velocity patterns in the surface and bottom. You can image them as two layers with slippery green soap between. During normal Kelvin wave conditions (spring tide) the tidal velocities are alongshore southward during the ebb, alongshore northward during flood and zero during the two slack tides (Kelvin wave). These patterns hold for the entire depth. However, during periods of stratification the velocities in the surface layer behave differently showing pronounced differences over depth. The surface layers starts to rotate clockwise under the effect of Earth rotation, unimpeded by friction with the bottom layer from which it is detached. This causes a counterclockwise rotation in the bottom layer (Fig. B-3.2). Due to the opposed surface and bottom velocities the cross-shore velocity differences (shear) arise over depth up to 50 cm.s^{-1}. These shears deform the salinity field in a process known as tidal straining (Fig. B-3.3). These cross shore velocity differences alternatingly advect the fresher surface layer offshore and onshore. This process, known as tidal straining, is the dominant process during neap tides.

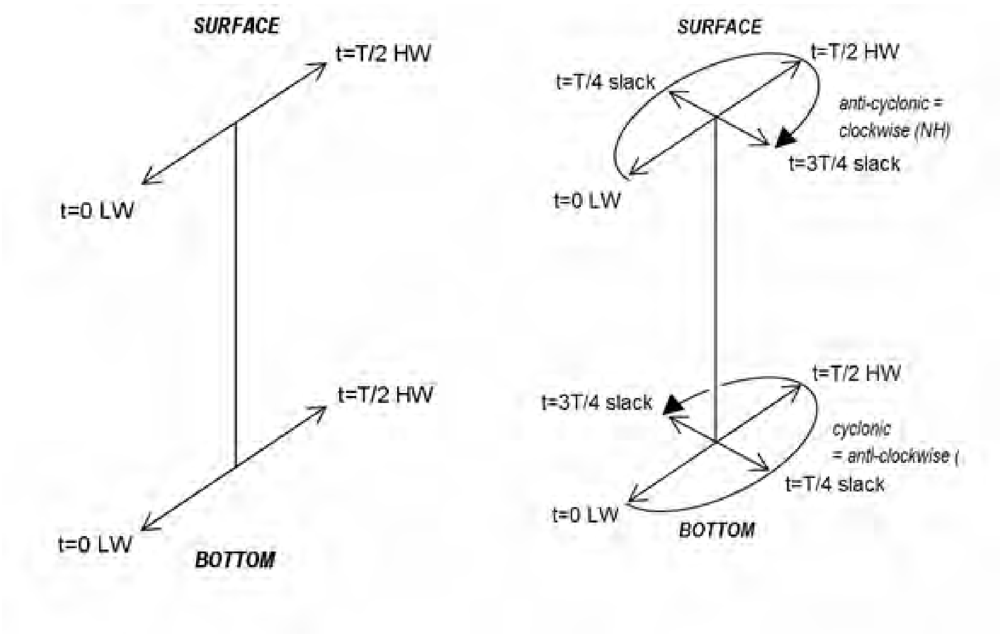

Fig. B-3.2: Sketch of velocity profiles during normal cases (left) and stratified neap cases (right) in the Dutch coastal zone.

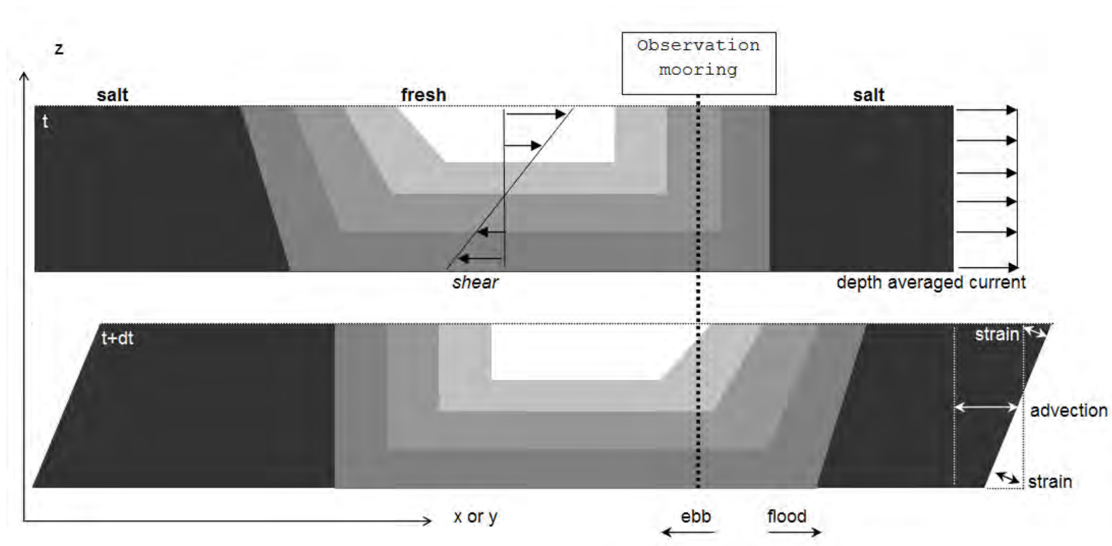

Fig. B-3.3: A sketch of the combined effects of tidal straining and advection. Tidal straining causes the deformation of a depth averaged horizontal density gradient by a velocity shear, whereas advection describes the displacement of a low salinity structure (implying a vertical variation of the horizontal density gradient) by the depth averaged current without deformation. At a fixed mooring an observed increase in stratification can thus be caused by both advection and straining, in either x or y direction. The two processes have opposite effects on the opposite sides of the Rhine ROFI.

In this study it was hypothesized that the known cross shore tidal straining process should theoretically lead to alternating up and downwelling near the coast. This cyclic upwelling pattern due to the tide was hitherto unknown. We corroborated its theoretical finding with remote sensing imagery and an idealized numerical model.

Remote sensing images could be used to detect the effects of tidal straining because the stratified areas in which this phenomenon occurs respond differently to solar heating than well-mixed waters. Solar radiation is adsorbed mostly in the surface layer, and is only subsequently mixed down into deeper layers. However, stratification inhibits mixing of warmer water into the bottom layer, leaving the heat in the surface layer. Therefore a stratified area shows a stronger increase in surface temperature than ambient well-mixed waters (Fig. B-3.4).

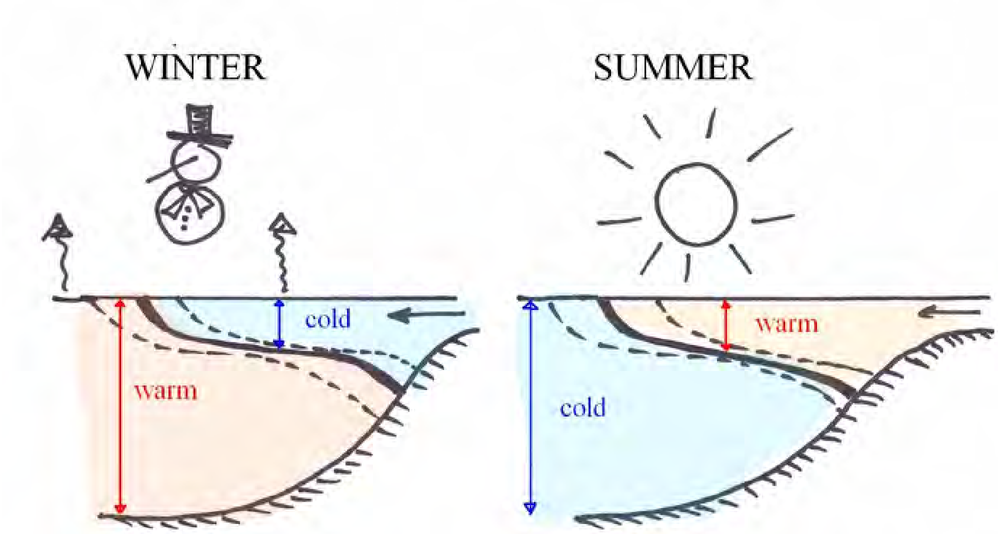

Fig. B-3.4: *Stratification by vertical gradients in salinity yields in summer a surface signature on the response to solar heating, and in winter time cooling.*

In May 1990 an excellent long series of Sea Surface Temperature images from NOAA-KNMI was available (Fig. B-3.5). Usually SST imagery have too low a temporal resolution to be able to detect tidal effects. But due the large number of unclouded images this series is a nice exception. The series of images shows the characteristic highlighting of the stratified area due to midday and afternoon solar heating, and cooling overnight. Remarkably, a 5 to 10 km wide band of cold water, with cold being the ambient temperature, appeared every high water, whereas at low water the band was very absent. The timing of the reappearing narrow band indicates this is due to the newly found tidal upwelling mechanism.

Next, a simple hydrodynamic model of a stratified Rhine plume was used to asses this assumption. In the model alternating up and downwelling was visible in the 3D velocity pattern, not possible with field measurements. After switching on atmospheric heat fluxes, the numerical plume shows the same characteristic SST response as observed in the remote sensing images. The presence of the narrow upwelling band in the model of the same area confirmed the presence of upwelling induced by tidal straining.

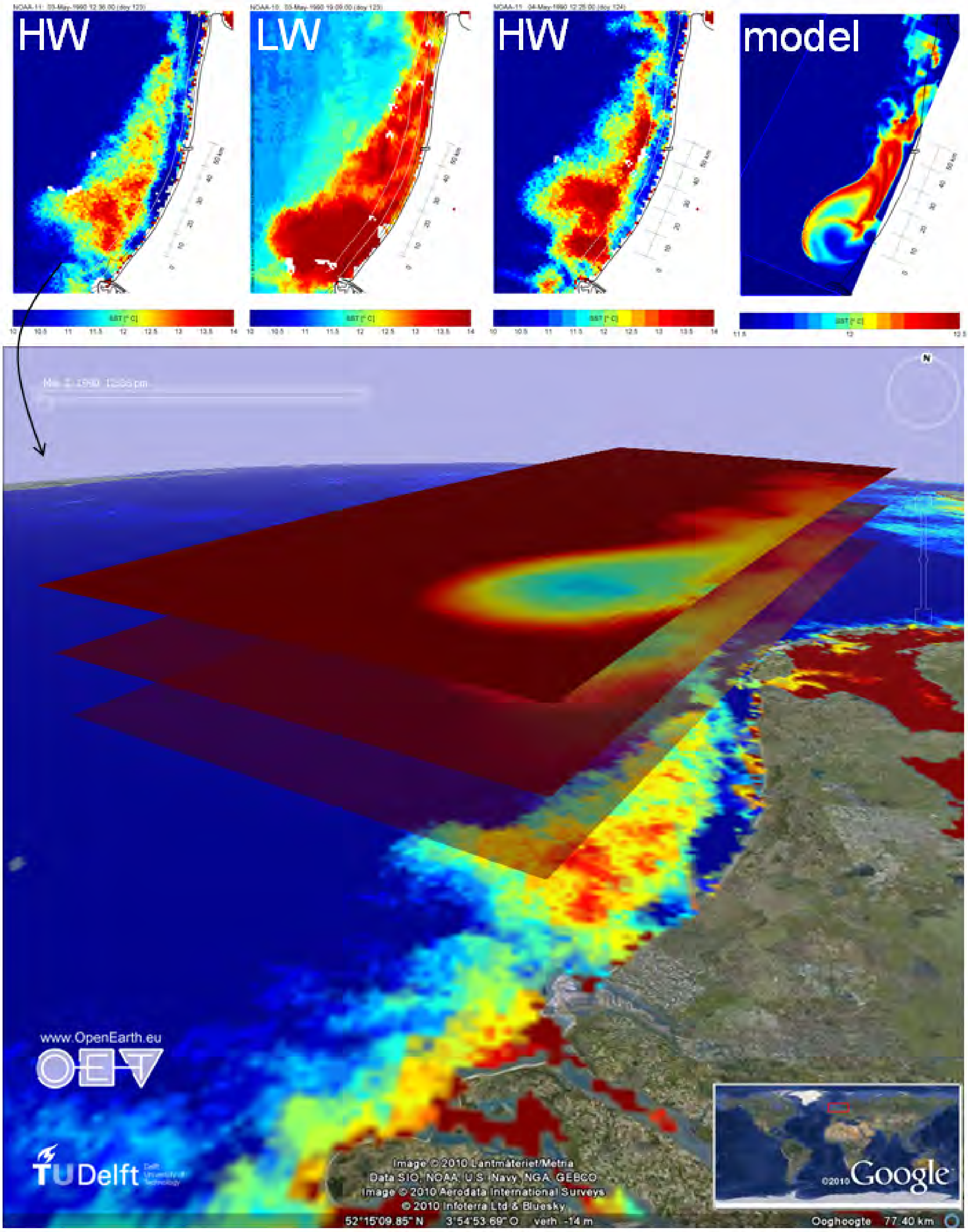

Fig. B-3.5: *Three subsequent KNMI NOAA SST satellites image of water surface temperature on May 3rd 1990 (blue=10°C, red=14°C). The 1st is high water, the 2nd is low water and the 3rd is the next high water, the 4th panel is the temperature calculated with an idealized numerical model at high water. The 1st satellite image is shown again in the Google EarthTM mapping service panel. The blue cold band along the Dutch coast is caused by upwelling induced by tidal straining. Overlaid in the Google Earth panel are results of the 3D salinity structure from an idealized numerical model of the water movement in this area (blue fresher, red ambient salinity). The newly discovered upwelling induced by tidal straining is caused by the dominant stratification during neap tides as represented by the blue shades in the 1st and 3rd panel.*

iii. New: capturing the essence of 4D data

In addition to the cross-shore tidal straining mechanism and the associated upwelling, the SST images also display a bulge of warmer water moving alongshore, independent of the cross shore straining. The movement of this bulge does not fit the cross-shore tidal straining paradigm. Therefore, a framework was subsequently developed that combines the observed tidal straining paradigm with the observed alongshore movements. This forms the second simple, yet powerful contribution to meet our objectives.

For this framework the full potential energy anomaly equation suitable for the analysis of 3D numerical models is first derived. The ten terms that dominate the evolution of stratification in the Rhine ROFI are selected. These principal terms are the cross-shore and alongshore straining and cross-shore and along shore advection of horizontal density gradients. In addition, non-linear shear dispersion terms representing correlations between density and velocity perturbations over the vertical control horizontal exchange in the cross-shore and alongshore directions. Moreover, in the vertical direction one term describes the effect of vertical mixing on the density profile, while the other term is related to vertical advection, which we refer to elsewhere as upwelling and downwelling.

These ten terms are examined using the neap tide simulation of the Rhine ROFI that was used to analyze tidal upwelling before. Analysis of the model results using the potential energy anomaly equation allows us to present a detailed overview of the spatial distribution of the terms affecting the evolution of stratification. The results corroborate the important role that cross-shore tidal straining is known to play in the downstream coastal current region of the plume. In addition, the roles of alongshore advection, as well as alongshore and cross-shore straining are also of importance in the Rhine ROFI, in particular in the region of the bulge near the river mouth (Fig. B-3.6). The term ASIPS (advection and strain induced periodic stratification) is introduced in order to identify the joint action of these terms. ASIPS is shown to be a natural extension of the SIPS concept introduced by Simpson et al. (1990), but also forms the key subset of the terms in the potential energy anomaly approach. Near the edges of the river plume shear dispersion and upwelling and downwelling terms also play a significant role, indicating that a different physical balance is dominant than in the ROFI interior. Additionally, near the river mouth advection of fresh water lenses plays an important role. The results for the Rhine ROFI show that the potential energy anomaly equation and ASIPS constitute powerful tools to analyse the mechanisms contributing to mixing and stratification in coastal seas and estuaries.

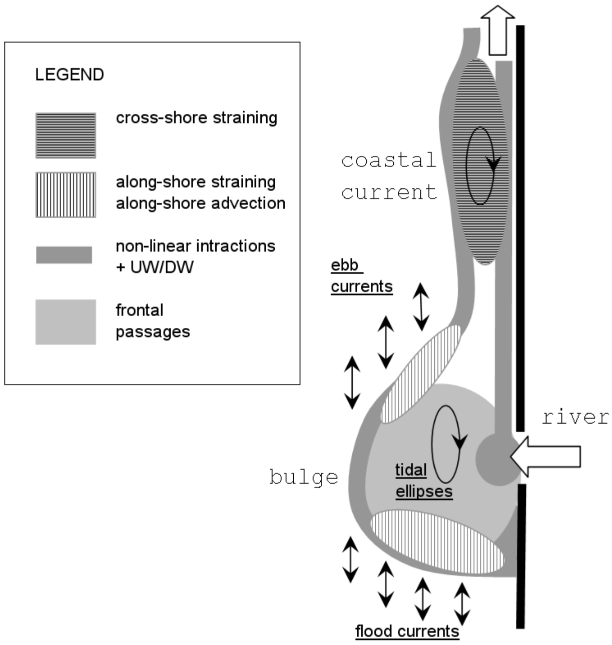

Fig. B-3.6: A sketch summarising the dominant terms controlling stratification and mixing within the Rhine ROFI.

In combination with temporal correlation analysis, the full potential energy anomaly equation allows for powerful aggregation of the plethora of 4D (x,y,z,t) data into manageable a 2D (x,y) bulk parameter fields. As the numerical models gain finer resolution nowadays in both space and time, the PEA method to obtain data reduction proved a very useful tool.

iv. Conclusions

In this LOICZ study two new concepts were found. First, upwelling induced by tidal straining was discovered to play a major role in the dynamic distribution of fresh water masses in the Rhine ROFI. Second, the full potential energy anomaly analysis was elaborated upon and proved an essential tool to aggregate 4D model outputs. Both new concepts led to a better understanding of the complex hydrodynamics required to assess suspended fine sediment transport into the Wadden Sea.

The main limitations for proper and further assessment of the fine sediment flux is the scarcity of in situ data in our opinion. Our main recommendation is therefore to aim for and organize an operational coastal observatory of the Dutch coastal zone, after the successful launch of similar coastal observatories in for instance Liverpool bay (UK) and the German Bight.

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4. Mechanisms involved in salt-marsh rejuvenation

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Abstract

Under favourable environmental conditions, such as benign hydrodynamics, a certain base elevation, and sufficient silt availability, the capacity of Spartina anglica to alter the environment is crucial to set off rapid marsh formation. This small-scale 'ecosystem engineering' of Spartina induces several other processes, sometimes with large-scale consequences. First, by reducing current velocities and capturing sediment Spartina stimulates its growth locally. This may result in erosion along the tussocks edges with strong current velocities, which inhibits lateral growth. Plus, the presence of thresholds is induced, implying that with sufficient biomass feedbacks enable Spartina settlement, while settlement is not possible under similar conditions with low biomass. This induces non-linear response of marsh ecosystems to changing environmental conditions, which complicates predicting the exact response to external changes.

On the scale of a complete marsh, on barrier islands sedimentation is mostly driven by the slope of the pre-marsh sand surface. During marsh growth independent, nested patterns develop superimposed on this gradient. Spatial patterning was also found in the occurrence of sand layers within the salt-marsh sediment. These indicate that salt marshes may develop under rougher conditions than previously thought, and that the contribution of washover sediment to an established salt marsh is smaller that expected.

Further we tested the applicability of natural γ-radiation of sediment for salt-marsh research. Identifying sources and sinks of sediment in relation to salt-marsh rejuvenation was not possible with the radiometric and corer methods, partly because the radiometric fingerprint of the fine-grained sediment seems to be homogeneous within the Dutch Wadden Sea. Measuring salt-marsh accretion with the radiometric method was only possible to a certain extent, but the method was successful in mapping grain-size variations on the intertidal flats adjacent to the salt marsh.

i. Problem

Organisms changing their environment, also called ecosystem engineering, can be a potentially important process in structuring salt-marsh pioneer zones. To obtain a better insight in the formation of salt marshes on barrier islands, sedimentation processes on larger time and spatial scales were examined. Based on these results and those from the large database of soil cores, we addressed questions related to salt-marsh development. This concerns environmental conditions, sediment type and quantity, sediment sources and spatial and temporal patterns.

ii. Aim

In this project, we examined this hypothesis by studying the consequences of ecosystem engineering by the common cordgrass Spartina anglica, on species interactions, ecosystem dynamics, and spatial structure. Our aims were twofold: first, we tried to explain the patchy distribution of Spartina anglica in salt-marsh pioneer zones, and to provide insight in how ecosystem engineering affects the dynamics of this zone. Second, we generalized these findings for developing a more common knowledge of implications of ecosystem engineering on species, community, ecosystem and landscape scales.

This was done through spatial characterization of salt-marsh sediment, using a combination of established (soil corer) and new (γ-radiation) measurement techniques (www.medusa-online.com). The use of natural γ-radiation for the spatial characterization of salt-marsh sediment was evaluated through the following questions: are there variations in γ-radiation at and around the salt marsh? If yes, what are these variations related to? Does the application of the method have advantages over already established methods?

iii. Results

Ecosystem engineering in the pioneer zone

Heterogeneity in the form of strongly contrasting patches of vegetation on bare intertidal flats is considered an indicator for the presence of thresholds and alternative stable states (Fig. B-4.1a). In salt-marsh pioneer zones, ecosystem engineering by Spartina anglica, resulting in a positive feedback (Fig. B-4.1b), induces a threshold in vegetation response to environmental conditions. The presence of thresholds enables Spartina patches to persist, while existing conditions do not support the establishment of Spartina seedlings on bare sediment, suggesting the presence of alternative stable states.

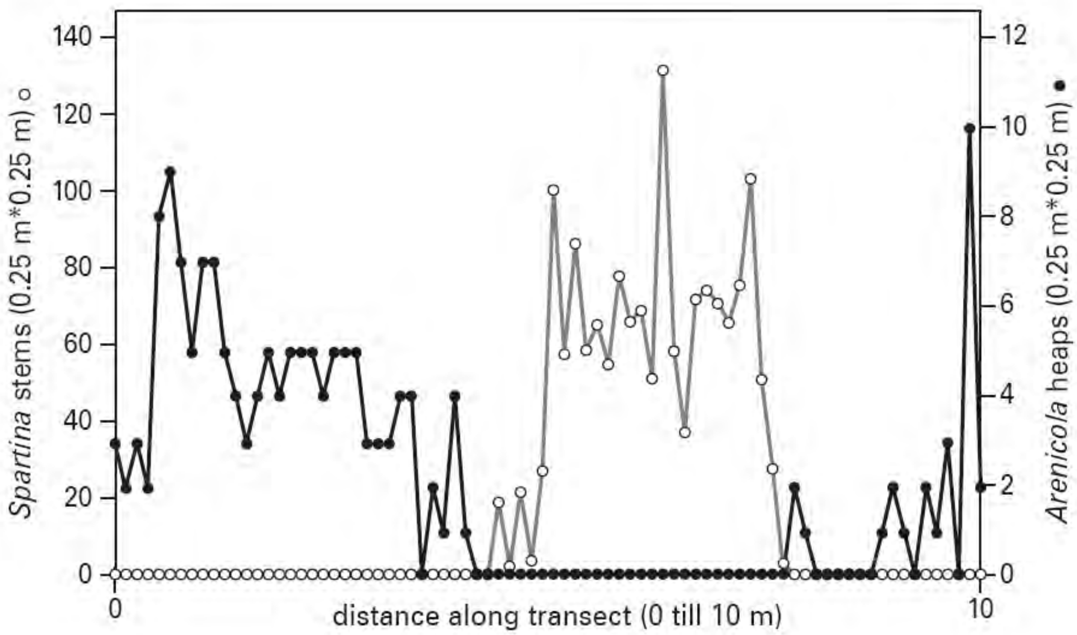

Fig. B-4.1: *Schematic representation of expected processes, induced by ecosystem engineering, that play a role in structuring salt-marsh pioneer zones, such as A. Decrease and increase of current velocities, B. Mutual exclusion by changing sediment properties (stabilization and destabilization), C. Biomass thresholds and shifts.*

Although our experiments confirmed the presence of alternative stable states on local, within-patch scales, a study of long-term vegetation development did not support the idea of alternative stable states, as patches were found to extend and contract simultaneously on longer time scales (Fig. B-4.2).

Recruitment of Spartina by seedlings does not happen easily in natural systems.

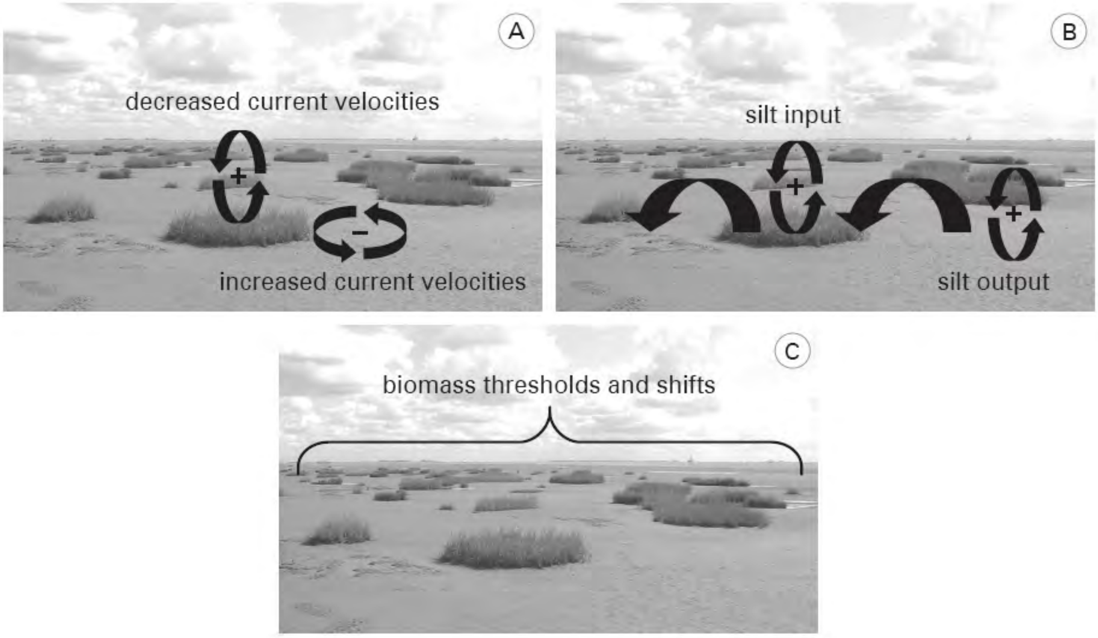

Fig. B-4.2: Example of one transect showing Spartina anglica (open symbols) and Arenicola marina (closed symbols) distribution over an intertidal flat with salt-marsh pioneer vegetation in Krabbekreek, Oosterschelde. In general, the species did not co-occur in the same patch (n = 866, P < 0.0001).

Processes of recruitment were demonstrated to be very episodic, implying that in some years massive recruitment events take place, while in other years seedlings are almost absent. From the established seedlings few are able to survive. Especially in areas that are occupied by the lugworm Arenicola marina, seedling survival is low. From our transplanting experiments, where we transplanted different sizes of Spartina (seedlings, 1-2 stems and 20 stems), it became clear that in many areas with Spartina tussocks settlement by seedlings on bare sediment was unsuccessful. Transplanted higher biomasses of Spartina, small plugs of about 20 stems, almost always survived. These results underline that the presence of Spartina tussocks in salt-marsh pioneer zones does not indicate the potential of Spartina to settle by seedlings. This implies that thresholds for Spartina disappearance and settlement are present. In many intertidal landscapes, patches of Spartina anglica are found to alternate with open areas dominated by the lugworm Arenicola marina (Fig. B-4.3).

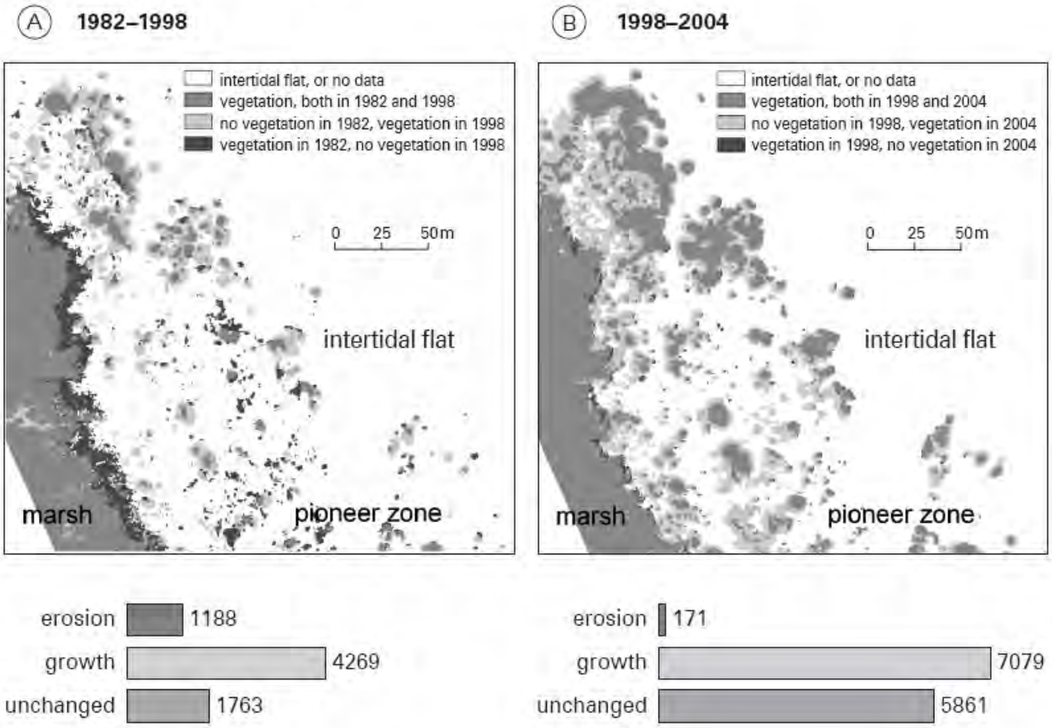

***Fig. B-4.3:** Growth and erosion of Spartina tussocks in a salt-marsh pioneer zone of Paulinapolder, Westerschelde. The picture shows vegetation that had been present between an interval (dark grey), vegetation that has developed in the period (light grey) and vegetation that had eroded in this interval (black). Figure A shows the interval from 1982 – 1998 and Figure B from 1998 – 2004. Bars and numbers underneath the panels show the exact area of vegetation (m²) in the pioneer zone that has been eroding or growing in both periods.*

Strikingly, both species are hardly ever found together in the same patch, suggesting a negative interaction between them. Our research revealed that both species transform sediment properties in opposite ways, in the patches that they occupy: Spartina increases the accumulation of silt, while Arenicola maintains more sandy sediment by increasing silt transport out of the system. This way, both species negatively affect the persistence of the other species. These negative interactions by ecosystem engineering emerged as an important structuring mechanism explaining the patchy occurrence of these species.

Ecological theory emphasizes facilitation as an important structuring interaction in stressful environment. However, the research in this project reveals that negative interactions by ecosystem engineering can play an equally important role under stressful conditions. If ecosystem engineering effects are counteracted by an organism exhibiting an opposite feedback with environmental properties, they can possibly explain patchiness in ecosystems.

Next to problems with settlement, Spartina also experiences problems with expansion. Inside vegetation feedbacks were positive implying that current velocities were reduced and sedimentation increased. This resulted in a negative feedback at the borders of tussocks where increased current velocities enhanced erosion and gully formation, retarding vegetation development (Fig. B-4.1c). These gullies will form the template for future creeks in high marshes. This study demonstrates that intraspecific effects of the engineer on the environment vary with scale.

Both intraspecific and interspecific consequences of engineering are likely to depend on the environmental context as well. Flume studies showed that effects of Spartina on sedimentation and erosion became more pronounced with high current velocities and were almost absent with low water currents. This implicates that intraspecific engineering effects of a species on the environment subside with decreasing stress, confirming the idea that engineering is more important with high stress conditions. Interestingly, this suggests that engineering effects of a species on the environment may not exist in the absence of stress. Further, the presence of thresholds and non-linear response implies that salt marshes may still show sudden state changes, despite the absence of alternative stable states.

Development of the salt marsh

Measurements of γ-radiation, done both in-situ and on sediment samples revealed that there are spatial variations in natural γ-radiation at and around the salt marsh. These variations are mainly related to the grain size of the sediment: fine-grained salt-marsh sediment (e.g., silt and clay) can be radiometrically distinguished from sand from the intertidal flats and dunes. These variations are however obscured by variations in the water content of the sediments. We developed a method to correct for this, which works well for situations that have vertically homogeneous and known water contents.

The radiometric method is in principle capable of distinguishing between the fine-grained sediment that constitutes the salt-marsh deposits and the underlying sand. On the salt marsh, it was possible to use in-situ γ-radiation for reproducing the general trend in top-layer thickness, as measured from soil cores, within a factor two to four. Better agreement was not possible as natural variations in water content and sediment composition affect the measured signal too strongly. Although the uncertainty in the soil-corer (manual) method turned out to be somewhat larger than expected (1–2 cm instead of 1 cm), the uncertainties in the radiometric method are still too large to compete with the traditional soil coring. Therefore, the radiometric method is not suited for measuring accretion rates on the scale of months to a few years, as required for quantifying marsh sedimentation. The method is most suited for quick-scans (e.g. from an airplane if flying low), producing qualitative maps of top-layer thickness in potentially less time than with soil cores. In contrast, the radiometric method was successful in – at least qualitatively – reproducing known patterns of grain-size distribution on the intertidal flats, with higher spatial resolution than existing maps and much less sampling effort (Fig. B-4.4).

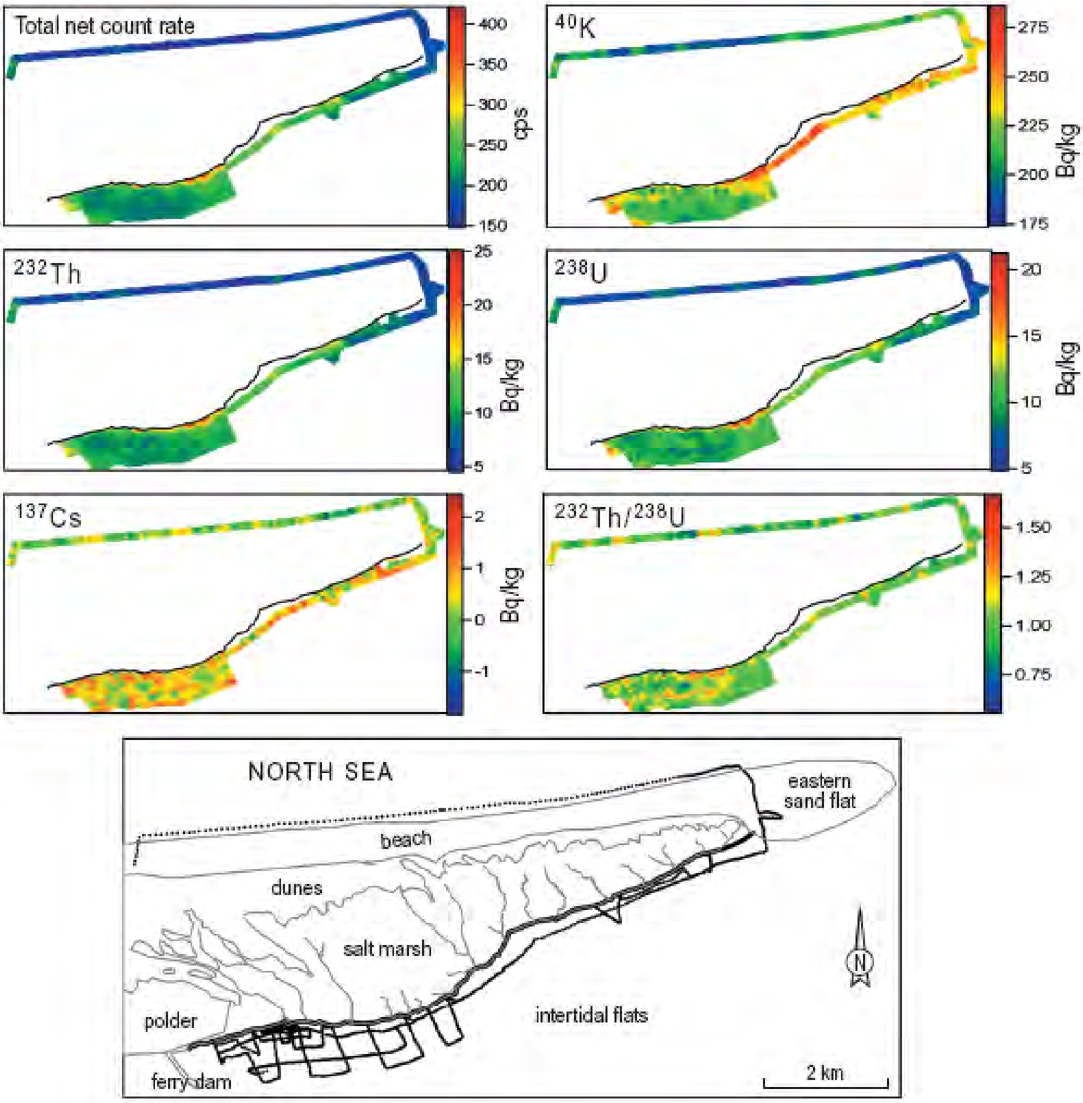

Fig. B-4.4: *Radionuclide activity concentrations on part of the intertidal flats and beach of Schiermonnikoog measured in situ with the PANDORA detector. Higher values indicate a larger contribution of fine-grained sediment. The thick solid line indicates the transition between intertidal flats and salt marsh at the time of measurements. Data points (dots) are given in the lower panel, together with the topography of the area.*

Traditional soil cores demonstrated that the environmental conditions during salt-marsh formation vary spatially within a marsh. Part of the marsh develops under calm conditions and part under conditions rough enough for the transport of sand. The spatial distribution of the conditions is related to the slope of the underlying sand surface, in combination with the presence of dunes or artificial sand dikes that provide shelter from overwash and aeolian activity from the direction of the open sea.

As the marsh evolves, the layer of marsh deposits increases in thickness and forms spatial patterns that change in size and structure through time. There are at least three hierarchical levels in these spatial patterns, indicating that controls on sedimentation act on all spatial scales (Fig. B-4.5).

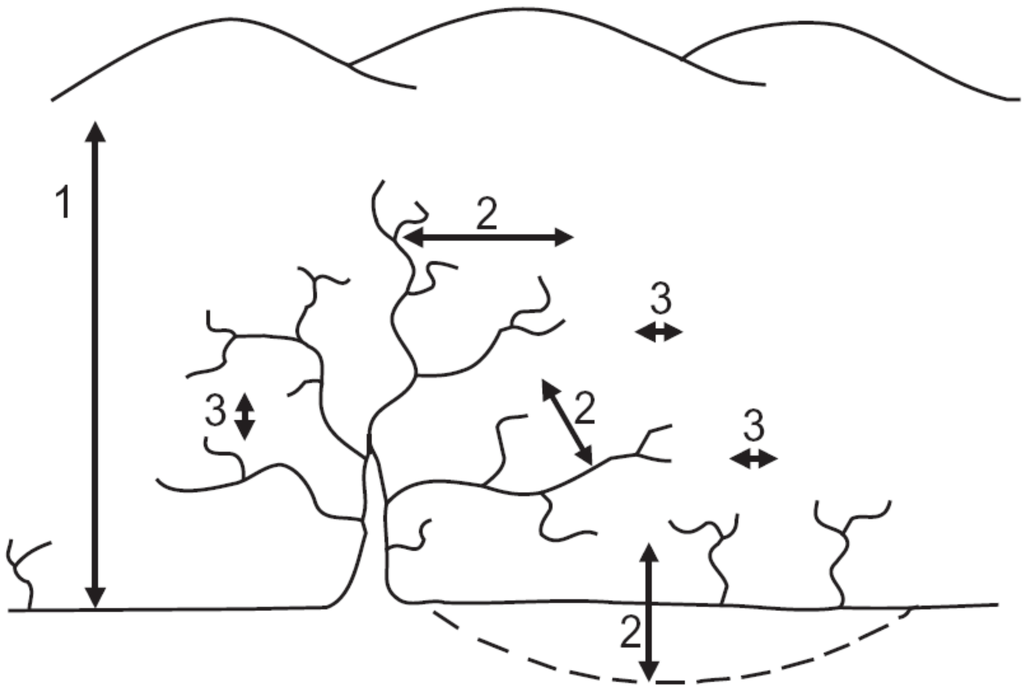

Fig. B-4.5: *Schematic overview of the hierarchical spatial scales in salt-marsh accretion and their forcings. Number 1 represents the gradient in base elevation from the dunes to the intertidal flats; numbers 2 represent the distance to the nearest sediment source, influenced by creek development and he lateral marsh growth; numbers 3 give the local influence of e.g. the vegetation.*

On the largest scale (number 1 in Fig. B-4.5), the elevation of the underlying sand surface is the initial control on inundation frequency and duration, setting the potential for future sedimentation. Its influence decreases during marsh development, when independent accretion patterns develop. The independent patterns are most probably created by the ongoing creek development, including levee development, and lateral marsh growth, (numbers 2 in Fig. B-4.5).

Both processes affect the distance of a certain location on the marsh to the nearest sediment source, which is the second important control on marsh accretion. Finally, on the local scale (number 3 in Fig. B-4.5), vegetation may create irregularities on the marsh surface and lead to variations in current velocity.

Spatial patterning is observed, too, in sand layers that occur within the salt-marsh deposits. They are the result of severe storms, during which waves and currents may take up sand from the intertidal flats and creek bed and deposit it on the marsh surface, within a limited distance from the salt-marsh edge and creeks. Additionally, water from the open sea may breach though the dunes and deposit sand eroded from the beach and dunes. Sand from dunes or areas left bare by overwash may subsequently be taken up by the wind and deposited on the marsh. The sand layers were dated using the known ages of the salt marsh. The occurrence of sand-depositing storms on Schiermonnikoog has been approximately decadal, although an increase in sand deposition and extreme tide levels were observed in the past few decades. This may be related to the overall increase in high-tide levels in the Dutch Wadden Sea.

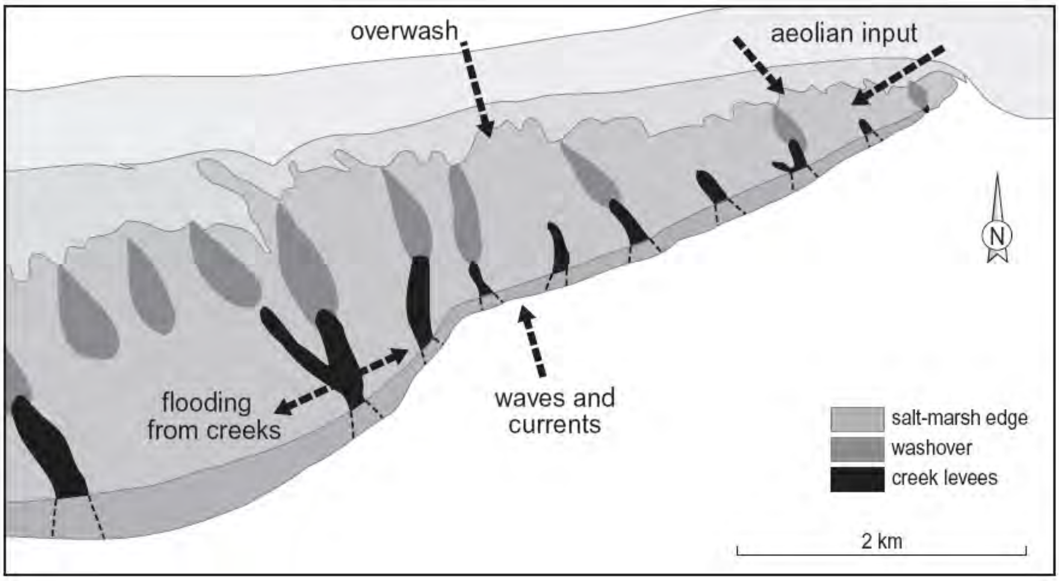

Fig. B-4.6: *Schematically representation of dominant sand deposits on the salt marsh of Schiermonnikoog, based on measurement results.*

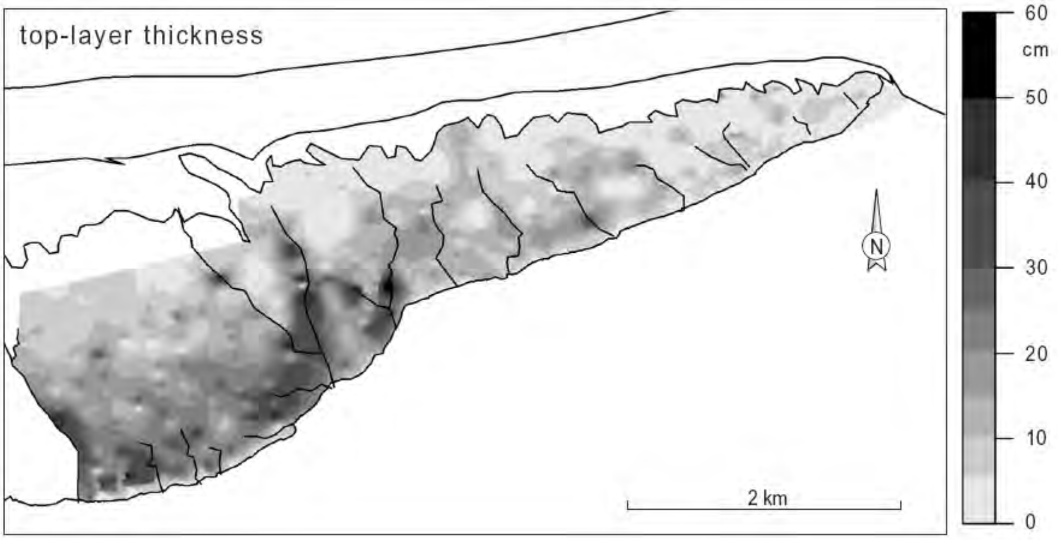

Fig. B-4.7: *Upper panel: map of top-layer thickness on the salt marsh on Schiermonnikoog, interpolated using kriging. Lower panel: standard deviations of the interpolated values. Dots represent measurement locations.*

The locations with most sand layers (Fig. B-4.6) resemble those where top-layer thickness is generally largest (Fig. B-4.7): along the salt-marsh edge and creek levees. The patterns for both types of sediment reflect the proximity to the sources of sand, wind and water. The sand layers were mostly deposited at the time a certain marsh area was relatively young. This indicates that, again in analogy with the fine-grained sediment, ongoing creek development, lateral marsh growth and further dune building affect the accessibility of the marsh to sand, wind and water, and thus affect the depositional patterns.

iv. Conclusions

Pioneer zone

In many cases the positive feedback between Spartina and sedimentation forms the basis for salt-marsh formation. Under ideal conditions, Spartina can rapidly invade a bare intertidal flat and form a homogeneous vegetation cover. Capturing of fine-grained sediment by Spartina stands, raises soil elevation and makes the habitat suitable for invasion of other salt-marsh plants. However, many salt marshes in the Netherlands are eroding and Spartina, if present at all, is found in scattered patches on the intertidal flat. Several processes that are spin-offs of ecosystem engineering on local scales, can limit expansion of present Spartina tussocks and prevent recruitment of new seedlings.

First, ecosystem engineering can induce positive feedbacks on local, within-patch scales, with resultant negative feedbacks on larger, between-patch scales. These feedbacks can limit tussock expansion and, consequently, give rise to more complex structures on ecosystem or landscape scales. Furthermore, ecosystem engineering can be a mechanism for negative species interactions, resulting in exclusion and patchy species distributions in ecosystems. Further, habitat modification is found to give rise to thresholds in ecosystems, resulting in unpredictable and irreversible ecosystem changes in response to environmental change. Finally, ecosystem engineering can generate the development of strong contrasting habitats along gradients of stress. For all these effects it should be kept in mind though that they vary considerably depending on environmental background conditions and spatial scale.

Salt marsh

Most of the findings were based on measurements from Schiermonnikoog, which is a long-term study site for salt-marsh ecology and was therefore the first choice for conducting field research. The surveys involving soil cores on Terschelling and Skallingen show that, on the investigated high and middle marsh (sub-catchment scale), the general pattern is comparable. There are only small differences between the islands in past environmental conditions as identified from the sediment record and spatial patterns in accretion. The relation between top-layer thickness and in-situ γ-radiation was also comparable between the investigated marshes. It is therefore expected that the findings on marsh development are generally applicable.

One of the initial questions was to identify sources and sinks of sediment in relation to salt-marsh rejuvenation. Unfortunately, with both the radiometric and corer methods, it was not possible to recognize sources and sinks of the fine-grained sediment within the marsh of Schiermonnikoog. The radiometric fingerprint of the fine-grained sediment seems to be homogeneous within the Dutch Wadden Sea. The most probable explanation for the small-scale variations in radionuclide concentrations of the sediments at and around the salt marsh are thus variations in the hydrodynamic conditions under which the sediment was deposited.

v. Recommendations

For successful restoration and conservation of salt-marsh systems it should be kept in mind that vegetation development often is a slow process. It might be a profitable strategy to create benign physical conditions for vegetation settlement and growth, on a temporary basis, for example by using brushwood groynes. Once vegetation is actually present with high biomass it is expected to be rather resilient to changes. Still, our results suggest that salt-marsh pioneer zones have the capacity to suddenly shift from a vegetated to an unvegetated state in response to environmental changes.

Future research should extend on the conceptual framework that we developed for negative species interactions via the environment, including both empirical and modeling studies. Furthermore, it will be interesting to examine whether engineering effects of a species on the environment, can only be detected under high stress conditions and are absent when conditions are benign. Another line of research that is worth pursuing is investigating the implications of patchiness in ecosystems and, specifically, in transition zones between different systems. Possibly effects on transition zones can cascade through a system and affect both ecosystems that border the transition zone. A more thorough understanding of dynamics in transition zones could benefit successful management and conservation of complete ecosystems. Hypotheses should aim to examine if patchiness is a characteristic of transition zones and whether these zones are in general maintained by positive feedbacks. This will give insight into the vulnerability of transition zones to changes and help to estimate response of transition zones to climate change. This line of research will also allow us to predict response of salt marshes, and specifically salt-marsh pioneer zones, to future sea-level rise.

In the Dutch Wadden Sea, there is concern about the change in ecosystem functioning related to e.g. shellfisheries and the disappearance of mussel beds and seagrass beds. These changes may be reflected in sediment composition. A method that can quickly map the intertidal flats on sand and mud may therefore benefit the ongoing research on these subjects, and the radiometric method has good potential. It works best if the only differences in radiometric fingerprints are between the fine-grained sediment and sand. Therefore, a pilot experiment in which the fingerprints are established should always be done before applying the method to a new area.

The presence of multiple levels of spatial patterns in salt-marsh accretion has implications for measuring salt-marsh accretion. To obtain reliable values for accretion, measurements should sufficiently sample the extent of the patterns. As the size of these patterns is difficult to predict beforehand, it is wisest to spread measurements as much as possible over the entire area of interest. Predictions of salt-marsh resilience to sea-level rise that are based on only a few measurements, spatially clustered measurements, or data from only one marsh zone should therefore be treated with caution.

Currently, there is much interest in the importance of overwash deposits for the functioning of salt marshes on barrier islands, related to the presence of artificial sand dikes on the Dutch Frisian islands. The exploratory study in this project indicates that the total contribution of sand from washover deposits to the salt marsh on Schiermonnikoog is in the order of one or two percent. Under the current conditions, the active marsh does thus not rely on washover sediment for keeping pace with sea-level rise. For the development of the distal end of the island as a whole, however, the contribution of washover deposits may be much more important for instance by creating accommodation space for marsh growth and introducing landscape variety.

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5. Macrophytes in Estuarine Gradients

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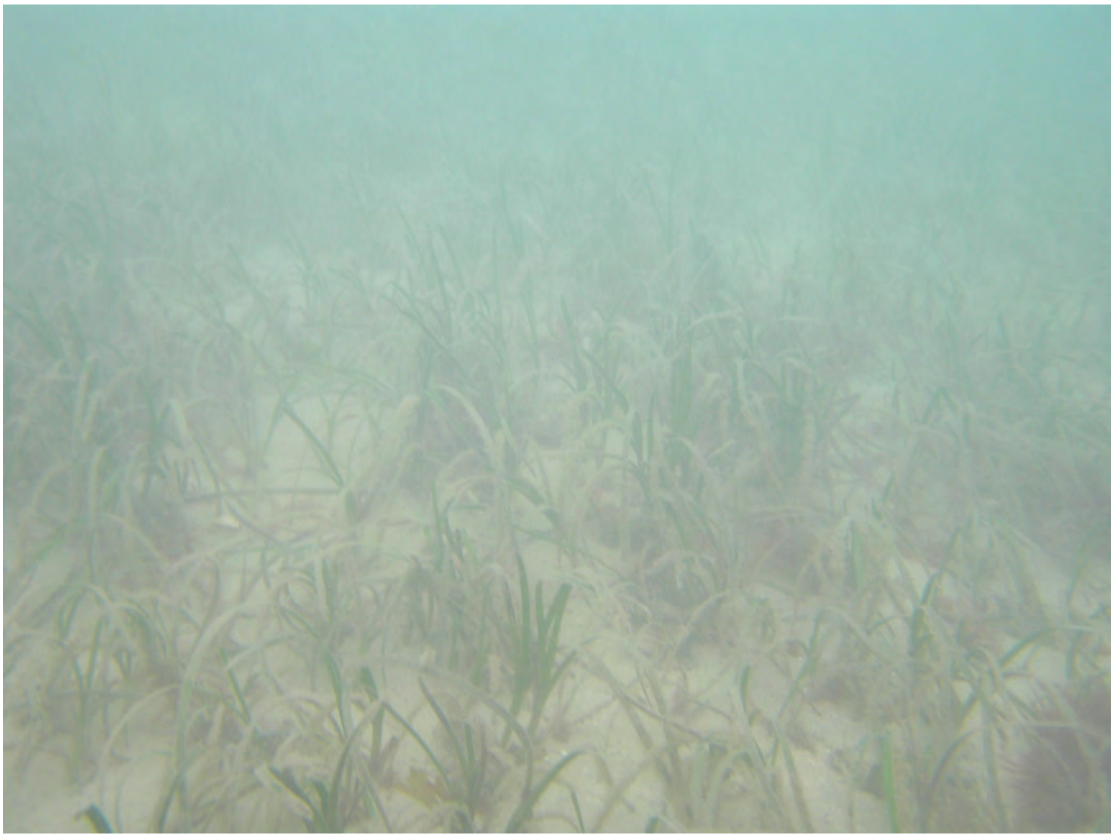

Fig. B-5.1: *Macrophytes*

Abstract

To study the interaction of estuarine vegetation with its environment, a physics-based model was developed and validated, accounting for the flexibility of plants. Using this model, the eco-engineering capacities of seagrasses and cordgrass in similar conditions were compared and breaking strategies of salt marsh plants were investigated on a local spatial scale. On a larger scale, the sediment transport patterns in a seagrass-covered bay and the long-term development of an intertidal flat in the presence of stiff and flexible vegetation were studied. To assess the potential for survival of eelgrass, for which water clarity is important, the developed biogeomorphological model was coupled to a model for eelgrass growth.

Accounting for flexibility of vegetation is important, especially in local-scale studies. The actual eco-engineering capacity of plants depends on the combination of plant properties like density, shape and stiffness as well as the environmental conditions depth and flow velocity.

i. Problem

Macrophytes in estuaries are often considered to be 'eco-engineers'. By their presence they alter their environment in a way favourable to themselves or to other organisms. By doing so, these plants provide important functions to the estuarine ecosystem. For example, aquatic plants can stabilize the seabed, decrease turbidity by trapping sediment, reduce waves and provide a food source as well as a shelter to many animals. This feedback between plant presence and environment is probably crucial to their own existence in some situations: without plants the conditions are to tough to survive, with plants the conditions are sufficiently toned down to be endured. Such mechanisms support the existence of alternative stable states (Scheffer et al., 2001) and are relevant for the protection and possible restoration of macrophyte populations.

The difficulty however, is to express these feedbacks quantitatively: by how much is the turbidity decreased, how much is the bed stabilised? Because the strength of these effects not only depends on plant properties like biomass, length and flexibility but also on environmental properties like water depth, flow velocity and sediment composition, purely experimental research would only cover a small part of the situations that occur in the field.

ii. Aim and approach

The aim of this study therefore was to develop a generic, process-based computational model that can be used to quantify feedbacks between aquatic vegetation and its environment.

In order to incorporate the effect of macrophytes on flow, a model for the interaction between flow and flexible vegetation was developed: Dynveg (Dijkstra and Uittenbogaard, in press). Dynveg uses a finite-element approach to calculate the position of a plant and the hydrodynamic forces acting on it, based on measurable plant properties such as stem thickness, length, buoyancy and elasticity.

Subsequently, Dynveg was linked to Delft3D (Lesser et al., 2004), which is able to simulate flow, waves and sediment transport in estuarine –but also riverine and coastal- areas well. This link was made by adapting the height and the drag coefficient of the stiff vegetation already present in Delft3D, according to the actual depth and flow velocity, thus representing flexible plants.

After validation of this combined model (Dijkstra, 2008), several studies have been performed. The first of these studies compared the local eco-engineering properties of three different species that occur at similar depth zones in estuaries (Dijkstra and Bouma, in prep.). The species used were the long and flexible, sparse seagrass Zostera marina, the short and flexible seagrass Zostera noltii that occurs in high densities and the practically stiff cordgrass Spartina anglica. The reduction of the bed shear stress, reduction of flow velocity and the canopy flux were used as proxies for the eco-engineering capacity of a meadow.

In a second study, eight salt marsh species along a depth gradient were compared based on a 'bend or break' strategy: in low but dynamic areas it is more efficient to bend under load, whereas in higher, quieter areas with more competition between species a breaking strategy is a more energy-efficient investment.

A third study compared the effect of four different vegetation configurations on sedimentation-erosion patterns in a macro-tidal bay in Brittany, France (Dijkstra, in prep.). First, the model performance was compared to field measurements on flow velocity and sediment transport in this bay. Second, the density and stiffness of the vegetation was varied to study which vegetation property affects the environment the most.

One step further, the effect of stiff Spartina versus that of flexible Zostera noltii on long-term (30 years) development of an intertidal flat in the Western Scheldt was compared by extending the Delft3D-Dynveg model with rules for vegetation growth (Bouma et al., subm.). These rules were based on inundation time and bed shear stress among other things, as calculated by the morphodynamic model.

The final study links the possibility of survival of plants to changing environmental conditions, using the changes in the Dutch Wadden Sea as an example. In this area, seagrass used to be abundant until the 1930's, when a combination of the worldwide wasting disease Labyrinhtulae zosterae, high turbidity and altered tides due to the construction of the Afsluitdijk, combined with high nutrient levels from fertilisers caused Zostera marina to disappear (Den Hartog, 1975). Several small-scale restoration attempts failed; hence it would be interesting to see if Zostera marina can survive at all in the present conditions. This work is still in progress.

iii. Results

The performance of the Dynveg-model was tested against measurements of plastic strips of different lengths and stiffness for a range of flow velocities. In all cases, the model reproduced both the forces and the positions of the strips well. A comparison with flume experiments on flow through artificial seagrass performed by Nepf and Vivoni (1999) showed that also the effect of plants on hydrodynamic properties such as turbulent kinetic energy and eddy viscosity were simulated accurately. Figure B-5.2 shows the changes in plant position and flow velocity profile for a range of environmental conditions and plant properties. At higher velocities, plants bend more (Fig. B-5.2a). For larger water depths, the plant positions are very similar but the effects of plants on the flow velocity profile becomes less (Fig. B-5.2b). Plants with a higher elasticity modulus bend less, thereby having a more pronounced effect on the velocity distribution (Fig. B-5.2c). The same occurs for a larger number of plants per area (Fig. B-5.2d).

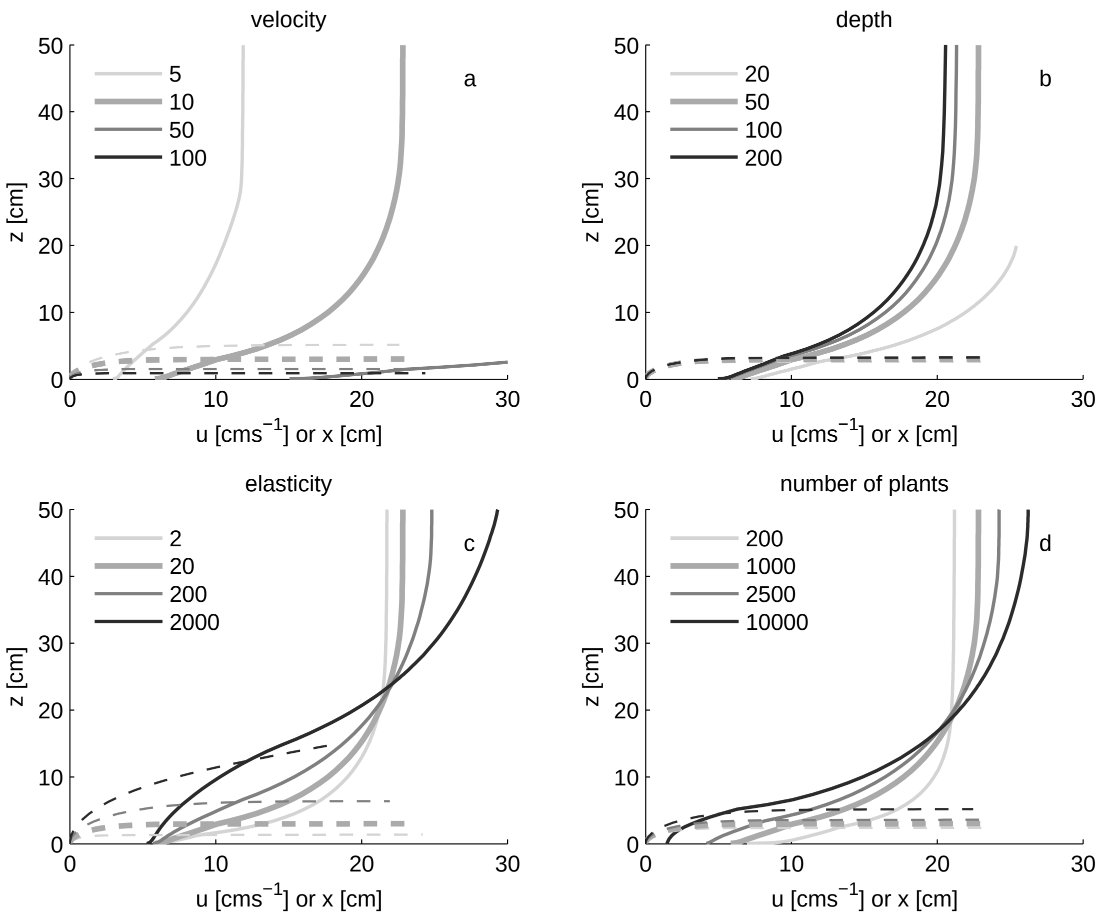

Fig. B-5.2: *Flow velocity profiles (continuous lines) and plant positions (dashed lines) in a flume for a) various depth-averaged velocities (cm.s^{-1}); b) various flow depths (cm); c) various elasticities (MPa); d) different plant densities (per m^{2}).*

The integration of Dynveg into Delft3D enabled the study of spatial adaptation patterns in meadows. As Figure B-5.2 shows, this integrated model captures the adaptation of the plant position and the velocity profile very well, for two different species. The adaptation length of meadows of Spartina, Zostera marina and Zostera noltii is rather similar, in the order of 0 to 2 meters in the most common flow conditions. The eco-engineering capacity of these species differs however (Fig. B-5.3), with Spartina having only a minor effect on bed shear stress but with a large canopy flux, whereas Z. noltii strongly reduces the bed shear stress and has a small canopy flux, indicating a strong potential for sediment stabilisation but little for sediment trapping.

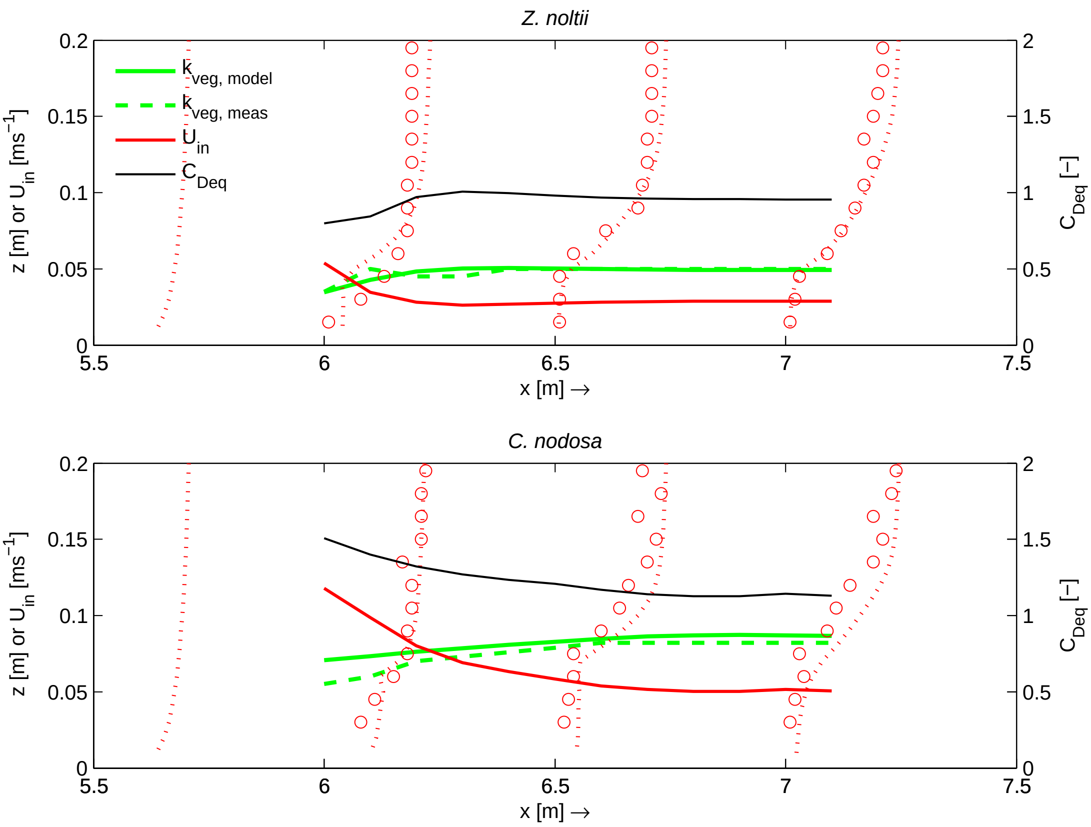

Fig. B-5.3: *Longitudinal cross-section of the flume as used by Morris et al. (2008), with hydrodynamic and plant properties predicted by the model compared to measurements. Circles and dotted vertical lines indicate measured resp. modelled flow velocity profiles. a) Zostera noltii b) Cymodocea nodosa*

The study of Bouma et al. (subm.) shows how these different eco-engineering properties affect landscape formation over several years: a tidal flat colonized by Spartina will develop into a system with several deep unvegetated channels, whereas a flat colonized by Z. noltii will be densely and uniformly covered with plants.

Similarly, the sedimentation patterns in and around a bay differ according to the type of vegetation present (Fig. B-5.4): a rather sparse canopy (RV in Fig. B-5.4) captures some of the sediment and stabilises it, giving the highest import into the bay. If no vegetation is present (NV), sediment is eroded too, whereas dense or stiff (FV resp. SV) vegetation prevents some of the sediment from entering the bay. The fine sediment fraction, which is suspended throughout the entire water column, is less affected by the presence of plants than coarser sediments, which are transported close to the bed.

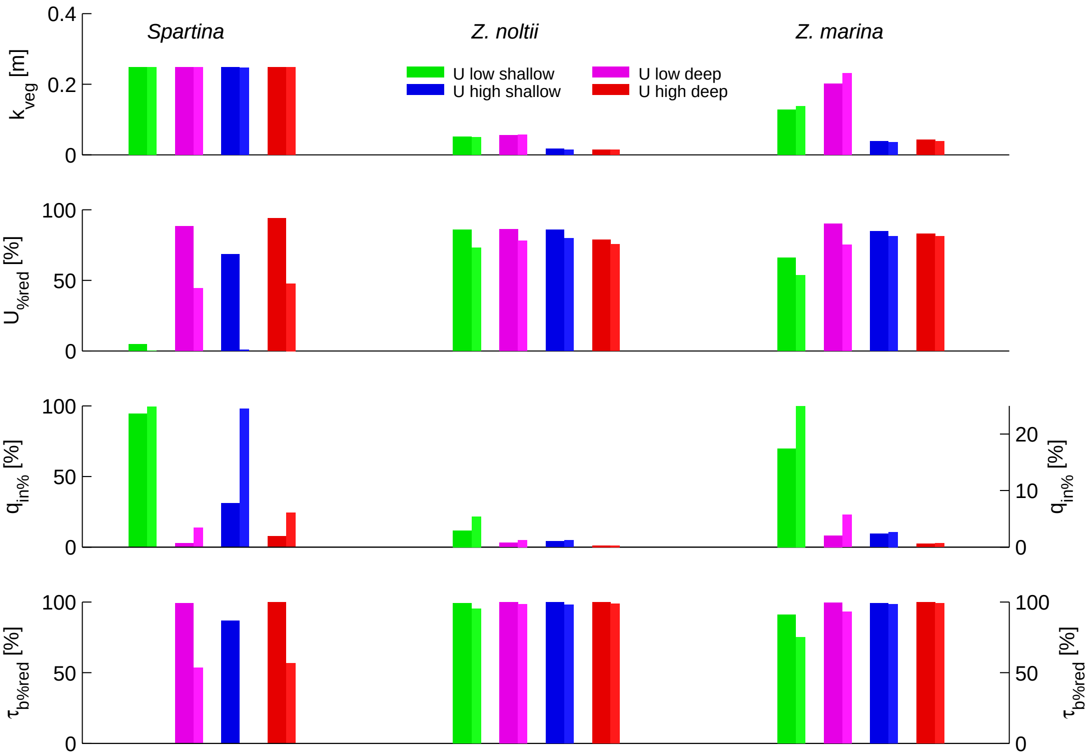

Fig. B-5.4: *Relative performance of the eco-engineering performance of Spartina, Z. marina and Z. noltii. U%red means percentage of reduction with respect to d.a. velocity, qin% the canopy flux as percentage of total discharge, τb%red is percentage reduction of bed shear stress with respect to a bare bed. For Spartina in shallow water and a low flow velocity, τb is increased instead of reduced.*

When studying the effect of different environmental conditions and the presence of seagrass itself on its growth and survival, the amount of light available for photosynthesis seems the crucial factor. Preliminary results show that the timing of the vertical tide –the water level- and the horizontal tide –flow velocity, advection of sediment- is very important. As seagrass meadows are not able to alter processes on this meta-scale, their presence might contribute only little to their chances for survival.

iv. Conclusions and recommendations

Flexible plants affect hydrodynamics in a way different from stiff plants. Dynveg is able to simulate the interaction between flow velocity and plant position well for a range of environmental conditions. Moreover, because Dynveg is based on measureable plant properties, it is generally applicable.

The coupling of Dynveg with Delft3D showed that flexible vegetation can be simulated as stiff vegetation, provided its properties are adapted according to flow conditions. The spatial gradients in meadows –i.e. the length of the leading edge- are in the order of 0-2 metres usually. Different species that occur at the same elevation have very different eco-engineering capacities. Therefore, these eco-engineering capacities cannot simply be related to the amount of biomass per square metre or the leaf area index.

Application of the model to real environments such as the macrotidal coast of Brittany and the mesotidal Western Scheldt show that different plant species have different effects on the development of the environment. The strength of these effects depends as much on plant properties like stiffness and density as well as on environmental properties such as the water depth and sediment characteristics. It is difficult to obtain general rules for such biogeomorphological interactions.

The survival of seagrasses seems to depend more on factors that are not affected by the presence of meadows, such as the water depth and the advection of fine sediments, than on factors that can be affected locally, such as bed stabilisation.

Two processes that can have considerable effects on plants in coastal environments are not taken into account in this study: the direct trapping of sediment particles against leaves and the reduction of wave energy. Especially the latter requires considerable attention in future studies, as it relates strongly to the survival of plants in storm conditions, sediment transport and coastal safety. Despite the fact that not all processes are incorporated in the biogeomorphological model treated above, it can be a useful tool to study ecosystem- and landscape dynamics in estuaries, rivers and coasts.

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C. Cycle of carbon and related compounds

1. Interview with Prof. Dr. Ir. H. de Baar
2. Uptake of CO_2 by the North Sea in interaction with phytoplankton blooms
3. Benthic calcification in the Dutch Coastal zone and effect on ocean acidification on the growth of commercially important bivalve species

1. Interview with Prof. Dr. H. de Baar

Photo: Frank van Driel

The role of carbon in coastal seas

Over the past few decades, rising CO_2 concentrations in the atmosphere and the associated effects of this have led to a significant boost in fundamental research on carbon cycles and the cycles of related chemicals in coastal areas, says Professor Hein de Baar. He works at the Royal Netherlands Institute for Sea Research (NIOZ) and the University of Groningen and leads various projects within the LOICZ-NWO Programme. Coastal areas are naturally very productive areas and that means that a lot of carbon is sequestrated by algae and then broken down. Knowledge about the pathways and fate of carbon in coastal areas is vital for ensuring that the right measures can be taken in the future.

What is the relationship between seawater and carbon dioxide?

De Baar: Our research was on the carbon cycle of the entire North Sea and how CO_2 is sequestrated from the atmosphere into the sea. That is a natural, but very slow process. As more CO_2 dissolves in the water, the water's chemistry changes. Certain dissolved forms of CO_2 function as a buffer for the pH. If the pH changes then a different environment will develop. What effect will this have on the organisms in the water? We investigate whether this is good or bad for the organisms. The highest biological productivity is in the coastal seas. In the middle of the open ocean hardly anything grows or lives. The water there is crystal clear due to the lack of life. Changes in the CO_2 concentration are therefore dependent on the location. In the ocean the changes are minor, but along the coast, in the Marsdiep near Texel, these changes in CO_2 concentration and pH can be considerable. We examine the natural fluctuations over the course of the year in relation to the gradual increase in CO_2 over the longer term.

When did you start the research?

During the first trips in 2001 and 2002 we measured that the North Sea sequestrates three times as much CO_2 per square kilometre at three times as fast a rate than occurs in the Atlantic Ocean. Since then we have performed these measurements once every three years and this observation remains unchanged. These results have been incorporated in two different computer simulation models that were funded by LOICZ. Both models give roughly the same outcome. The validity of these models has been demonstrated with each set of measurements collected. That is good news because a model that works well demonstrates that you have a good understanding of the underlying mechanisms. However, we have not finished yet.

Why do you see such large differences in the CO_2 concentration between the North Sea and the Atlantic Ocean?

The water in the Atlantic Ocean takes up less CO_2 than that in the North Sea. We think that a biological pump underlies these differences. The southern North Sea along the Dutch coast has an average depth of 50 metres but the northern North Sea has a depth ranging from 400 to 800 metres, therefore far deeper. In the summer, the northern part becomes stratified with warm water at the surface and cold water in the deeper parts. The algae in the upper layer sequestrate the CO_2. If the algae die or are eaten, the material containing carbon ends up in the deeper layer where it is decomposed by bacteria and CO_2 is released again. The deeper water is replenished from the Atlantic Ocean. A sort of conveyer belt exists with deep water entering the North Sea at the Shetland Islands and then flowing back there again about a year later after a large detour. Deep water with a low CO2 concentration therefore flows in at the Shetland Islands and deep water with a slightly elevated CO2 concentration flows out again into the Atlantic Ocean.

Is the ocean sink capacity for CO_2 stable?

In 1957, the American researcher Roger Revelle theoretically calculated that the sink capacity of the oceans decreases over time. And that has proven to be the case. There are two possible complications for this: the interaction with the sea floor and exchanges with the Wadden Sea. In the open ocean, the seafloor does not play a role due to its great depth being separated from surface waters.

What does this mean for the future?

Our hypothesis is that these fluctuations will not have any significant effect in the shorter term (100 years). The variations concern the budget of where the fossil fuel CO_2 is being stored: the balance between fossil fuel CO_2 in the oceans and fossil fuel CO_2 in the atmosphere. That is currently about fifty-fifty. According to Revelle, we can expect that increasingly less will be sequestrated by the oceans, so the CO_2 concentration in the atmosphere will increase even more rapidly than it has the past century. We have received funding for a new project from NWO in which three PhDs will do further research on CO_2 sequestration in the North Sea. This is a good move because it is a long-term issue.

Is this CO_2 research a specialism in which the Netherlands is playing the leading role?

All of the countries bordering the North Sea bear a responsibility for monitoring it. We need to set up a joint knowledge base. We are now taking part in an initiative for a wide-ranging report on the state of the North Sea and climate. Ideally such a report will next be published again every seven years with the newest insights and measurements, just like the IPCC producing a new report once every about seven years. Worldwide scientists bundle the knowledge they have acquired and draw their conclusions about the latest developments in climate change. Several years ago a similar report about the Baltic Sea was already published and very well received. Such a scientific status report needs to be published for the North Sea as well.

2. Uptake of CO_2 by the North Sea in interaction with plankton blooms

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Abstract

The processes of uptake and increase of CO_2 in the entire North Sea are investigated by a combination of various field observations and biological-chemical modeling, also providing some assessments of shifts of the chemical composition of seawater.

The project has produced the following major results:

1. observational time series database of CO_2 and plankton distributions and CO_2 air/sea exchange fluxes,

2. observational database of CO_2 datasets collected during dedicated cruises,

3. integrated modeling of North Sea carbon cycle including air/sea CO_2 fluxes, estuarine exchanges, and exchanges with the Atlantic Ocean,

4. annual air/sea CO_2 flux estimates show that the North Sea is a strong net sink for uptake of CO_2 from the atmosphere. The "biological pump" combines with deep waters exchange with the North Atlantic in an overall "continental shelf pump" for drawdown of CO_2 from the atmosphere.

i. Problem

Due to combustion of fossil fuels and some other human activities large amounts of carbondioxide (CO_2) are emitted in the atmosphere. More than half of the extra CO_2 remains airborne causing a steady increase of the partial pressure of CO_2 in the atmosphere. Seas and oceans take up another large portion (about 40 %) of the emitted CO_2. This uptake is partly by strictly physical-chemical processes, partly by biological fixation in photosynthesis by phytoplankton in the sea. Overall, the pool of dissolved CO_2 in seawater is increasing and the ensuing shifts in the chemical composition of seawater are a cause of concern with regards to conceivable effects on marine biota. One major shift is a general decrease of the hydroxide ion (OH-), in other words the seawater becomes less alkaline (Van Santen, 2007; De Baar, 2008).

ii. Objectives

The overall aim is to quantify changes in CO_2 uptake by the North Sea via plankton blooms by means of field measurements, and to quantify the role of climate change by ecosystem modelling.

iii. General Methodology

This research program on the North Sea carbon cycle is in the fortunate situation to rely on a previously collected comprehensive basinwide data set collected during cruises in four seasons (Thomas et al., 2004, 2005a; Bozec, 2005; Bozec et al., 2005, 2006). The North Sea has been sampled repeatedly in 1-month cruises (8/2001, 11/2001, 2/2002, 5/2002) taking some 23,000 surface water values of p CO_2 and occupying each time 97 stations for sampling the complete water column for the CO_2 system and a suite of 20 other parameters. In addition a summer cruise was performed in 2005. All five cruises were aboard RV Pelagia of Royal NIOZ. Two more basinwide summer cruises in summers of 2005 and 2008, integrated simulation modeling of the carbon cycle of the North Sea, and time series observations of atmospheric CO_2 at a fixed position, all leading to a suite of estimates of the air/sea CO_2 gas exchange rate.

In all four seasons it was found there is a strong North-South transition in the entire North Sea coinciding with the transition at the Frisian Front from shallow waters (<50 m depth) in the southern part of the North Sea to deeper waters in the northern North Sea. In contrast, the gradients in east-west direction are modest. This distinct transition at the Frisian Front is also comprised in the Netherlands Continental Platform (NCP) jurisdictional part of the North Sea.

The strong North-South trends led us to design a long term multi-year observational program through all seasons along the North-South transect from Bergen (Norway) to IJmuiden (The Netherlands) in a collaborative program between the universities of Bergen (Norway) and Groningen and the Royal NIOZ, with additional subsidy support in context of the EU Integrated project CARBOOCEAN (2005-2009). During several years data was collected of pCO_2 in sea surface and air by a Voluntary Observing Ship (VOS) the TransCarrier sailing between Bergen (Norway) and IJmuiden (The Netherlands). At the start of the project the TransCarrier had a weekly track with triangular shape from Bergen to IJmuiden to Immingham (England) to Bergen. However sometimes the track was changed and as a result the most continuous long term set of observations is in the North-South direction from Bergen to IJmuiden and back again.

Towards the first interpretation (Omar et al., 2010) of the first three years 2005-2007 this Bergen-IJmuiden transect database of TransCarrier has been combined with data of an East-West VOS line aboard the Nuka Arctica of Royal Arctic Lines with the scientific program of pCO_2 and ancilliary measurements by A. Olsen of the University of Bergen. Moreover the pCO_2 and ancilliary data of the above mentioned five Pelagia cruises were included, as well as pCO_2 data calculated from some 'ancient' NIOZ cruises in 1987 aboard the vessels Aurelia and Holland.

iv. General Results

By normalization of the pCO_2 as function of the atmospheric pCO_2 in anyone given year, a composite of the pCO_2 trends during every month of the annual cycle was constructed. From this one clearly observes a strong pCO_2 minimum in the spring time due to intensive CO_2 uptake by photosynthesis of phytoplankton. Budget assessments of this biological CO_2 sink term are consistent with the abundance of phytoplankton biomass derived from SEAWIFS satellite observations of chlorophyll color of the sea surface.

Alternatively when looking at the increasing trend of pCO_2 over the years, here also including some very 'ancient' data of 1970, one finds that the pCO_2 in surface waters of the northern North Sea increases with $61 \pm 33 * 10^{-6}$ atm. over 40 years, more or less tracking the atmospheric CO_2 increase (~1.6 * 10^{-6} atm/yr observed at Mauna Loa) in agreement also with our recently published community estimate of pCO_2 growth rate in North Atlantic surface waters (Takahashi et al., 2009). This emphasizes that waters originating of the North Atlantic are compatible with the northern North Sea (Thomas et al., 2007). However, this consistency with open Atlantic Ocean trends should not be extrapolated to the shallow southern North Sea (Schiettecatte et al., 2007). Here the Alkalinity effect tends to cause perturbations, this is due to anaerobic alkalinity generation within anoxic sediments notably of the Wadden Sea (Thomas et al., 2009).

Observational database of CO_2 datasets collected during cruises

The very large and comprehensive database collected aboard of the PELAGIA from 19 August to 11 September 2008 is completed and stored at the central Data Management Group (DMG) of NIOZ. This latest basinwide North Sea dataset continues from previously collected similar large datasets in the summer of 2005 and the summer of 2001, as well as the similar datasets for three other seasons autumn, winter and spring in 2001-2002. When comparing the consecutive summers of 2001, 2005 and 2008 in the below Figure C-2.1 one notices differences between years but also the distinct North-South gradients.

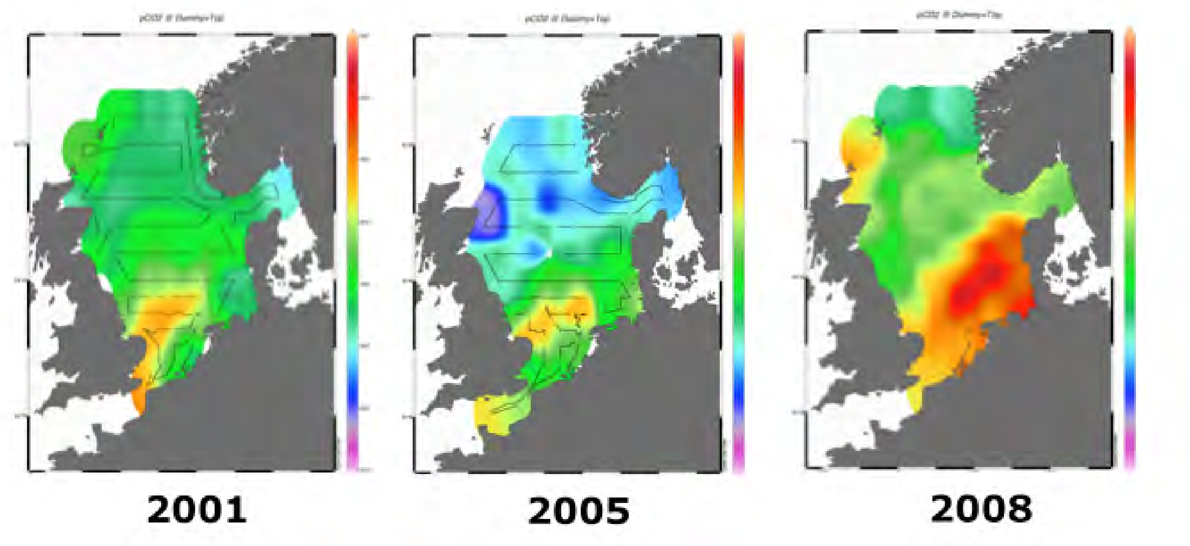

Fig. C-2.1: *Summer values of delta-pCO_2 in surface waters of the North Sea in years 2001, 2005 and 2008 (Salt et al., 2011).*

When comparing the corresponding pH values in surface waters over these same years, there is an observed decrease of pH in the 2001-2005-2008 intervals. This is consistent with but stronger than the predicted world ocean trend of increasing ocean acidification due to uptake of anthropogenic CO_2 in seawater. The larger pH decrease of 0.06 unit between 2005 and 2008 as compared with 0.01 unit between 2001 and 2005 is in the expected direction because the increasing CO_2 content is known to cause a decreasing general buffer capacity of seawater. Otherwise the pH trend is stronger than predicted for the open oceans, where the more intense dynamics of biological production and decomposition in coastal seas (Thomas et al., 2004), as well as interactions with estuaries and underlying sediments play a role.

The latest summer cruise in 2008 was an improvement over the previous cruises in the sense that all four measurable parameters pCO_2, DIC, pH and Alkalinity of the CO_2 system in seawater were measured directly. Given the fact that in natural oceanic waters one needs to measure only two distinct parameters and then can calculate the others, one is able to verify internal consistency of the dataset. For example from measured DIC and Alkalinity one may calculate the pCO_2 value and compare this with the actual measured pCO_2 value. Having done such systematic intercomparisons of internal consistency we found some intriguing trends. Briefly, in the central northern North Sea there is excellent internal consistency between all four parameters. Quite remarkably when approaching either Britain to the west or Wadden Sea and Kattegat to the east, deviations become apparent. We are currently assessing possible causes. Firstly this may be due to pH calibration issues. Secondly this may partly be due to the Alkalinity effect emanating from shallow sediments (Thomas et al., 2009). Alternatively or complementary the Dissolved Organic Carbon moieties in nearshore waters may also interfere with the inorganic CO_2 system, notably the determination of the measured Alkalinity values. Thirdly river inflows with variable compositions of dissolved salt content of the river water, may interfere with the general law of constant proportionality of seasalt (Dittmar, 1884) in the oceans. In other words devations of this Law of Dittmar in coastal waters may, or may not, affect the calculations of the CO_2 system variables which rely on the measured salinity of the seawater sample as one of the input variables.

The findings of the summer 2008 cruise have been worked out into three different draft manuscripts by Lesley Salt in context of the preparation of her PhD thesis.

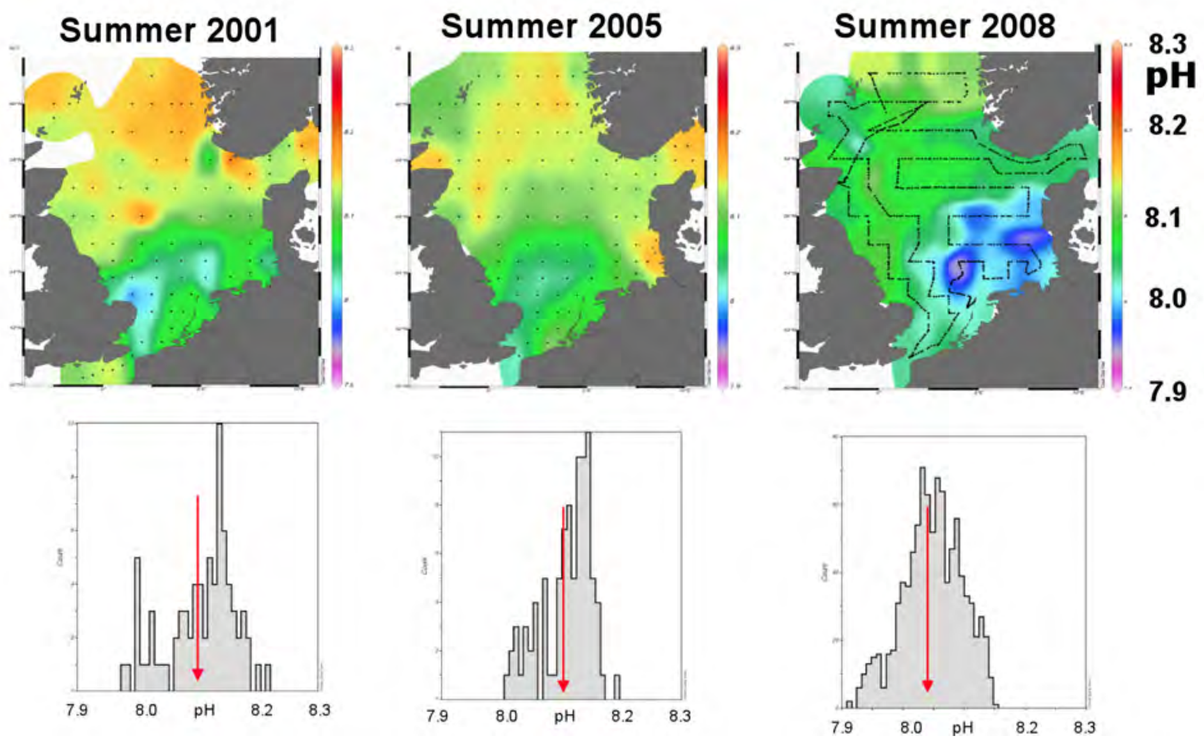

Fig. C-2.2: Summer values of pH in surface waters during consecutive summer cruises in 2001, 2005 and 2008. The lower graphs show the ranges of pH values for these same years. The average values of pH are indicated by the red arrows, with a decreasing trend of 0.01 pH unit between 2001 and 2005 and 0.06 pH unit between 2005 and 2008. Given the wide range of pH values in every of the three years, the average decreasing trend is of only modest significance thus far.

Integrated modeling of North Sea carbon cycle

The datasets as mentioned above have been utilized as reference framework for basinwide computer simulation modeling of the carbon cycle within the North Sea (Prowe et al., 2009). The modeling integrates the key physical, chemical and biological processes and interactions in the water column extending from the shallow ~50m vertically well-mixed deep southern North Sea and the deeper vertically layered northern North Sea. The mechanisms driving the air–sea exchange of carbondioxide (CO_2) in the North Sea are investigated using the three-dimensional coupled physical–biogeochemical model. We validate our simulations using field data and identify the controls of the air–sea CO_2 flux for two locations representative for the North Sea's biogeochemical provinces. In the seasonally stratified northern region, net

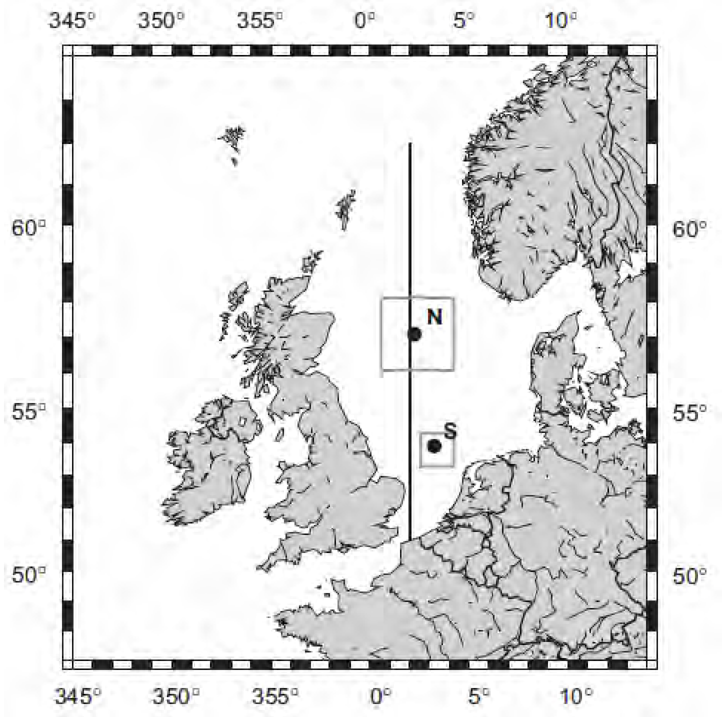

Fig. C-2.3: *Chart of the model domain including the North Sea. Within the model (Prowe et al., 2009) the section along 2°E is used to illustrate the strong north-south trends largely coinciding with the transition from deep northern North Sea to shallow southern North Sea. The regions N and S are used as representative examples of these two regimes in the below Figure C-2.4.*

CO_2 uptake is high (2.06 $mol.m^{-2.}a^{-1}$) due to high net community production (NCP) in the surface water. Overflow production releasing semi-labile dissolved organic carbon needs to be considered for a realistic simulation of the low dissolved inorganic carbon (DIC) concentrations observed during summer. This biologically driven carbon drawdown overrules the temperature-driven rise in CO_2 partial pressure (p CO_2) during the productive season. In contrast, the permanently mixed southern region is a weak net CO_2 source (0.78 $mol.m^{-2}.a^{-1}$). NCP is generally low except for the spring bloom because remineralization parallels primary production. Here, the pCO_2 appears to be controlled by temperature.

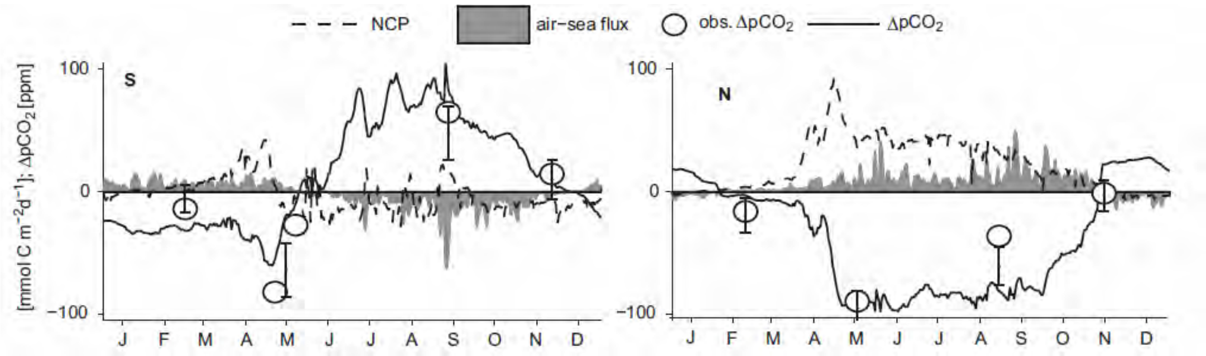

Fig. C-2.4: *The annual cycle of model-derived air-sea flux of CO_2 based on model-derived delta pCO_2 and Net Community Production (NCP). Also shown is the observed delta pCO_2 throughout the seasons of the year. Left graph is for southern region S in the shallow southern North Sea (see Fig. C-2.3) which is vertically mixed throughout almost the whole year. Right graph is for the northern region N in the deep northern North Sea (see Fig. C-2.3) where in large part of spring-summer-autumn there is strong vertical stratification of surface waters well distinct from deep waters.*

Modelling Climate Change: doubling of the p CO_2 concentration in the atmosphere

The ERSEM-model is applied to forecast the effect of doubling the pCO_2 concentration of the atmosphere on the pH of the North-Sea ecosystem. For the possibility to apply the GETM-ERSEM to model changes with respect to the dynamics of dissolved inorganic carbon (DIC) the following additions are implemented:

- routine which describes the DIC-speciation (CO_2, HCO_3-, CO_3^{2}-) as controlled by Alkalinity, salinity, temperature, nutrients and pH. This routine is public-domain available at http://www.ipsl.jussieu.fr/OCMIP/ phase2/simulations/Abiotic/HOWTO-Abiotic.html .

- separate routines for the pelagic and benthic systems which describe processes which modify alkalinity such as nitrification, denitrification and anaerobic mineralization, re oxidation of anoxic constituents (e.g. sulphide).

- separate routines for the pelagic and benthic system which describe processes which modify the DIC-dynamics such as light induced primary production, oxic respiration, chemical induced primary production (nitrification) and anoxic respiration.

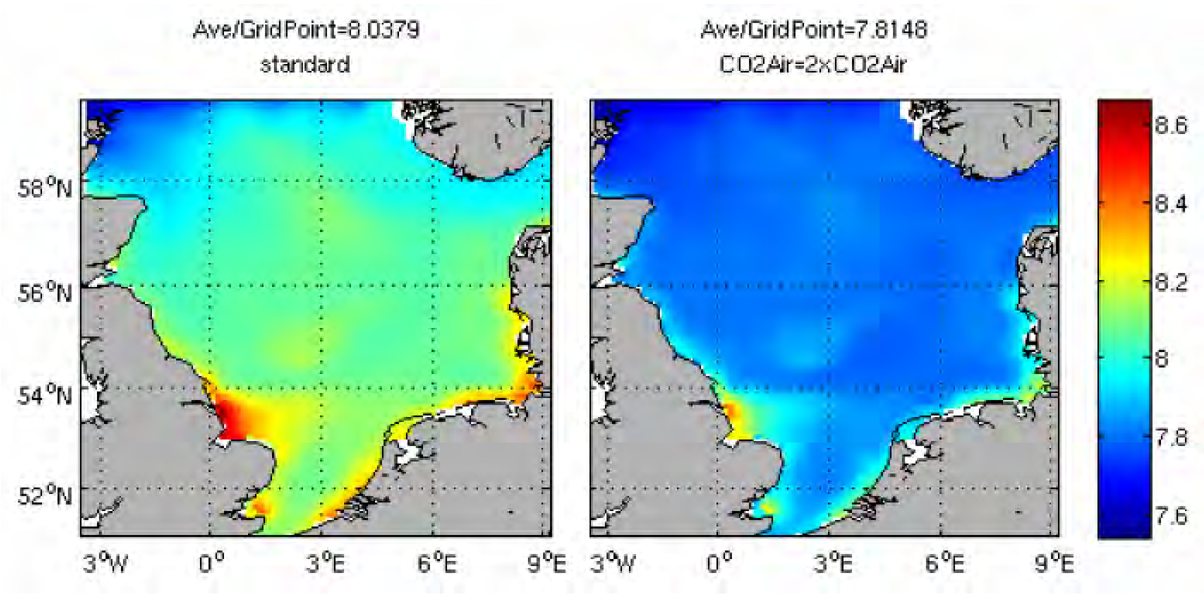

Fig. C-2.5: *Comparison of two model simulations at modern pCO_2 and double pCO_2 in the air expected at about the end of this century (IPCC, 2007). The ensuing annual average values of pH are decreasing but comparatively less than the actually observed average decrease of pH over 3 years time intervals in Figure C-2.3. However the latter observed average decrease is not significant due to the large natural variability in the observed data.*

A two-year run is made to verify the consequences of a change of CO_2 in the atmosphere. In this run only this forcing is changed. It is assumed further that a higher CO_2 concentration in the water has no direct effect on the primary production. This assumption is based on the fact that the most limiting process in a cell is the transfer of inorganic carbon to organic carbon. The uptake capacity of a cell to take up CO_2 and/or HCO_3- at the prevailing pH conditions is such that it will not be a controlling factor for the primary production. If we look to the whole North Sea (Fig. C-2.5) and to the pH averaged over the whole year we see a difference of maximally 0.2 units on the pH-scale.

Please notice that in this modeling run the pH is always greater than 7, implying that the seawater is and will remain alkaline, i.e. the major change being a decrease of the OH- ion that however will remain more abundant than its counterpart H+ in the well known water equilibrium $[H+][OH-]=10^{-14}$. Thus the seawater will not become acidic ($[H+]>10^{-7}$ hence pH<7) and the popular phrase 'Ocean Acidification' is somewhat of a misnomer.

When comparing the model simulation (Fig. C-2.5) with the observations (Fig. C-2.3) there appear to be discrepancies. Notably the decrease of pH over three years intervals of observations (Fig. C-2.3) is admittedly not significant due to large variability, yet appears much stronger than the model simulation (Fig. C-2.5) would suggest. These inconsistencies are not well understood yet partly ascribed to effects of Alkalinity changes due to interactions of the seawater in the North Sea with the adjacent Wadden Sea (Thomas et al., 2009a) and the biogeochemical reactions in the underlying sediments. These unresolved questions will now be addressed in a new project 'Dynamics of acidification in the North Sea: documentation and attribution' that has started in year 2010.

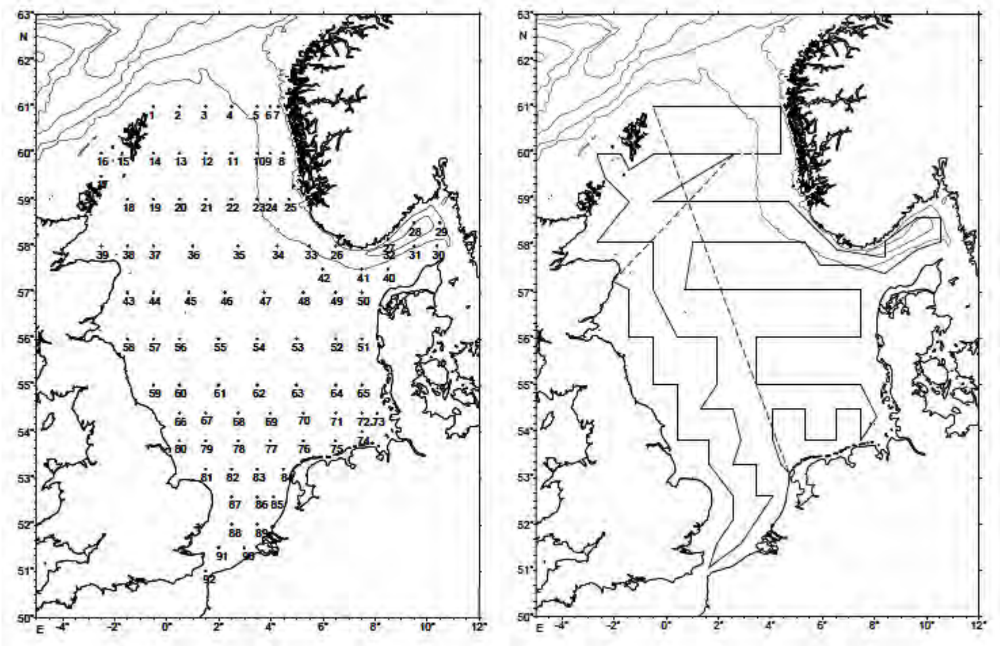

***Fig. C-2.6:** Left is station grid of the summer 2008 cruise, identical to station grids of the preceding cruises in 2001-2002 and 2005. At each station all four variables pCO_2, DIC, Alkalinity and pH were determined at 12 depths. Right is the cruise track from station to station in 2008, underway there was semi-continuous measurements of pCO_2 in surface waters plus ancillary data (S, T, wind velocity). Please refer also to Figures C-2.1 and C-2.2, Salt et al., 2011).*

Annual air/sea CO_2 flux estimates

The flux estimations have been addressed in several ways. Firstly for all the basinwide cruises in four seasons of 2001-2002 and summers of 2005 and 2008 (Fig. C-2.6) large datasets of air/sea CO_2 gas exchange fluxes have been produced. Underway along the cruise track (Fig. C-2.6, right hand graph) there was semi-continuous measurements of pCO_2 in surface waters plus ancilliary data (S, T, wind velocity). In combination with once every two hours pCO_2 values in the air this provides an overall about 20,000 data points of delta pCO_2. In combination with the air-sea gas exchange coefficient parameterized as function of the measured wind velocity this yields about 20,000 estimates of air/sea CO_2 gas exchange rates. Similarly datasets of about 20,000 values of air/sea gas exchange rates are available for the previous five cruises in four seasons of 2001-2002 and summer 2005. One is aware that the empirical parameterization of CO_2 gas exchange rate coefficient as function of wind velocity is not perfect, therefore we are also working on a more direct quantification by eddy correlation (Zemmelink et al., 2009).

Secondly we obtained atmospheric time series observations at the F3 Platform (Luijkx et al., 2009; Van der Laan-Luijkx, 2010). This atmospheric measurement site F3 (Fig. C-2.7) is situated (54°51'N, 4° 44'E) in the central North Sea, close to cruise station 63 (Fig. C-2.6 left graph). The closest land (The Netherlands) is located 200 km away from the measurement station. It is therefore an ideal location for measuring atmospheric background concentrations and studying air-sea interaction of CO_2 and partitioning of CO_2 emissions between the land biosphere and oceans. The data from this measurement station are a valuable contribution to the existing European data sets of atmospheric O_2 and CO_2, since only few atmospheric measurements stations exist that are equipped to measure atmospheric O_2 continuously. Moreover, this station is the first sea based atmospheric measurement station with on-site continuous O_2 and CO_2 measurements.

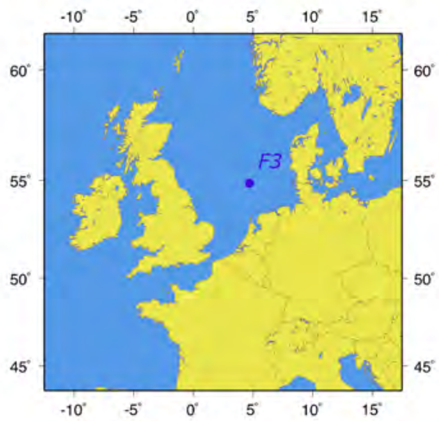

Fig. C-2.7: *The F3 platform (left graph) consisting of the larger actual production platform and the smaller accomodation platform, and its location (right graph) in the central North Sea.*

As the prevailing wind direction is south-west, potential leakages or fires are blown away from the accommodation platform. The ideal situation for atmospheric measurements is therefore on the south-west corner of the accommodation platform. This is where the air-inlet of the measurement system is situated. The air inlet is on the topmost deck, which is around 50 meters above sea level.

Next to the atmospheric pCO_2 values, the additional data of atmospheric O_2/N_2 ratio values and trends does provide fundamental constraints to discriminate the CO_2 exchange between the air and on the one hand the sea and on the other hand the land (Van der Laan-Luijkx, 2010). The continuous measurements for delta O_2/N_2 and CO_2 have been started at the end of August 2008. Flask samples have been collected on a weekly basis, generally during well-mixed atmospheric conditions and preferred wind direction, i.e. between south and west. Figure C-2.8 shows the combined first data from the F3 platform for continuous and flask measurements between August 2008 and June 2009. Although the measurements do not yet cover an entire year, the amplitude of the seasonal cycle can be estimated. In this section only the peak-trough difference will be discussed, which we call the amplitude in the rest of the text. The seasonal amplitude for CO_2 is about 16 ppm. For delta O_2/N_2 a single harmonic fit of the data yields an amplitude of about 110 per meg. When looking at the data however, this is likely to be too small, and an estimate by the eye would produce about 150 per meg.

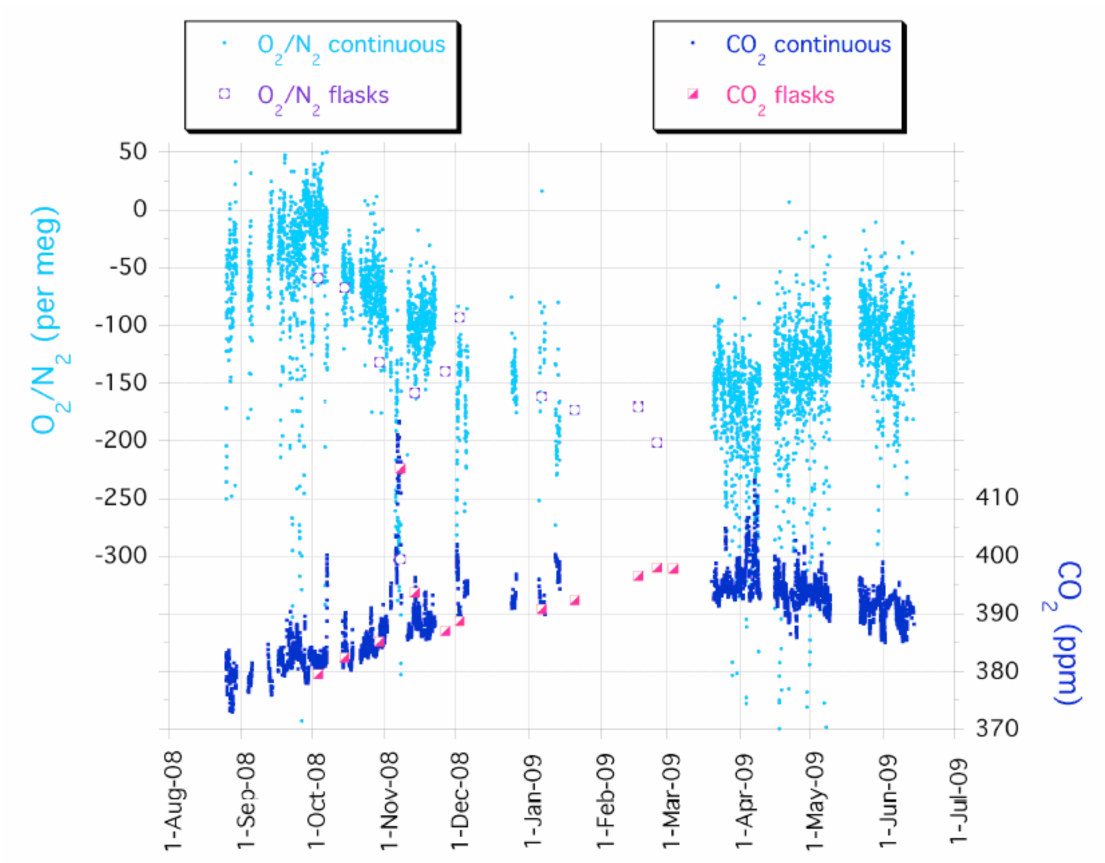

***Fig. C-2.8:** Observations at the F3 platform for the period August 2008 through June 2009. The continuous measurements of delta O_2/N_2 (small light circles) and CO_2 (small dark squares) were performed with the Oxzilla/CarboCap setup as described by Van der Laan-Luijkx (2010). The data points are half-hourly averages and include all measurements. Also shown are measurements of flask samples (open symbols). Both y-axes have been adjusted so that their ranges are nearly the same on a molar basis. Although the measurements do not yet cover an entire year, the amplitude of the seasonal cycle of delta O_2/N_2 can be estimated. The seasonal amplitudes are about 150 per meg for delta O_2/N_2 and 16 ppm for CO_2.*

For CO_2 the seasonal amplitude compares well to the marine boundary layer reference from the same latitude from the GLOBALVIEW-CO_2 (2008) database with an amplitude of 15 ppm. Both O_2 and CO_2 amplitudes can be compared to the observations at other stations at similar latitudes. For station Lutjewad (53º24'N, 6º21'E) at the coast of the WaddenSea in the Netherlands the seasonal amplitude of CO_2 is 14 ppm (Van der Laan-Luijkx, 2010). This value is based on continuous measurements. For both Lutjewad and Mace Head, Ireland (53º20'N, 9º54'W), flask data show a seasonal amplitude of 153 and 102 per meg for delta O_2/N_2 and 16 and 14 ppm for CO_2 respectively.

Thirdly in the simulation model by Prowe et al. (2009) as illustrated in the above Figure C-2.4 we have estimated the annual cycle of the air/sea CO_2 gas exchange in the North Sea. As shown the validity of the modeling simulation derived delta pCO_2 is verified versus the observed delta pCO_2 in the cruises.

In summary there is the combination of three distinct approaches to assess air/sea gas exchange of CO_2 in the North Sea:

(i) large datasets of gas exchange rates obtained from shipboard measurements of delta pCO_2 and wind velocity in the context of thus far six basinwide cruises;

(ii) annual cycle dataset of atmospheric CO_2 and delta O_2/N_2 at F3 platform from which the CO_2 exchange between air and sea or land respectively, is assessed;

(iii) integrated simulation modeling of the carbon cycle in the North Sea including estimates of the air/sea exchange rate in the seasons.

v. Future Work

The research is continued with a new granted project entitled 'Dynamics of acidification in the North Sea: documentation and attribution. This will comprise the next summer survey cruise scheduled in September 2011, as a continuation of the once every three years summer cruises in 2002, 2005 and 2008. By comparison over these 3-years intervals we observe increasing CO_2 contents of the seawater and related chemical changes. Moreover additional focus will be on exchanges with surface sediments and the adjacent intertidal Wadden Sea, notably towards assessing perceived changes of Alkalinity in the water column of the North Sea.

vi. Acknowledgements

Throughout the 2001-2013 period there is and has been significant and necessary support from several sources and organizations as follows:

- Netherlands LOICZ Program, Focus III 'Carbon and other cycles in the coastal zone'; grant entitled: 'Budgeting of carbon and related nutrient pools and fluxes in the North Sea employing a coupled hydrodynamic ecosystem model' (2002-2005; ALW/NWO project number 014.27.001)

- two grant entitled: 'The continental shelf pump; a pilot study in the North Sea' (2001-2005; ALW/NWO project number 810.33.004 and 810.33.007)

- grant entitled: 'CO_2 Buffering Capacity of the North Sea' (2008-2012; ALW/NWO project number 817.01.004);

- investment grant entitled: 'Observation Facility of the Oceans in a High-CO_2 World' (2005; ALW/NWO project number 834.05.005);

- grant entitled 'Dynamics of acidification in the North Sea: documentation and attribution' (2010-2013; ALW/NWO ZKO NorthSea project number 839.10.500)

- the EU CARBOCEAN Integrated Project (www.carbocean.org) in 2005-2009 with subsidy support to Royal NIOZ and to University of Groningen;

-the subsidy of the 'Klimaat voor Ruimte' program (http://www.senternovem.nl/bsik/projecten/hoogwaardig_ruimtegebruik/klimaat_voor_ruimte .aspBSIK); subproject Climate related shifts in the Netherlands Continental Platform ecosystem, and consequences for future spatial planning.

- the company SeaTrans AS for availability of the commercial vessel Transcarrier as a Voluntary Observing Ship platform;

- the Nederlandse Aardolie Maatschappij (NAM, Netherlands Petroleum Company) and afterwards Gaz de France (GdF) Suez for allowing access and supporting time series observations at the F3 platform in the central North Sea

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3. Benthic calcification in the Dutch Coastal zone and effect on ocean acidification on the growth of commercially important bivalve species

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Abstract

In the frame of this study, it has been shown that benthic calcifiers (dominated by bivalves) have a very important contribution to the local carbonate cycle in the Dutch coastal zone, especially in areas used for aquaculture (e.g. the Oosterschelde estuary and the Wadden Sea). As a consequence of the incorporation of anthropogenic carbon dioxide by the ocean, it is expected that its pH will decrease by 0.3 to 0.4 unit by the end of the century. This acidification will most likely have consequences on marine calcifiers such as bivalves. In the present study, it has been shown that calcification rates of adults of the blue mussel (Mytilus edulis) and the Pacific oyster (Crassostrea gigas) decline linearly with increasing pCO_2 with a potential decrease of 25 and 10 % toward the end of the century. Moreover, this acidification will also affect the early life stages of these economically important species as it has been shown that the growth of mussel (Mytilus edulis) larvae is significantly affected by a decrease of pH to a level expected for the end of the century.

i. Problem

The Intergovernmental Panel on Climate Change (IPCC) predicts atmospheric CO_2 partial pressure (pCO_2) ranging from 490 to 1,250 µatm in 2100 (IPCC, 2007). Because one third of anthropogenic CO_2 emissions has been stored in the oceans, ocean pH has already declined by 0.1 unit compared with pre-industrial values (Orr et al., 2005) and is projected to decrease by an additional 0.4 unit by the end of the century (Caldeira and Wickett, 2003). Seawater acidification will lead to a shift in inorganic carbon equilibria towards higher CO_2 and lower carbonate ion (CO_3^{2-}) concentrations. The calcium carbonate saturation state (Ω) will decrease although the surface ocean will remain almost entirely supersaturated ($\Omega > 1$) with respect to calcite and aragonite, the only exception being $\Omega_{aragonite}$ in cold waters (Orr et al., 2005). The carbonate ion is one of the building blocks of calcium carbonate ($CaCO_3$) and changes in its ambient concentration can thus affect the ability of calcifying organisms to precipitate $CaCO_3$. Indeed, marine organisms such as coral reefs, foraminifera, coralline algae, echinoderms and molluscs can produce calcareous skeletons or shells. As, at a constant salinity, calcium concentration is rather constant in the ocean, the calcification process mainly depends on the availability of CO_3^{2-}.

Since the seminal paper of Broecker and Takahashi (1966) reporting a dependency of calcification rates on $CaCO_3$ saturation state, several experimental studies have investigated the effect of a pCO_2 increase on the growth of calcifying organisms. At the start of the project, several experiments have shown a reduction of calcification at elevated pCO_2 in corals, coralline algae, coccolithophorids, pteropods and foraminifera (Gao et al., 1993; Spero et al., 1997; Leclercq et al., 2000; Riebesell et al., 2000; Langdon et al., 2003; Orr et al., 2005). At that time, few studies have investigated the detrimental effect of acidic waters on benthic heterotrophic calcifiers such as molluscs and echinoderms (Bamber, 1990; Michaelidis et al., 2005; Berge et al., 2006). Finally, the contribution of coastal benthic calcifiers to the global carbonate cycle suffers from a serious lack of knowledge. An estimate of the future effects of ocean acidification on the global and regional carbonate cycle requires important efforts in that direction.

ii. Aim

In the frame of this project, we aimed at:

1) estimating the production rates of calcium carbonate in the Dutch North Sea and to identify the major contributors in this region

2) studying the effect of ocean acidification on two bivalve species of a great economic value for this region: the blue mussel and the Pacific oyster and,

3) as early life stages of calcifying organisms are generally considered to be more sensitive to environmental disturbances (Raven et al., 2005), conducting experiments on the effect of ocean acidification on the larval development of the two bivalve species cited above in collaboration with the commercial hatchery Roem van Yerseke (Yerseke, The Netherlands).

iii. Results

In order to estimate the calcification rates (production of calcium carbonate) of the major calcifying species of the Dutch coastal zone, several databases of macrobenthic distributions along the Dutch coast from the Netherlands Institute of Ecology (NIOO-CEME) and from the Netherlands Institute for Fisheries Research (RIVO) have been linked. Moreover, the database from the North Sea Benthos Survey (NSBS-ICES) performed in spring 1986 and covering the whole North Sea has been integrated (see Fig. C-3.1 for the sampling design).

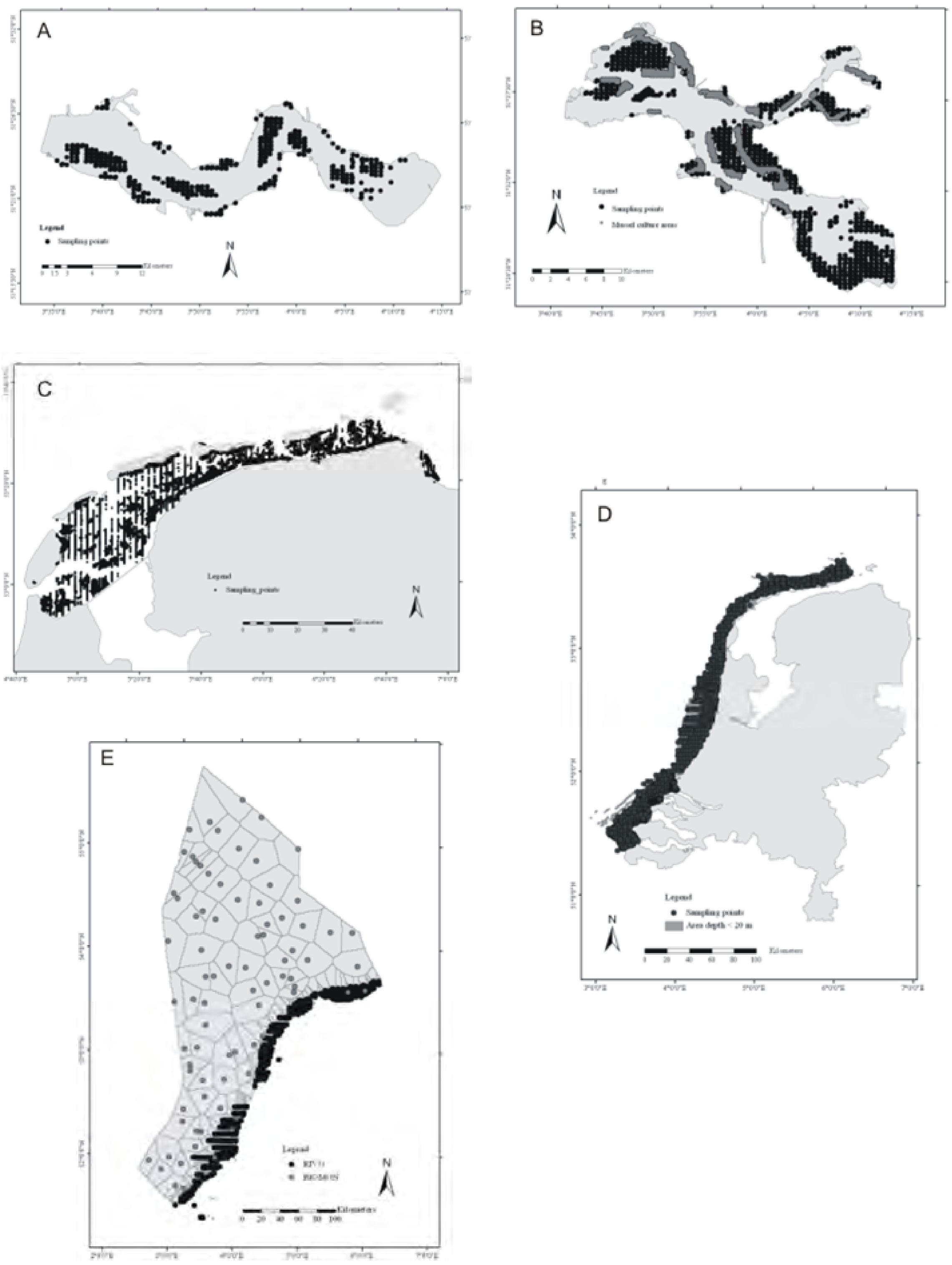

Fig. C-3.1: *Maps of the investigated areas showing the distribution of the sampling stations from which data of densities and biomass of the major benthic calcifiers were gathered (see text). A: Westerschelde estuary, B: Oosterschelde estuary, C: Wadden Sea, D: coastal North Sea and E: Dutch North Sea*

Empirical relationships linking size of the most abundant organisms and their shell weight have been established based on literature data. Rates of productivity for several species such as mussels and cockles have been found in the literature and compared with rates estimated from our database, which has allowed estimating the calcimass production of these species in the Westerschelde, the Oosterschelde, the Wadden Sea and the coastal North Sea area. Additionally, the shell content of the sediment in the Southern part of the Dutch coast has been analyzed in order to provide insights into the accumulation rates (production-dissolution-export) of calcareous structures in this area.

Results of this study, that shows a very important contribution of benthic calcifiers (dominated by bivalves) in areas used for aquaculture (e.g. the Oosterschelde estuary and the Wadden Sea) to the local carbonate cycle, are currently incorporated in a manuscript that will soon be submitted to an international peer-reviewed journal.

Effects of ocean acidification on commercially important bivalve species (adults)

A first study has been conducted at the Netherlands Institute of Ecology (NIOO-CEME) to assess the effect of ocean acidification on the net calcification rates of 2 ecologically and economically important species that are reared in Dutch coastal waters: the blue mussel (*Mytilus edulis*) and the Pacific oyster (*Crassostrea gigas*). This study, that has been published in a peer-reviewed journal (Gazeau et al., 2007), has showed that the calcification rates of these 2 species decline linearly with increasing pCO_2 (Fig. C-3.2).

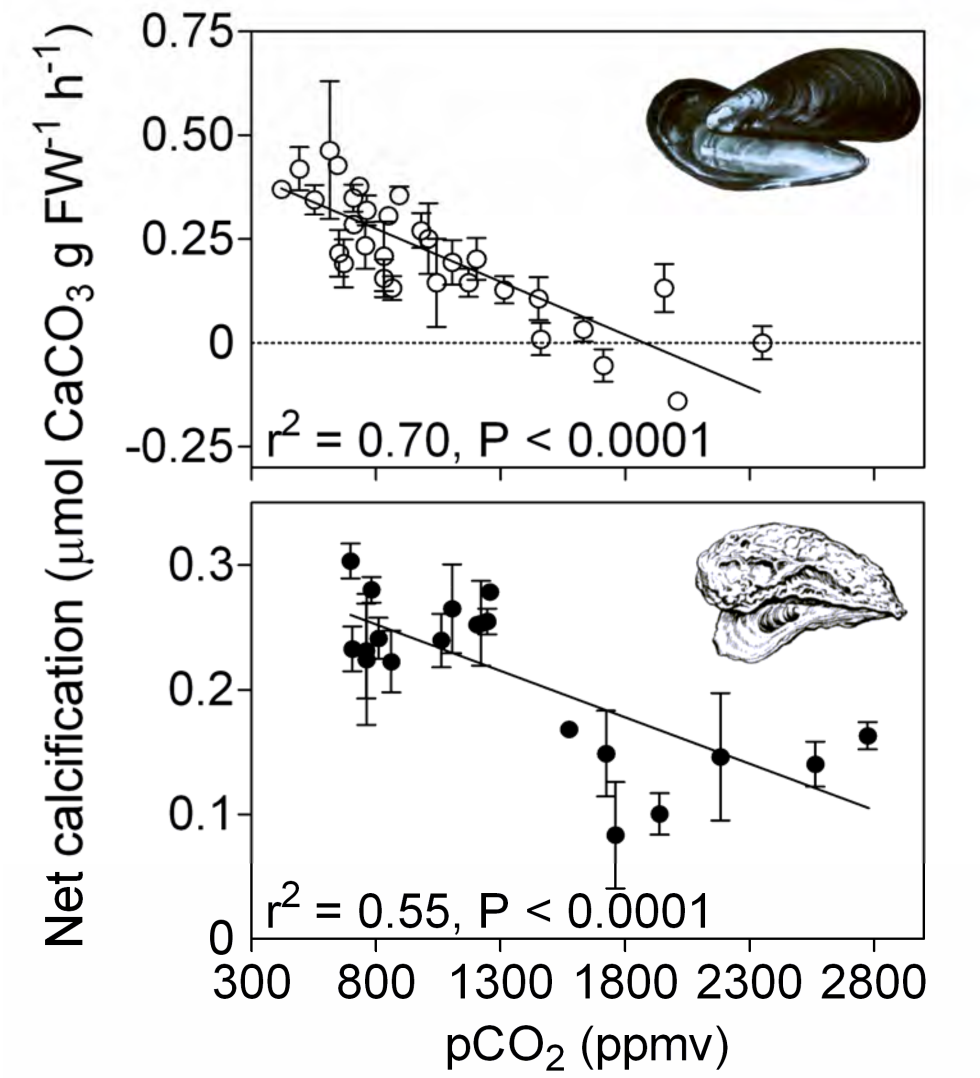

Fig. C-3.2: *Net calcification rates of Crassostrea gigas (Pacific oyster) and Mytilus edulis (blue mussel) as a function of seawater partial pressure of CO_2 (adapted from Gazeau et al., 2007).*

Indeed, mussel and oyster calcification may decrease by 25 and 10 %, respectively, by the end of the century, following the IPCC IS92a scenario (740 µatm in 2100). Moreover, mussels dissolve at pCO_2 values exceeding a threshold value of 1800 µatm. As these two species are important ecosystem engineers in coastal ecosystems and represent a large part of worldwide aquaculture production, the predicted decrease of calcification in response to ocean acidification will probably have an impact on coastal biodiversity and ecosystem functioning as well as potentially lead to significant economic loss.

Effects of ocean acidification on the blue mussel larval development

A study has been conducted at the hatchery Roem van Yerseke on the effect of ocean acidification on the larval development of the blue mussel (Mytilus edulis). This study that has been published in a peer-reviewed journal (Gazeau et al., 2010) has demonstrated that the growth of planktonic mussel (Mytilus edulis) larvae is significantly affected by a decrease of pH to a level expected for the end of the century (Fig. C-3.3).

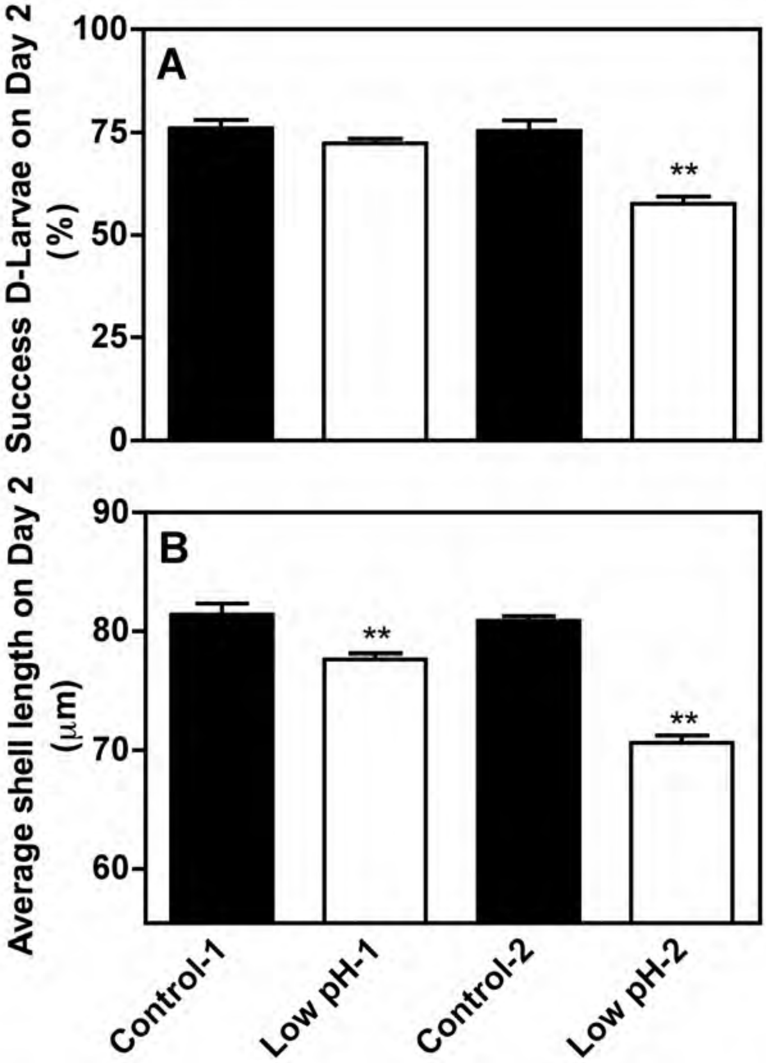

Fig. C-3.3: *Effect of ocean acidification on the larval development (first 2 days) of the blue mussel (Mytilus edulis). Empty bars: control pH (~ 8.1), black bars: low pH 1 (~ 7.8, oversaturation in aragonite), low pH 2 (~7.6, undersaturation in aragonite) (from Gazeau et al., 2010)*

Even though there was no significant effect of a 0.25-0.34 pH unit decrease on hatching and mortality rates during the first 2 days of development nor during the following 13-day period prior to settlement, final shells were significantly smaller at pH ~7.8 than at a control pH of ~8.1. More severe impacts were found with a decrease of ~0.5 pH unit during the first 2 days of development which could be attributed to a decrease of calcification due to a slight undersaturation of seawater with respect to aragonite. Although these results show that blue mussel larvae are still able to develop a shell in seawater undersaturated with respect to aragonite, the observed decreases of hatching rates and shell growth could lead to a significant decrease of the settlement success.

Effect of carbonate chemistry alteration on the early embryonic development of the Pacific oyster (Crassostrea gigas)

Although several recent studies have shown decreased growth rates and increased proportions of abnormal development under low pH conditions (see for instance above), they did not allow attribution to pH-induced changes in physiology or to decreases in aragonite saturation state. This study aims at assessing the impact of several carbonate-system perturbations on the growth of Pacific oyster (*Crassostrea gigas*) larvae during the first 3 days of development (until shelled D-veliger larvae). Seawater with five different carbonate chemistry conditions was obtained by manipulating separately pH, total alkalinity and aragonite saturation state (calcium addition). Results showed that the developmental success and growth rates were not directly affected by changes in pH or aragonite saturation state but were highly correlated with the availability of carbonate ions (see Fig. C-3.4).

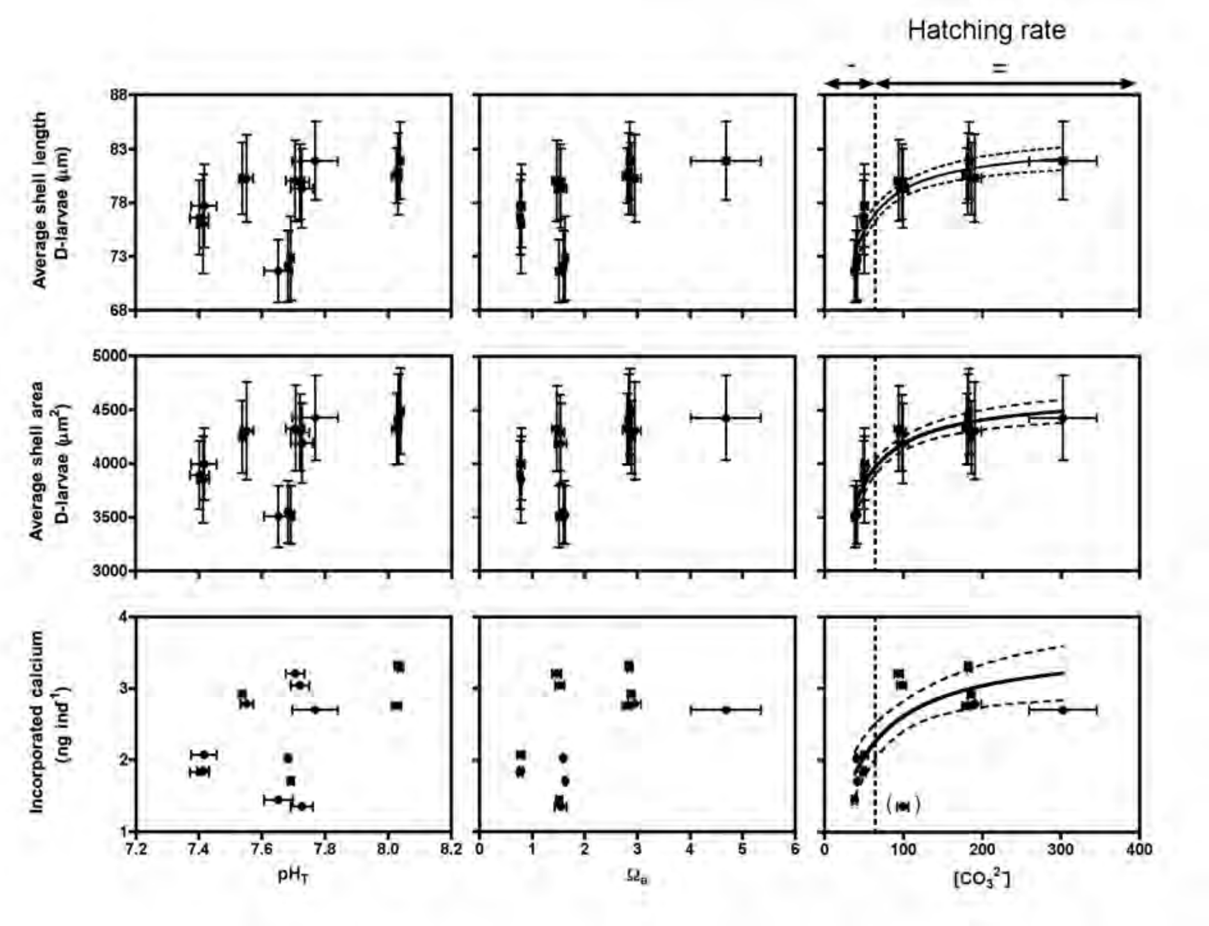

***Fig. C-3.4:** Relationships between the average (±SD) shell length and area of D-veliger larvae as well as the amount of calcium incorporated at the end of the 72 h incubation period, and the average (±SD) conditions of the carbonate chemistry in the five treatments; pHT: pH on the total scale (left plots), Ωa: saturation state with respect to aragonite (middle plots) and [CO_3^{2-}]: carbonate ions concentration (right plots). On the right plots, the dotted lines refer to the carbonate ions concentration at the aragonite saturation level (from Gazeau et al., submitted).*

In contrast to previous studies, both hatching and growth rates were not significantly altered as long as carbonate ions concentrations were above aragonite saturation levels, but they strongly decreased below saturation levels. These results suggest that the mechanisms used by these organisms to regulate calcification rates are not efficient enough to compensate for the low availability of carbonate ions under corrosive conditions. This study has been submitted to an international peer-reviewed journal (Gazeau et al., submitted).

iv. Conclusions

In the frame of this project, for the first time, an estimate of the calcium carbonate production by benthic calcifiers has been carried out in the Dutch North Sea. This is the first regional study since Smith (1972) in Southern California. The calcifying benthic communities, in this area, are dominated by bivalve mollusks that are cultivated especially in the Oosterschelde estuary and the Dutch Wadden Sea. Several studies have been conducted in the frame of this project to assess the effect of ocean acidification on these economically important species. These studies revealed that both mussels and oysters are will be at risk in the coming decades.

v. Recommandations

In order to accurately predict the future of commercially important species in a high-CO_2 world, research efforts will need to be made in order to:

1) investigate the cumulative effects of both warming and acidification on these species,

2) study their sensitivity to these perturbations under conditions that better reflect their natural environment (presence of predators, competitors etc.),

3) assess their capacity to acclimate and/or genetically adapt to such modifications of their environment.

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D. Socio-economic influences

1. Interview with Prof. Dr. S. Hulsher
2. The sustainability challenge: an analysis of prerequisites for an integrated coastal zone management in the Netherlands
3. Congruent scales in economics, coastal engineering and Morphology
4. Long term institutional continuity and change in Dutch coastal zone and river management

1. Interview with Prof. Dr. S. Hulscher

How the coastal zone is experienced

"We still know too little about the physics of the coastal area. Many questions remain unanswered", says Suzanne Hulscher, professor at the University of Twente and project leader of LOICZ socioeconomic aspects. Still a lot of questions? "Yes, when we started the research we assumed that we would be able to draw upon a considerable knowledge base in this area. But we were sorely disappointed. In fact, hardly anything was known. This meant that we first of all had to itemise what was known and then fill in the gaps in

knowledge before we could start on the actual aim of the research, namely bringing together the morphological aspects and the socioeconomic dimension."

What exactly was not known?

Hulscher: We knew little about the dynamics of the dune areas and exactly how the dunes are managed. Up until now all the safety models assumed that the coastal area was static and remained unchanged, even though that is clearly not the case. There is nothing more changeable than the dunes. If you want to make socioeconomic statements about that area then you need to know more about dune dynamics.

And about safety?

Yes, and about safety. Although they number but a few, some people live on the unsafe side of the dune erosion line. These people like living there even though they know there are risks involved. They appear to be prepared to run those risks. Yet are they really aware of what those risks are? And what factors other than safety play a role in their choice? Just exactly how rational or emotional is the choice made? Can we discover patterns in these decisions?

And what if we know all of this?

Then the next question is whether the government has the duty to inform these people about the risks involved. We can ask ourselves if society has the obligation to prohibit people from living at these locations. What do these considerations mean for the price of the houses concerned? Our research can reveal how risk perception affects people's choices to live by the sea at locations in the safety zone.

What was the first step in the research?

We first of all documented the various management measures over the past thirty years. At the same time, we investigated the dynamics of the dunes in the Netherlands and an unmanaged area of dunes along the Danish coast. We wanted to know the effect of planting European marram grass and how quickly dunes shift.

Why did you want to know that and how could that information help a policy maker?

If you know how the dunes change, how quickly, and why, then you know what to expect and how to allow for that. Then you can respond to the changes. Should you issue permits to residents for houses outside of the safety zone? How can you reach responsible choices?

What's new in the research?

Until quite recently the research mainly focussed on the physical and morphological phenomena. How high or wide are the dunes? At this moment we are mainly interested in the socioeconomic aspect of the area. The research has become more complex because it has become multidisciplinary. We want to know more about the physical aspects of safety. We want to possess enough knowledge to make sustainable choices for the longer term. Stabilising the dunes is too expensive, because you need to perform a range of interventions to keep the dunes in place. However, it is not only expensive. It also goes against the natural dynamics, and nowadays our ethos is more attuned to working with nature: Building With Nature. That can be more responsible from an ecological perspective as well as cheaper. We need to get away from our small-scale approach to working. I am calling for a national and integrated approach in which we not only look at the morphological changes but also the sociological and economic effects of these.

2. The sustainability challenge: an analysis of prerequisites for an integrated coastal zone management in the Netherlands

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Abstract

This project aimed to develop multidisciplinary knowledge for a more sustainable and integrated coastal zone management by reflecting on existing forms of coastal governance and knowledge use. A review of coastal governance on different levels as well as a review of the usefulness of decision support system for coastal management has resulted in a list of conditions that have to be fulfilled in order to enhance the changes for a more successful integrated coastal zone management. This set of prerequisites was used to structure action research on the development of integrated coastal zone projects in Bulgaria. The project has also resulted in the development and testing of QUASTA, a computer-based tool that can be used in structuring societal debates by visualizing the relations between stakeholder ideas. The Quasta tool is among others tested in a project in which explorative scenarios for the future of Netherlands coastal zone were elaborated.

i. Problem

Coastal zones are multifunctional areas. In the Netherlands coastal zone, both economic functions (shipping, tourism, bulb growth, fisheries, and drinking water extraction in the dunes) as well as ecological functions (wetlands of international importance) can be found. Dunes not only have an ecological value, but – on together with the dikes - are of major importance in protecting the low-laying hinterland against flooding. Moreover, many parts of the coastal zone have important cultural functions as well.

The sustainable development of the coastal zone asks for an integrated management, a coherent territorial approach of policy problems and different interests. Such an integrated approach, that aims to optimise the economic, ecological, social and cultural well-being of the coastal area and its (future) users, also has the ambition to respect natural processes and dynamics and to take into account the limits (carrying capacity) natural processes set. In practice this means that several levels of decision-making, several policy sectors and a large number of stakeholders are involved in integrated coastal zone management. Integrated coastal zone management can be considered a multilevel, a multi-sector and a multi-actor governance process, in which knowledge plays a key role. Scientists do provide this knowledge, but there has been a growing recognition that other stakeholders have relevant knowledge as well about sustainable coastal development. Dialogues between these groups are important in order to stimulate learning processes.

ii. Aim

This project aimed to develop multidisciplinary knowledge for a more sustainable and integrated coastal zone management in the Netherlands. More specifically we wanted to get insight in the functioning of governance networks and in the way knowledge was used in coastal decision-making. By conducting document analysis, by interviewing key informants and by organizing focus group sessions, insight in the functioning of governance networks and in knowledge use was gained. Following this a list of prerequisites for a successful integrated coastal zone management has been developed.

Furthermore we had the ambition to explore new methodological pathways to address knowledge-related problems. This ambition is realized by developing and testing the Quasta-tool.

iii. Results

Characteristics and functioning of governance networks

Governance networks dealing with the coastal zone area appeared to be multilevel, multi-sector and multi-actor (Dieperink et al., 2003). Policies have been made both on the European, the national and the regional level. We first focused on the steering capacities on the European level. Effective governance requires a clear conceptualization of the required activities of the actors that have to take action. Moreover these actors have to accept the requirements as legitimate.

Our research revealed that on the European level both the intergovernmental Council of Europe and the supranational European Union have been involved in the process of developing a regime for integrated coastal zone management (ICZM) since 1970 (Benoît-Rohmer and Klebes, 2005; Commission of the European Communities, 1995 and 2000; Council of the European Communities, 2002). The Council of Europe consist of a Parliamentary Assembly and a Congress on Local and Regional Affairs with respectively a consultative and an advisory status. Decision-making powers are only vested in the Committee of (Foreign Affairs) Ministers of the Member States. The European Union also has a ministerial Council, but this European Council can only make decisions based on the initiatives of the Commission and in cooperation with the European Parliament. Both institutions have produced an ICZM regime by issuing principles, norms and rules aiming at a more integrated coastal zone management. Although both regimes have unique features, their contents mainly overlap. In principle the EU has more steering capacities as it is able to issue legally binding regulations. However, so far both organisations have only issued legally non binding Recommendations and Policy Documents addressing national governments (although the Council documents also address coastal developers and engineers). Both organisations conceptualize integrated coastal zone management by issuing guiding principles instead of more concrete obligations. The 2002 Recommendation of the European Parliament and Council on ICZM (Council of the European Communities, 2002) recommends member states' coastal policy makers to work from a broad "holistic" perspective (thematic and geographic); to have a long term perspective; to use adaptive management (responding to new information and conditions) during a gradual process; to reflect on local specificity while solving problems; to work with natural processes; to use participatory planning to involve all relevant stakeholders; to support and involve all relevant administrative bodies; and to combine instruments to ensure coherence. The EU further stimulates Member States to develop a strategic ICZM approach by suggesting general procedural steps to be taken. Moreover the EU has funds (LIFE, INTERREG) to stimulate ICZM in practice. As both regimes appear to overlap or complement each other, the existence of two regimes on ICZM is neither curse nor blessing.

The existence of two ICZM regimes might be confusing, but this appeared not too problematic for Member States as our research also made clear that Dutch coastal governance practice was hardly influenced by EU ICZM-policies (Dieperink and Steyn, 2005). Formally the Netherlands implemented the EU Recommendation on Integrated Coastal Zone management in time, but 'the' Dutch national strategy appeared to be very abstract and fragmented and could only be identified after analysing and combining different policy documents like the Third Coastal Policy Document and the National Spatial Strategy (Ministerie van Verkeer en Waterstaat, 2000 and Ministeries van VROM, LNV, VenW en EZ, 2006), that don't address both land and seaside at the same time. As a result the division of tasks and responsibilities within and between different coastal governance networks remained unclear. Further assessment of the practical application of the eight above mentioned principles of integrated coastal zone management in five regional coastal zone projects (the "Memorandum Integrated Coastal Zone Management West Zeeland Flanders, the Project Integral Vision Delta waters", the 'Integrated development of the South Holland coast' and the 'Duinzoom Plan Den Helder / Zijpe' and the "Management plan for the island Rottum" in the Wadden Sea) revealed that in most projects the principles were addressed, although not explicitly. The involved actors were barely aware of the existence of the EU recommendation and the principles played only an implicit role during the policy process.

The analysis of the European regimes and the implementation of the EU-regime in the Netherlands made clear that governance networks on different levels operated too a large degree independent from each other. Therefore we decided that prerequisites for an ICZM had better be sought following an in-depth analysis on the project level. In order to define a priori prerequisites to structure this research a literature review concerning integrated policy making was done to be followed by an assessment of the Zeeland Weak Chains Projects (Voskamp, 2006; Voskamp and Dieperink, 2006). These projects aim to reinforce weak points in the coastal defence structure but also to improve spatial qualities of the coastal areas. The assessment revealed that most of theoretically relevant success conditions for an integrated approach were present (like an appropriate institutional structure, a good understanding of the area, an adequate process development). In the early phases of the projects actors involved showed enough political will and support for an integrated approach. In the end, however, the Public Works Department, the initiator of the project was only willing to pay for measures directly improving coastal defence. Additional financing had to be provided by other actors.

In order to enhance the societal relevance of our research we decided to further specify the prerequisites found by an additional literature review. This list of 15 conditions found was tested and refined in action research on the development and evaluation of 4 integrated coastal zone projects in Bulgaria (Dieperink et al., 2010; MyCoast, 2010).

Knowledge management: sources, models and policy relevance

For getting more insight in the use of knowledge we first have identified the extent to which existing Decision Support Systems (DSSs) specifically designed for ICZM were helpful in meeting sustainability challenges (Van Kouwen et al., 2008a). These systems are aimed at making relevant knowledge about biophysical or socio-economic processes interactively accessible for decision-makers. A number of knowledge- and process-related challenges were identified for ICZM, which resulted in a set of required DSS functionalities that might be helpful in meeting these challenges. Next we identified which of these functionalities have been incorporated into existing DSSs. We discovered that many functionalities were not or only rarely offered by these existing tools. As none of the investigated tools combined all functionalities, there appeared to be a dichotomy between policy-oriented problem structuring tools and research-oriented impact assessment tools. In this respect, the tools did not bridge the gap between research and policy-making, but appeared to be rather part of the problem.

The second part of the research aimed at exploring possibilities for a new type of computer-based tool (Van Kouwen, 2007; Van Kouwen et al., 2008b; Van Kouwen et al., 2008c). The formalism of Qualitative Probabilistic Networks (QPNs) was designed in the 1990s and can be used to analyse diagrams based on cause-and-effect relationships. These diagrams, known as Cognitive Maps, have nodes representing variables and arrows representing causal relationships between these variables. Three properties jointly distinguish the formalism of QPNs from other methods for analysing Cognitive Maps. Firstly, the analysis is purely qualitative, allowing analysis of a Cognitive Map without any quantitative information. Secondly, contradictory influences on a variable will always be detected and highlighted as ambiguity, indicating that quantitative information is necessary for drawing unambiguous conclusions. Thirdly, QPNs allow forward and backward reasoning, which, graphically speaking, means that the direction of reasoning is in the direction of arrows, as well as in the opposite direction. This means that the technique can be used for both predicting and explaining. This has offered a practical starting point for an interactive problem structuring tool that can facilitate dialogues relevant to sustainability challenges.

This tool, called *Quasta*, was evaluated in four workshops in which various sustainability issues were discussed. During one of the workshops, part of the project Sustainable living in the Dutch coastal zone, four scenarios for a future coastal zone were explored (Van der Vlies et al., 2007). The scenarios differed with respect to the degree of concentration of economic values in the lower parts of the Netherlands and in the basic societal attitude towards the sea (control or manage). In these workshops, a facilitator invited stakeholders to put forward their issues, which were linked to each other after a short discussion. Quasta was used to visualize the argumentations of the stakeholders (see Fig. D-2.1).

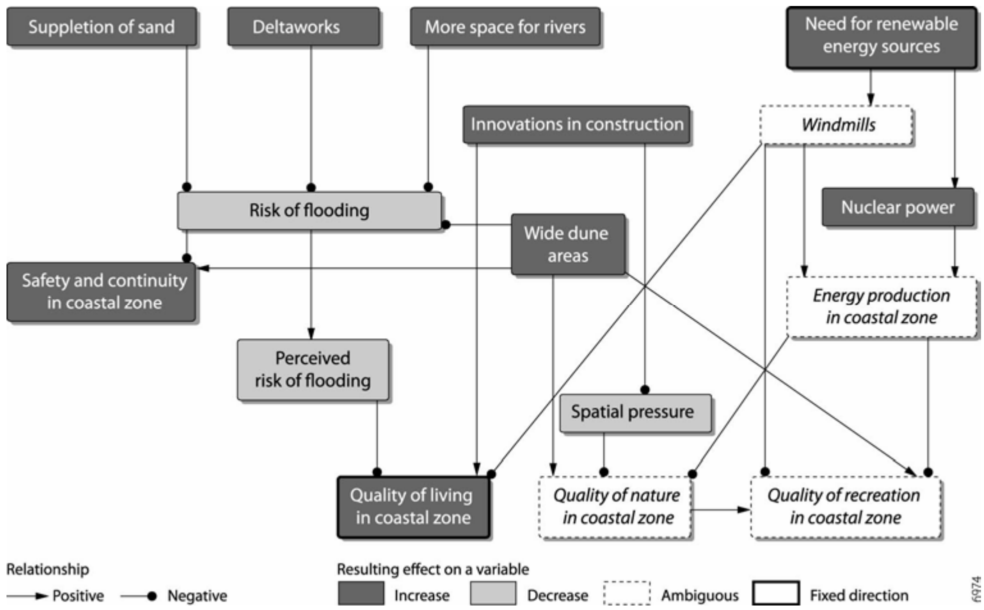

Fig. D-2.1. *Example of a scenario analysis with Quasta*

After the workshops the following four hypotheses were empirically tested (van Kouwen et al., 2009): Quasta (1) helps stakeholders to become aware of causal relationships; (2) helps in exploring possible scenarios; (3) identifies the need for further (quantitative) knowledge and; (4) has a low threshold for non-technicians. It was concluded that Quasta exhibits each of these four characteristics. However, there were a number of factors that may have affected the success of applying Quasta. Nevertheless, the results are positive thus far as the workshop participants came up with a number of additional arguments supporting the usefulness of the tool.

Compared to the existing DSS tools aimed at problem structuring, Quasta has some advantages (Van Kouwen et al., 2009). It can be used for backward reasoning ("backcasting") and in theory it can deal with uncertainty by linking it to analytical models, although an active linkage has not been tested in practice. The most important result is that Quasta is considered a useful tool for improving problem structuring; the tool helps to map out the ideas and knowledge of policy-makers, researchers and stakeholders in an explicit manner. As such, it offers a structured approach to start the process of jointly identifying a problem. Based on the results of the initial problem structuring step, the need for further (in-depth) knowledge can be clarified. By working this way, the tool promotes the generation of knowledge that will address the specific problems identified. Moreover, the Quasta tool is a flexible instrument; as soon as there are new insights and problem perceptions, the Cognitive Map can be adjusted, new scenarios can be explored, and the resulting need for further knowledge can be identified. During the workshops, Quasta acted as a 'mirror' for the arguments of the workshop participants. While the tool allows stakeholders to visualise the logical implications of their arguments, it often occurred that the outcomes of Quasta's scenario exploration did not entirely match the participants' expectations. A possible explanation for this is that, in these cases, the diagram was not consistent with the perceived problem structure; but this did allow the inconsistencies to be traced and corrected. The other possibility is that, after tracing the reasons for Quasta's outcomes, the analysis makes sense to the participants after all. In these cases, the tool has facilitated a learning moment by making participants aware of relationships that they did not see beforehand. This is also indicated by the workshop evaluations, in which participants confirmed that the computer analysis made them aware of causal relationships. In both cases, Quasta improved communication and contributed to a better utilisation of knowledge.

iv. Conclusions

Our research has resulted in 15 prerequisites for an integrated coastal zone management:

1) Important stakeholders must perceive a situation as undesirable; there should be a shared sense of urgency in society to improve the quality of a coastal area;

2) Those stakeholders who are absolutely indispensable in making strategic decisions and implementing policies are willing to participate;

3) Stakeholders with similar backgrounds and representing similar interest should be organized and speak with one voice;

4) Stakeholders should (be able to) respect each other's opinions and commitment;

5) Stakeholders have insight in mutual interdependencies and take major dependency relations between public and private actors into account;

6) Stakeholders should be able to incorporate new knowledge and views;

7) Stakeholders have a clear image of the role they have to play;

8) Participants must be willing to negotiate with each other: they must have enough scope to defend their own interests, but are also willing to consider new ideas and solutions;

9) Participants should have flexible mandates from their constituencies and the representatives should have authority within their stakeholders' community;

10) The process should be transparent (at least within the stakeholders' community) and clearly documented;

11) Intermediate and small step results should be emphasised to show the added value of the approach and act as a catalyst for next steps;

12) The results are accepted in formal political decision-making processes;

13) Process results can be formalised using existing legal instruments;

14) Personal and financial means are made available to organize and to participate in the process; stakeholders are willing and capable to organize or host meetings, to put forward discussion topics and time schedules;

15) Apart from the politically responsible initiator a dedicated neutral and skilled process manager should be present who organizes the entire process in such a way that participants are kept at the table, remain interested and learning.

The research also showed that Quasta can help to improve the use of knowledge in coastal zone management. However, it is not clear yet if it will do so in the future, as the role of Quasta has yet to be tested in 'real' decision-making processes. Further development and more applications are required to investigate its potential role in these processes. Nevertheless, the results of our research indicate that the Quasta approach provides some added value in comparison to existing methodologies. Later applications of Quasta in other projects like a stakeholder discussion about climate change adaptation in the Rotterdam port area confirm this (Quasta, 2010).

v. Recommendations

Policy makers who develop future ICZM-projects should be aware of the prerequisites that enhance the successes of their projects and to consider the possibilities of the Quasta-approach. Although Quasta has been developed during this research, it has a much wider application for problem exploration and policy development in multi-stakeholder settings as it can speed up problem analysis.

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3. Congruent scales in economics, coastal engineering and morphology

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Abstract

Complex human-environment systems are characterized by a diversity of components and local interactions among them that produce nonlinear feedbacks between different scales. Lack of understanding of micro-foundations of macro-phenomena (such as total economic value of the area or patterns of dune formation) can make coastal zone management and spatial planning policies inefficient and unpredictable. This research project aimed to understand what the links between micro and macro scales in economics and coastal morphology are. Two research projects (one with the focus on coastal morphology and another on economics) have generated knowledge and models that contribute to the understanding of this challenge. We focused on the Dutch coastal towns with 'outside-flood defense' areas, where the flood defense consisted of foredunes. In this case, the so-called safety line serves as a linking element between the two subprojects. The safety line is the line that is based on the estimated erosion line but can be adjusted (e.g. moved landwards) depending on the value of economic activities at risk. This report first briefly introduces the problem. Then the aim and results from both subprojects are discussed. Namely, the results of the economic land market modeling under various assumptions about individual behavior and implications for coastal policy are discussed. Further, a conceptual model regarding the impact of soft coastal engineering measures on foredune development over a range of scales is presented, which resulted from morphologic analyses of differently managed foredunes along the Dutch and Danish coastlines. Finally, we provide conclusions and some recommendations that resulted from this research effort.

i. Problem

Coastal zone management (CZM) is a field where a variety of disciplines meet, such as coastal engineering, coastal morphology and economics. It requires insight into long-term coastal developments, both economically - to examine how economic activities can adapt to the dynamic coastal environment- as well as morphologically - to determine the space available for socio-economic developments. CZM policy in the Netherlands aims at reducing risk, which is defined as the probability of a disaster (coastal erosion and flooding) multiplied by economic damage (Rijkswaterstaat, 2005a). In coastal areas with sandy shores this probability of disaster not only depends on the probability of occurrence of an extreme storm event, but also on the morphology of the coastal dunes that protect the hinterland. In the Netherlands, the dunes even act as a formal part of the flood defense system, in particular the foredunes.

Obviously, dunes are not static and their actual strength at the time of a future storm event depends on both long-term evolution of the dune area as well as short-term, small-scale developments. Direct economic damage depends on land use patterns and value of properties under risk, which, in turn, are the outcomes of individual microeconomic interactions in a land market. Thus, large-scale patters and macro-phenomena (e.g. economic values under risk or a position of the erosion line) are the emergent outcomes of numerous interactions at micro-level.

The challenge is to understand the links between different scales both in economics (subproject 1) and in coastal engineering and morphology (subproject 2), and to shed light into how this knowledge may help guiding CZM to reduce flood or erosion risk in coastal areas. The linking element between the two subprojects is the so-called safety line, which is based on the estimated position of the erosion line due to an extreme storm event, but which can be adjusted (e.g. moved landwards) depending on the value of economic activities at risk (Fig. D-3.1).

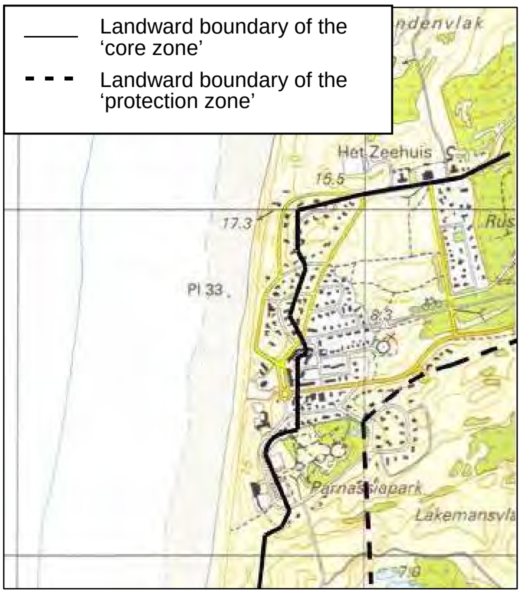


Fig. D-3.1: *A coastal town under risk (source: Rijkswaterstaat (2005a).Sea-side town in the Netherlands with coastal protection zonation (safety lines) that affects the regulations regarding land-use and activity allocation. In this area the flood protection is provided by coastal dunes. The zonation is hence derived from a safety assessment of coastal dunes based on storm erosion calculations and economic value under risk. The 'core zone' refers to the zone that is currently part of the coastal defense against flooding. This zone has no legal protection level with respect to coastal erosion or flooding. The 'protection zone' is the zone that may become part of the coastal defense zone in the next 200 years due to expected rise in sea level.*

Direct economic damage depends on land patterns and value of properties under risk (Rijkswaterstaat, 2005b), which, in turn, are the outcomes of individual microeconomic interactions in a land market (Alonso, 1964). However, the transition from micro-scale individual homeowners' behavior in a land market to macro-measures used by policy-makers is discontinuous, non-linear and may be associated with emergent effects and properties. This transition from micro-foundations to macroeconomic phenomena happens through the mediation of markets. Aggregation is usually possible by assuming a rational representative agent and the existence of a unique equilibrium. Moreover, the majority of economic models is aspatial. Few 2D models assume only two characteristics of the landscape (distance to the employment center and either environmental amenity (Wu and Plantinga, 2003) or hazard risk (MacDonald et al., 1987; Tatano et al., 2004) but not the latter two together). The challenge is to construct a model that can comprehend the direct modeling of a market (to allow tracking the micro-macro economic links) where agents with heterogeneous preferences and perceptions interact in the 2D landscape.

When dunes act as coastal flood defense, a short-term dune erosion model is used to predict the position of the so-called erosion line due to the occurrence of a predefined normative storm event. This erosion line controls to a large extent which part of the coastal area can be currently considered part of the flood defense. The assessment of the part of coastal area needed for long-term flood defense purposes (e.g., in 200 years) requires information on the future state of the coastal dunes, and in particular of the foredunes. Current knowledge about evolution of coastal dunes at the decadal time-scale is however limited. Moreover, where dunes act as coastal flood defense, their evolution will not only be determined by natural processes, but they will also be influenced to some yet unknown extent by human interventions (e.g. sand nourishments). Besides this lack of knowledge, the large-scale morphodynamic models that will be needed for long-term prediction of coastal evolution are generally spatially aggregated and do not provide the level of spatial detail required for dune erosion modeling (Van der Burgh et al., 2007).

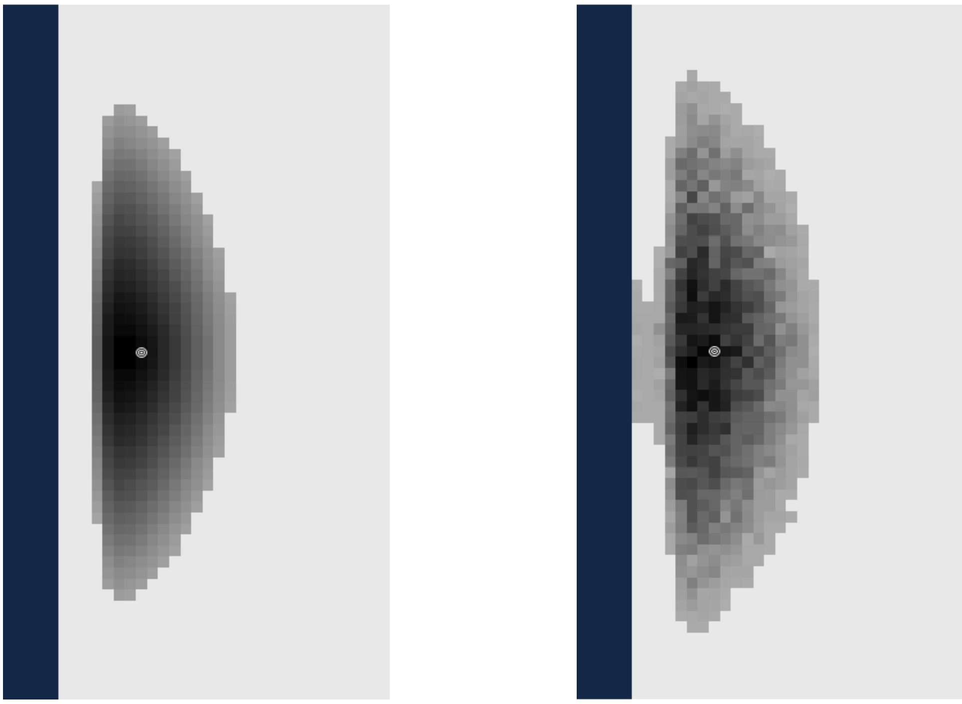
ii. Aim and results from economics and coastal morphology subprojects: Scales in economics in coastal areas

Aim:

The main aim of this subproject was to get insights into how aggregated economic phenomena in coastal area (land patterns and land prices that determine direct economic damage in the case of a coastal disaster) emerge from interactions of individual agents (e.g. households) in a land market.

Results:

To accommodate more spatial and agent heterogeneity and to allow the study to be spatially explicit, we adopt an agent-based approach, which helps to understand the effects of relaxing some of the conventional economic assumptions and their implications for coastal risk management policy. The newly developed model (ALMA) combines advantages of spatial economics and cellular spatial simulation models covering the methodological gap between the two (Parker and Filatova, 2008). We performed several sets of experiments with the model. Firstly, a structural validation of ALMA against conventional analytical urban model was successfully performed (Filatova et al., 2009a). Secondly, the simple urban model is extended to account for heterogeneous attributes of the landscape (environmental coastal amenities and flood/erosion risk in addition to distance to the employment center) to replicate the structure and complexity of a typical Dutch coastal town (Fig. D-3.1). Thirdly, we add heterogeneity among economic agents in order to move beyond the representative agent concept. Experiments with agents heterogeneous in their levels of flood risk perception demonstrate that individuals who underestimate coastal risk drive land market into economically inefficient high risk zone (Fig. D-3.2).



a) Representative agent b) Heterogeneous agents

Fig. D-3.2: *Land rent gradients (the darker the color the higher the land price) in a coastal town with spatial amenities and disamenities: a) representative rational agent model is usually used in economic models for policy decision support. It also shows the boundary for economically efficient allocation of urban developments. b) Agents with heterogeneous flood risk perception (average risk perception in the population is equal to the one of a representative model).*

This implies that a representative agent model normally used for policy decision support would underestimate developments in the flood-prone zone and, consequently, the direct flood damage (Filatova et al., 2009b). As a next step, we analyze the changes in the outcomes of a coastal land market due to the shift of the erosion line, i.e. increase of a probability of erosion because of climate change (Filatova, 2009). Finally, a survey, which explores coastal flood risk perception and location choices, was carried out in 2008 in the Zeeland province. The surveys analysis shows that coastal flood risk perception is low, while coastal amenity is an important factor. These factors affecting decisions to buy properties in flood-prone areas are likely to bias efficient coastal land market outcomes. The land market model parameterized with the actual survey data about individual risk perception of Dutch population shows that all the area seawards from the erosion line will be developed magnifying economic values at stake (Filatova et al., submitted).

iii. Scales in coastal engineering and morphology along dune protected coastlines

Aim:

This subproject aimed at improving the knowledge on decadal-scale variability of human-altered foredunes and to improve the understanding of the impact of coastal management strategies on the evolution of the foredune system on the long-term.

Results:

To improve the knowledge on decadal-scale variability of human-altered foredunes several case studies were performed on the decadal evolution of foredune morphology under various regimes of dune management in similar as well as different environmental settings. Study sites were located along the Dutch coast and the Danish Coast.

EOF-analysis of a large data set of repeated elevation measurements across the foredune along the Dutch west coast showed that these highly managed foredunes, where measures generally aimed at stabilization of the foredune, were still quite variable in shape at the decadal timescale (Bochev-Van der Burgh et al., submitted, a). In areas where dune management measures were most intensely applied, the shape of the foredune appeared to be more variable in time than in areas where hardly any measures were applied. This could be explained by the reactive nature of the dune management strategy applied at these sites, i.e. measures were only applied when changes occurred. Hence, the most dynamic areas were most intensely managed. Also, the applied measures essentially mimicked small-scale natural recovery processes When the coastal management strategy was more pro-active in nature and measures were not restricted to the dune area itself, i.e. beach and offshore nourishment were applied, the impact on dune morphology appeared to be more pronounced (Bochev-Van der Burgh et al., 2009; Bochev-Van der Burgh et al., submitted, b).

An analysis of similar coastal management strategies in different environmental settings (Wadden Island coast), as well as a comparison of foredune behavior in a situation with and without management measures (Danish west coast), led to the formulation of a conceptual model regarding the impact of soft coastal engineering measures on foredune behavior over a range of scales (Fig. D-3.3). The underlying concept is that coastal engineering measures that are generally applied to dunes with flood defence functionality usually have a natural counterpart but at varying levels in the coastal system hierarchy.

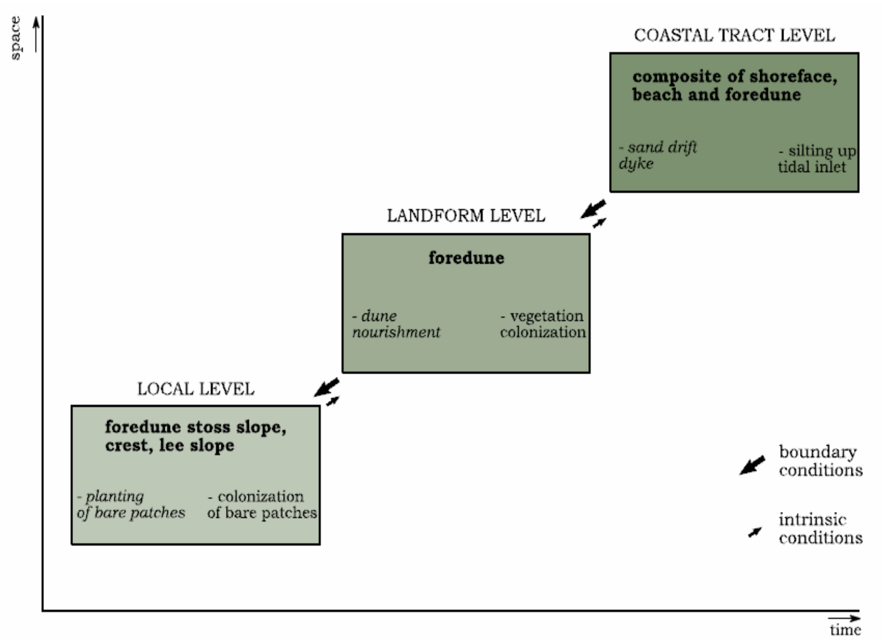


Fig. D-3.3: *Conceptual model on congruent scales in foredune morphodynamics and soft coastal engineering measures*

These natural counterparts provide insight in the extent of impact (temporally and spatially) that may be expected from certain measures in a given environmental setting.

iv. Conclusions and Recommendations

Economic subproject

A new spatially explicit land market model structure facilitates the coupling of economic models with the 2D morphological and ecological ones. The novelty of the ALMA model is that it combines the advantages of the analytical urban economics, cellular automata and spatial econometrics models by allowing direct modeling of a land market for heterogeneous agents in a 2D heterogeneous landscape. Thus, it serves as a computational laboratory to explore land patterns and land prices in a coastal land market emerging under different assumptions about individual economic behavior. Specifically, the outcomes of a land market parameterized with the results of our survey, which showed that in the Netherlands coastal flood risk awareness is low and attractiveness of coastal amenities is high, can be quantified and visualized in a 2D landscape.

We conclude with the following implications of this study for coastal risk management: 1) importance of accounting for individual and spatial heterogeneity: the conventional economic models used for policy making and decision support (general equilibrium or econometric ones – both assuming a representative agent), might misrepresent the aggregated behavior of the real-world economic agents that are highly heterogeneous. Our simulations showed that individuals with low flood risk awareness drive urban developments in coastal areas into the zone that a representative agent considers economically inefficient. Thus, potential damage from natural hazards in coastal towns might grow beyond the level anticipated by policy makers, especially in the outside-dikes areas in the Netherlands. This result holds even if erosion line shifts, i.e. probability of hazard increases due to climate change; 2) low flood risk awareness biases microeconomic decisions in a land market, and leads to inefficient land use outcomes and increase of risk in hazard-prone areas. Thus, measures to increase flood risk awareness at the individual level (such as risk communication, financial and technical instruments) can be employed by policy makers to reduce total flood risk along with traditional flood defense measures.

Coastal engineering and morphology subproject

The insights derived from understanding links between scales in coastal engineering and morphology in the case of dune protected coastlines, contributed both to the issue of translating information between scales as well as to guiding CZM by realizing coastal management measures at an appropriate scale. Regarding the translation of information from one scale to the other, it was suggested that EOF decomposition of observed dune profiles could provide simple but realistic dune shape functions to redistribute forecasted dune volumes from spatially aggregated large-scale morphodynamic models into realistic dune shapes in order to improve the knowledge on the possible future position of erosion lines due to extreme storm events. Regarding guiding CZM, the following insights were derived for dune protected coastlines. When proposed (soft) coastal engineering measures mimic natural processes that act at a higher level in the coastal system's hierarchy its impact on the foredune morphology (hence coastal safety) will not only be more pronounced, but it is also expected to control which, or whether, additional lower level measures are still needed.

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4. Long term institutional continuity and change in Dutch coastal zone and river management

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Abstract

The central question of this research project was: how can we understand long term continuity and change in institutions and policies in Dutch coastal zone and river management, and which factors are relevant to understand the patterns of continuity and change observed? In our research, we focused in particular on the changing role of Rijkswaterstaat. We concluded that new ideas and discourses, which are disseminated by coalitions or epistemic communities, focusing events, focusing projects, and elections turn out to be relevant to understanding institutional dynamics. In adapting to the changing societal and political circumstances, Rijkswaterstaat found itself caught on the horns of a dilemma: between preserving its expert status on the one hand and developing into a more responsive and efficient public organisation on the other.

i. Problem

Dutch flood management institutions and policies display both continuity and interesting dynamics. On the one hand, Dutch water managers continue building and strengthening dikes and other flood defences to protect the Netherlands against sea and river floods. On the other hand, they recently have developed various new 'soft-engineering' alternatives, such as the creation of room for the river, for example by removing dikes, or by depoldering agricultural areas. To understand these developments, we focused particularly on the changing role and positioning of one of the most important organisations in the Dutch flood policy domain, namely the organisation of Rijkswaterstaat, the policy-implementing agency of the Ministry of Transport, Public Works and Water Management. Rijkswaterstaat is generally known for its powerful position in the development of transport and hydraulic infrastructure in the Netherlands, for its engineering expertise, and for bringing the Dutch worldwide fame by realising major public projects, such as the Delta Works.

ii. Aim

The central objective of this research project was to describe the long term continuity and change in institutions and policies in the policy domain of coastal zone and river management in the Netherlands, with a particular focus on Rijkswaterstaat. In this way, we aimed to learn more about what has changed and what has remained stable over time, and why.

iii. Results

In the following, we present a historical and chronological overview of the main developments within the Dutch flood policy domain, and within the organisation of Rijkswaterstaat, from circa 1950 to the present. In this overview we touch upon various factors that are relevant to understanding the observed continuity and change in institutions and policies. These factors will be summarised in the conclusions.

The technocratic paradigm

The last dramatic sea flooding in the Netherlands took place on February the 1st, 1953, when more than 1800 people died. The Dutch Parliament reacted almost immediately in approving the so-called 'Delta Plan', which entailed the construction of a series of large dams to close the estuaries of the rivers Rhine, Scheldt and Meuse. The Delta Plan built on the plans that had already been developed by the 'storm water committee' before World War II (Meijerink, 2005). The basic idea of reducing flood probability by closing estuaries was not new either, since the Rijkswaterstaat engineers had constructed the Enclosure dam ('Afsluitdijk'), and by that closed the 'Zuyderzee', in 1932. The period of the 1950s and 1960s was the era of the hegemony of the technocratic discourse, the era of modernity. There was a strong belief in the possibilities for solving water management issues by taking technical engineering measures, such as the construction of dams and dikes. The policy image of dams was positive since they were deemed necessary for protecting the Netherlands against sea floods. This image was shaped by an epistemic community of Delft civil engineers, who were employed at Rijkswaterstaat, consultancies, construction firms, and research institutes, such as Delft Hydraulics. Moreover, some members of this community held important positions in Parliament. This community was able to sustain the technocratic policy monopoly for decades.

Waves of change, focusing projects and signs of disruption

In the 1970s and 1980s the tide turned. Several far-reaching social and political trends in the western world, and in particular Dutch society, put the position of Rijkswaterstaat and that of the epistemic community of civil engineers under pressure. The organisation entered a crisis and became nicknamed a 'state within the state' – a slogan that suggested that it had the power to take decisions autonomously.

First, in the early 1970s there was an explosive rise of the environmental movement (Tellegen, 1978; Cramer, 1989), induced, among other things, by the publication of The Limits to Growth by the Club of Rome (Meadows, 1972). As a result, the nationwide support that the Delta Plan had received in the 1950s and 1960s started to diminish. Environmental interest groups were established and many large water management projects became defined as 'environmental catastrophes' instead of 'major triumphs of civil engineering' (Disco, 2002). The rise of the environmental movement was accompanied by a democratisation and emancipation of Dutch society, which was prompted by the student revolts of the 1960s. This second 'wave of change' (Schwartz, 1993) is also known as the 'cultural revolution' (Lintsen, 2005). Citizens wanted to have more voice in decision-making processes and rose in revolt against the 'politics of expertise' (Fischer, 1990). The oil crisis of 1973 marked the beginning of the third far-reaching social process that heavily influenced the position of Rijkswaterstaat. Unable to control the resulting economic crisis, from the 1980s the Dutch government started to reform its political-administrative system. In line with the rise of the neoliberal politico-economic ideology in many western countries, budgets were cut drastically. Rijkswaterstaat, as one of the largest government organisations, had to contend with a fundamental reassessment of its formal position and the way in which it carried out its core tasks.

For Rijkswaterstaat, the search for a new organisational identity was a road with many obstacles. While its responsibility for carrying out several important public tasks, such as the protection of the country against floods from the sea and the rivers, require technical knowledge and expertise on the Dutch water system, it was also being criticised for its technocratic working style. Rijkswaterstaat therefore found itself caught on the horns of a dilemma (Van den Brink, 2009): it needed its renowned expert status to fulfil its public responsibilities, whereas it needed to distance itself from this expert status to be able to meet the increasing social and political imperative of developing into a more responsive and effective public organisation.

There were various 'focusing projects' (Lowry, 2006), clearly demonstrating the negative side-effects of the prevailing technocratic water management paradigm, in this period. In particular the damming of the Eastern Scheldt estuary, the reclamation of the Markerwaard, the planned river dike improvements and the new A27 motorway through the Amelisweerd estate near Utrecht functioned as focusing projects (Meijerink, 2005; Van den Brink, 2009; Van den Brink and Wiering, 2009). Here, we focus on the controversy about the damming of the Eastern Scheldt estuary, the final large dam that was envisioned in the Delta Plan. Rijkswaterstaat was in favour of carrying out the original Delta Plan drawn up after the disastrous flood of 1953, which included a complete closure of this estuary. However, as the proposed fixed dam would eliminate the saltwater ecosystem and associated fisheries, it became the object of massive and persistent popular protests. Rijkswaterstaat was forced by the government to come up with alternative designs that were both safe and ecologically acceptable, and, if possible, technologically challenging (Leemans and Geers, 1983; Goverde, 1976; Disco, 2002). In 1974, with the help of dredging and construction companies, Rijkswaterstaat proposed to partly close the Eastern Scheldt estuary with a storm barrier caisson dam. In normal circumstances the caissons are open, to a large extent maintaining the tidal regime in the estuary, but they can be closed entirely during unusually high sea levels (Bijker, 2002). This innovative ecological design saved the day for Rijkswaterstaat.

Rijkswaterstaat had already recognised the need for developing ecological knowledge in 1971. In this year a new Environmental Department was established within the Delta Department, and the first university educated biologist within Rijkswaterstaat, Henk Saeijs, was appointed head of this Section (Disco, 2002). Saeijs would attract more ecologists and biologists soon, thus contributing to the dissemination of ecological knowledge within Rijkswaterstaat. This new epistemic community started to build a knowledge-base on ecological issues, and contributed to the reframing of water and safety issues as multidisciplinary issues, including important ecological aspects. Saeijs, who later started working at the Ministry in The Hague, was one of the founding fathers of the concept of integrated water management, emphasising the need to include environmental and ecological issues in water management policies and projects (Saeijs et al., 2004).

New shock events

In 1993 and 1995 (near) river floods raised societal awareness of flood protection issues in the Netherlands, as well as awareness among river experts of the limits to controlling high water levels with higher dikes only. To be able to cope with potential flood disasters in the future, that is, to anticipate the projected impacts of climate change, sea level rise and increasing river discharges, Dutch water managers introduced new flood defence strategies. Building on the principle of integrated water management, the basic idea of the Room for the River safety strategy was to enlarge the discharge capacity of the Dutch main rivers by increasing the amount of space for the rivers (Wiering and Driessen, 2001). The aim of the National Spatial Planning Key Decision procedure was to develop a coherent river-widening plan for the Rhine river and its distributaries Waal, Nederrijn-Lek and IJssel. The initiating ministries were the Ministry of Transport, Public Works and Water Management (the main initiator), the Ministry of Housing, Spatial Planning and the Environment, and the Ministry of Agriculture, Nature and Food Quality. The first and most important objective was to improve the flood security of the roughly four million inhabitants of the riverine area. The second objective was to improve the spatial quality of the river landscape (Ministerie van Verkeer en Waterstaat et al., 2002). Three types of river-widening measures were defined: spatial measures on the river side of the dike (e.g. excavating old river branches), spatial measures on the landward side of the dike (e.g. replacing dikes or the construction of a new river branch), and, only if necessary, technical measures (e.g. strengthening dikes or the removal of obstacles).

The development and organisation of the National Spatial Planning Key Decision procedure has to be understood against the background of the increasing criticism of the technocratic culture and way of working of Rijkswaterstaat – the organisation was obliged to develop a more responsive attitude. The spatial nature of the Room for the River policy also called for a different, more democratic, way of working. As a result, river management became a political issue, instead of being simply and solely a technical issue (see also Van den Brink and Meijerink, 2006).

Towards a public-oriented government business

The first way in which Rijkswaterstaat adapted to the changing circumstances, and tried to deal with the dilemma it faced between preserving its expert status and developing into a more responsive and efficient public organisation was by incorporating the new ecological perspective in its predominantly technocratic system of meaning. This development is generally referred to as the 'ecological turn' in the technocratic water management paradigm (1970s–1990s). Concepts such as 'integrated water management', 'water system' and 'room for water' were developed, and biologists and ecologists were hired to assess the ecological impacts of water management projects and to make the environment and the landscape key issues.

In the same period, another turn took place in the technocratic paradigm, which would also greatly influence Dutch coastal zone and river management. The second way in which Rijkswaterstaat adapted to the changing circumstances was by embracing the new neoliberal politico-economic ideology. This development can be referred to as the 'managerial turn' (Van den Brink, 2009) in the technocratic water management paradigm. The period of the 1980s and 1990s constituted the first phase of this turn. In line with New Public Management ideas – the 'tool' to implement the neoliberal ideology (see Osborne and Gaebler, 1992; Kettl, 2000) –

Rijkswaterstaat introduced various management tools from private business to improve its effectiveness and efficiency. In the early years of the 21st century, the managerial turn accelerated under the influence of new external events – such as the publication of the findings of the temporary committee for infrastructure projects (Tijdelijke Commissie Infrastructuurprojecten, 2004) – and the separation, imposed by Parliament, of policy making and policy implementation. By introducing a Business Plan (Rijkswaterstaat, 2004), Rijkswaterstaat actively tried to transform itself into a 'public-oriented government business' and sought to develop a new identity as a policy-implementing agency. For instance, a new business model was introduced consisting of three internal steering relationships with the ministry, a new working style was adopted with the introduction of 'the market, unless' principle, and several radical internal reorganisations were implemented to create 'one Rijkswaterstaat'.

Rijkswaterstaat thus managed to successfully embrace and incorporate elements and practices of the new environmental and neoliberal managerial discourses. Nevertheless, it is still caught on the horns of a dilemma in concrete water planning practices: between its expert status on the one hand and the need to democratise its way of working on the other. This is illustrated by the IJssel Delta South project in the upper riverine area for the construction of a bypass of the river IJssel. IJssel Delta South is an integrated planning project, for which not Rijkswaterstaat, but Overijssel Provincial Executive is the initiator. The Rijkswaterstaat employees involved had difficulty with realising their ambition to be the discussion partner of the region: they wanted to balance a reviewing role, i.e. seeing to it that the strict conditions set by Parliament were met, and a collaborative thinking role. Whereas the local and regional parties mainly identified with the democratic governance discourse to interpret and develop their partner roles, the Rijkswaterstaat employees mainly participated on the basis of their engineering knowledge and expertise, from a managerial control perspective. This was in line with the managerial turn in the technocratic water management paradigm. Although the local and regional parties valued the efforts made by the Rijkswaterstaat employees, they did not perceive Rijkswaterstaat as a real partner. There was more to being a partner than bringing in technical knowledge and expertise and reviewing the plans of the region. Parties were only considered real partners when they were able to negotiate and to make decisions.

iv. Conclusions

In sum, policy beliefs and discourses have changed fundamentally in the Dutch coastal and river flooding policy domain in the past decades. Though the policy community in the field of Dutch water management is still well organised at different administrative levels, the engineering community is no longer able to capture the flood policy domain on its own. The engineering paradigm is at least partly replaced by an ecological and a managerial paradigm. The influence of new ideas and new actors in this policy community has forced undoubtedly the epistemic community of civil engineers to reflect on its policies and to change its technocratic approach in accordance with demands of openness, transparency and legitimacy in policy-making under democratic conditions.

Looking at the factors relevant to understanding continuity and change in the Dutch flood policy domain, we have seen that new ideas and discourses which are disseminated by coalitions or epistemic communities, focusing events, such as river flooding, focusing projects, such as the Eastern Scheldt storm surge barrier, and elections are all relevant to understanding institutional dynamics. The study also revealed how the organisation of Rijkswaterstaat has adapted to new societal demands and external pressures, and struggles with dilemmas, such as the dilemma between technocracy and democracy. To develop its positioning in integrated water planning projects, Rijkswaterstaat could reconsider its role of a technical expert in a democratic society. The challenge is to understand technical knowledge and expertise as part of the social context in which it is embedded and together with local and regional parties co-produce new plans.

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E. Flemish-Dutch collaboration

1. Interview with Prof. Dr. C. Heip
2. Carbon and nitrogen cycling in the Scheldt estuary: the major players, long term changes and an integrated view
3. N and Si cycling in freshwater tidal marshes
4. Diversity-productivity relationships in estuarine microphytobenthos
5. The structure and functional roles of tidal flat meiobenthos

1. Interview with Prof Dr. C. Heip

International collaboration

Carlo Heip, initiator and coordinator of the VLANEZO programme that merged with LOICZ in 2002. He describes the origins of the LOICZ-VLANEZO programme.

Heip: Vlanezo arose from the bordering countries' policy of the European Union. The then Dutch Education minister, Jo Ritzen, initiated and funded two collaborative ventures for sea research. One was NEBROC (Netherlands Bremen Cooperation), and the other was VLANEZO (Flemish-Dutch Cooperation in Coastal Research). The research was managed by NWO (Netherlands Organisation for Scientific Research). VLANEZO focussed on the estuary that the Netherlands and Belgium share, the 160 kilometre-long estuary of the Schelde. The research covered the unique tidal area from Vlissingen to Ghent with tidal differences of up to seven metres at Antwerp and still two metres at the freshwater head of the estuary in Ghent. We wanted to understand the ecology of the estuary and especially to understand the ecological effects of the intertidal flats and the salt marshes.

In the 1990s the Schelde was regularly in the news and not just because of the silting problem and the accessibility of Antwerp …

There were various problems such as chemical and organic pollution: the untreated wastewater from Brussels was then being discharged into the Schelde via the Zenne tributary. And on top of that there was the dossier about the deepening of the Westerschelde. We examined this from a biomorphological viewpoint, in other words: how do the various aspects affect each other? How do the habitats develop? How does the nitrogen-carbon cycle affect the system? At the start of the twenty-first century, the Schelde was a very damaged ecosystem. The freshwater part up until the border was a stinking anoxic water mass due to the organic pollution. In the saltwater part from the border onwards, the system was less damaged because the anoxic water was diluted with salty seawater. Since the construction of two water treatment plants in Brussels the situation in the Schelde has improved considerably.

What exactly could be investigated in a river that was so strongly polluted?

In the period that the river was anoxic, its ecology was dominated by nitrification, a process due to bacteria that use ammonium instead of the sun as an energy source. These bacteria oxidised ammonium into nitrite and nitrate using considerable quantities of oxygen in the process. We made an extensive study of that chemosynthesis process. The results revealed one advantage of that polluted situation: easily biodegradable organic material and carbon dioxide were removed from the system in a natural process. Now that the anoxic conditions scarcely apply, this no longer occurs.

And which research focussed on the Westerschelde?

A lot was already known about the macrofauna in that area. However, a gap in our knowledge were the microscopic organisms such as nematodes and diatoms. Diatoms, in particular, have a far from easy existence in the Schelde because the river is so turbid. At low tide, they photosynthesise as can be seen from the brown colour of the mudflats. These two studies have led to an enormous increase in our knowledge about organisms in the mudflats. They were found to be a large source of organic material. Birds can benefit from that at low tide and crabs and fish at high tide. They are, in effect, small factories of organic material.

In recent years (during the last Balkenende Cabinet) the Flemish-Dutch conflict about the deepening of the Westerschelde frequently made the news. Emotions often ran high.

Yes, there are proponents and opponents, but what are the facts? We barely know what the effects of deepening the Schelde are. Sediment transport is very difficult to understand and to model. The distance between Vlissingen and Antwerp is about 100 kilometres and some 10 million cubic metres of sediment is being dredged each year. If the process cannot be managed then the Schelde will silt up and Antwerp will lose its harbour function. One thing is certain: deepening the Schelde has created an imbalanced ecosystem. The Schelde is basically too deep for its width. We must examine the consequences of the third deepening of the Schelde, that is just finished now (2011) and where the geomorphological equilibrium point lies. One prediction is that the estuary may change from a multi channel system to a single channel system and that the morphology will be completely transformed. A Schelde without salt marshes and mudflats is beneficial for shipping but not for fish and for wildlife. That would mean that the objectives of Natura 2000 would not be achieved. Wrong decisions will have major economic and ecological consequences.

And then of course there is the coastal defence, the number one priority of water policy.

We have discovered that the plants, and in some cases the animals, are capable of stabilising sediments so that erosion is counteracted. A lot of research has been done on the formation of new salt marshes. A dike is strengthened if it has a salt marsh in front of it and that costs nothing. Islands of Spartina are the first stage of salt marsh formation. Over a period of several decades these islands develop into a new salt marsh that comes to lie in front of the old salt marsh. We have discovered that Spartina cannot grow at location with lugworms as these worms eat all the seeds. The Spartina capture sediments enabling the salt marshes to grow. You get a coastal defence free of charge and without any effort.

Via VLANEZO and LOICZ a lot of research has been done on the Schelde river as an estuary. That can contribute to a responsible policy for Flanders and the Netherlands.

VLANEZO is first and foremost a fundamental research programme to gather knowledge about processes. It is unclear what that knowledge contributes to societal processes because policy makers often have little understanding of ecology and it does not impact their decisions very much. On the other hand, the political process to prepare for the third deepening of the Schelde is an example of how it can be done. Here there was a good relationship between the scientists and the policy makers. From a strategic viewpoint, the research has also had a positive effect because both the Netherlands and Flanders successfully managed to collaborate in the work. We will experience far more of this worldwide as many problems are transnational and that is certainly the case with water. We must learn to work from such a transnational perspective as that is what Europe is about.

2. Carbon and nitrogen cycling in the Scheldt estuary: the major players, long-term changes and an integrated view

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Abstract

The Scheldt estuary is a highly heterotrophic, nutrient-rich, turbid, tidal estuary in a densely populated area (Belgium/The Netherlands). Here we present the results (1) on the long-term changes in nutrient loadings and transformations within the estuary and (2) on nitrogen cycling rate measurements obtained with isotopic tracers. Moreover, we have developed and applied novel techniques that allow direct linking of process rates to the identity and biomass of the organisms involved. Monitoring data and process studies have been used in numerical models to integrate the various biogeochemical cycles and to advance our understanding of the evolving estuarine filter function of the Scheldt estuary.

i. Introduction

Estuaries are the main transition zones between fresh-water and marine ecosystems. Before entering into the sea, rivers collect nutrients, organic matter and suspended particles from their catchments. The combination of high concentrations of nutrients and particles or colored dissolved organic carbon often causes primary producers in rivers and inner estuaries to be light rather than nutrient limited (Boschker et al., 2005). Estuaries are well known to modify and attenuate carbon and nitrogen transfer from rivers to the coastal sea. The efficiency of this estuarine filter influences the functioning of downstream ecosystems (continental shelves) and this filter function has therefore been studied in a number of estuarine systems. Most of these studies rely on concentration measurements and mass-balance approaches to quantify carbon and nitrogen losses. The most advanced studies on the estuarine filter function are based on state-of-the-art modeling tools to improve budgets based on sparse datasets or include some flux and transformation measurements. While these mass-balance oriented studies provide quantitative data on the retention efficiency of carbon and nutrient, they provide little if any mechanistic understanding, nor information on the organisms and mechanisms involved. For instance, the estuarine residence time has been identified as a key parameter determining the removal efficiency of P, N and Si, independent on the actual form in which N enters estuaries (particulate or dissolved organic nitrogen, ammonium, nitrate, nitrite, etc).

During the Flemish-Dutch co-operation for sea research, the universities of Brussels (VUB) and Antwerpen (UA) and the Centre for Estuarine and Marine Ecology of the Netherlands Institute of Ecology (NIOO-CEME) joined forces to study in detail the carbon and nitrogen cycling in the Scheldt estuary.

ii. Aim

The overall objectives were (1) to elucidate the links between carbon and nitrogen cycling, (2) to link the identity of organisms with their activity, (3) to integrate various biogeochemical processes via isotope labeling and numerical modeling, (4) and to reconstruct long-term changes in nutrient cycling.

iii. Scheldt estuary

The catchment of the Scheldt (350 km long) covers 21,863 km^2 and is situated in the northwest of France (31 %), the west of Belgium (Flanders, 61%), and the southwest of The Netherlands (8 %). Most of the river basin area is urban; the total population of the catchment numbers more than 10 million people, with densities varying from 100 to more than 2,000 inhabitants km^2 (averaging 400 inhabitants km^2). The Scheldt estuary is a broad (from ~500 m near Antwerp to ~6 km near Vlissingen), relatively shallow (10 m mean depth), and rather short (100 km) funnel-shaped, macrotidal estuary with a medium average freshwater discharge of 104 m^3. s^{-1} and a water residence time of 2 to 3 months depending on river flow. The tidal Scheldt is shallow generally well-mixed, but turbid because of high suspended matter concentrations maintained by tidal mixing. As a consequence the photic zone is shallow and primary production is light-limited in this nutrient-rich system. The Scheldt is a highly heterotrophic system characterized by oxygen undersaturation and carbon dioxide supersaturation and high rates of respiration and bacterial secondary production (Boschker et al., 2005).

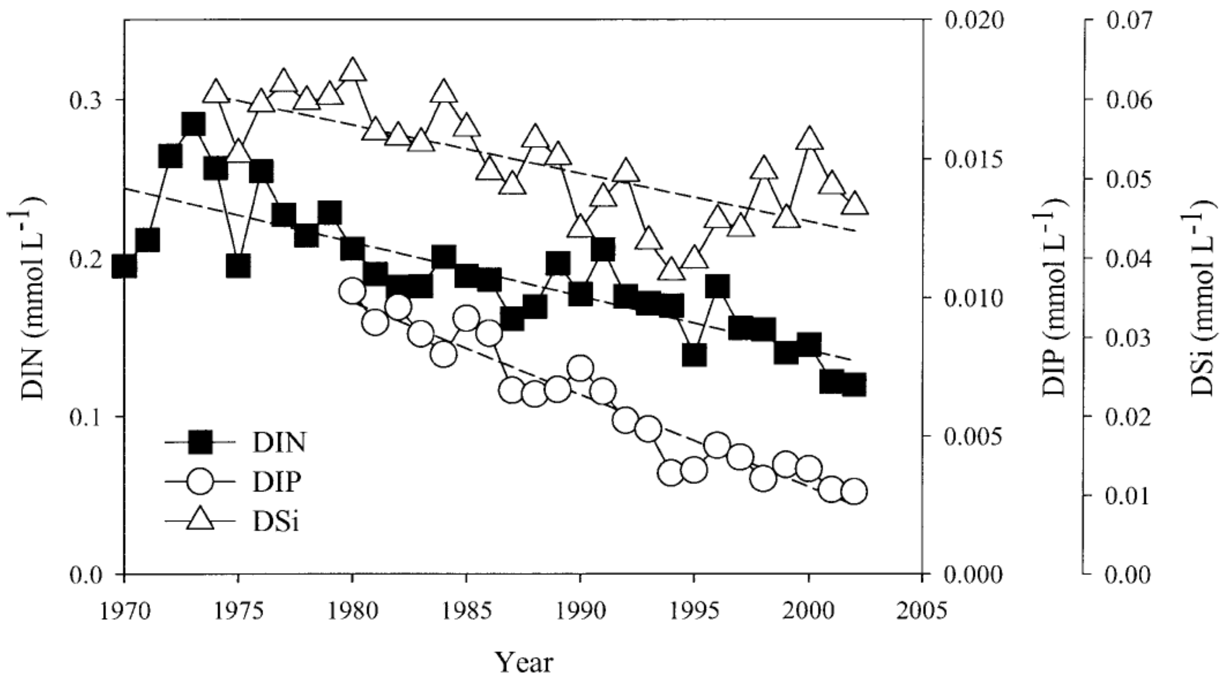

***Fig. E-2.1:** Long-term changes in dissolved inorganic nitrogen, phosphate and silicate concentrations in the Scheldt estuary (Soetaert et al., 2006)*

iv. Long-term changes in Scheldt estuary

During the Anthropocene and in particular during the last 5 decades, human activity has caused major changes in the riverine loads of suspended matter, organic matter and nutrients with dramatic consequences for some ecosystem properties. Moreover, global change may also have affected processes and organisms within the estuary. During the last 30 years large changes in the phytoplankton phenology were observed, with a general trend towards an earlier occurrence of the phytoplankton bloom, which seemed to be related to global warming (Kromkamp & van Engeland, 2010). The Scheldt estuary is one of the most studied estuarine systems and we assembled all available data to generate and exploit a database covering nutrients, oxygen and other monitoring data for the last 5 decades (Soetaert et al., 2006). Annually averaged concentrations of dissolved silicate (DSi), dissolved inorganic nitrogen (DIN), and phosphate (DIP) increased significantly until the mid-1970s, after which they declined linearly at rates of 0.6, 2.9, and 0.3 mmol L-1 y^{-1}, respectively. This co-occurred with a deterioration followed by a restoration of water column oxic conditions. Because of the differences in the reduction rate of DSi (1.2 % y^{-1}), DIN (1.7 % y^{-1}), and DIP (5.4 % y^{-1}), the N: P and Si : P ratios more than doubled from 1980 to 2002 (Fig. D-3.1). The Si :N ratio varied from 0.2 to 0.4 and was positively correlated with river discharge. The Scheldt estuary was a net sink for DSi during the entire period but evolved from a net sink to a net source for DIP, while the reverse was true for DIN. The release of P from sediments probably accounted for the additional DIP. This differential behavior of the estuary with respect to DIN and DIP strongly buffered the altered loadings to the upper estuary. The input of oxygen-consuming substances at the head of the estuary triggered a sequence of oxidation reactions. In the early 1970s, high loadings of ammonium and organic matter caused oxygen depletion and intense water-column denitrification in the upstream part and intense nitrification downstream, with a nitrate maximum succeeding a nitrite peak. With oxic conditions improving and the input of ammonium decreasing, water-column denitrification declined, the nitrification front migrated upstream, and the estuary evolved from a net producer of nitrite to a net consumer. Now, at the beginning of the 21st century, nitrate behaves almost conservatively over the entire estuary.

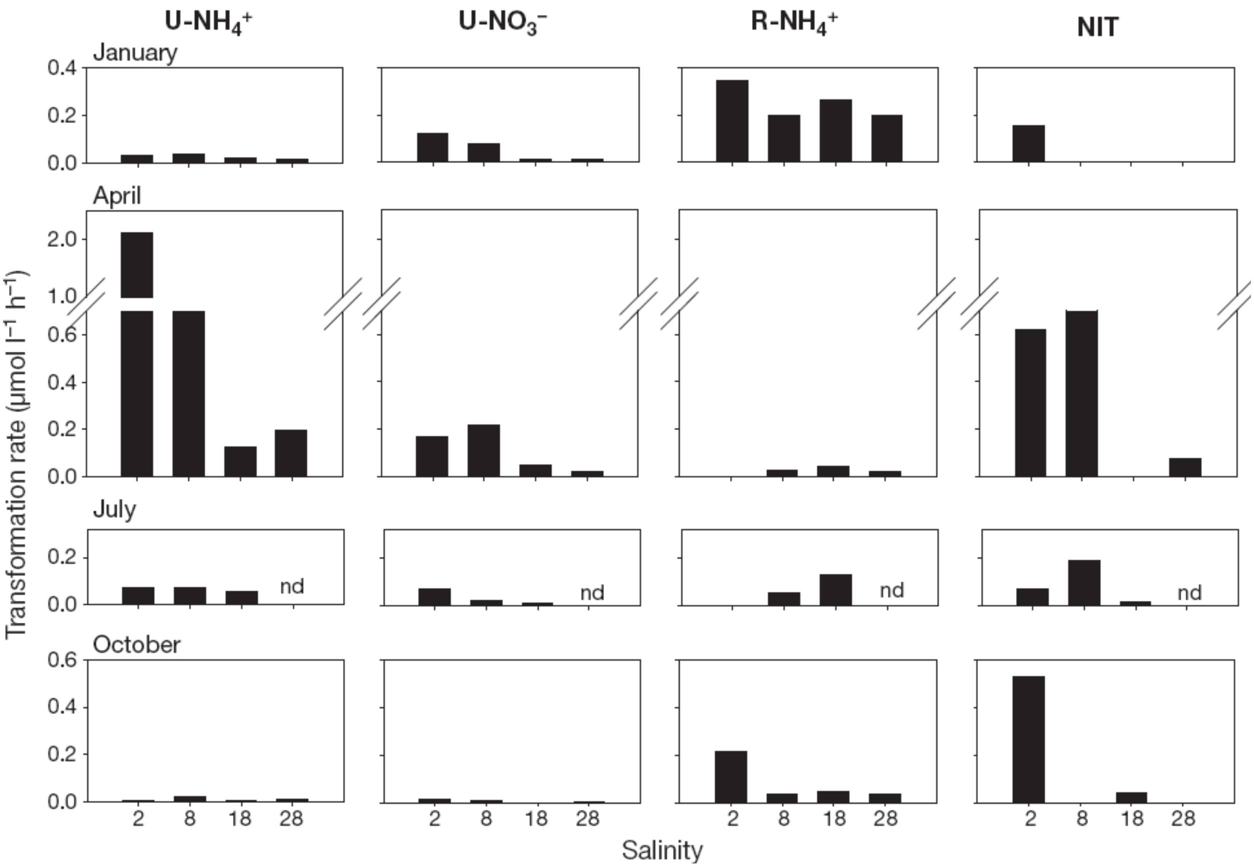

Fig. E-2.2: *Nitrogen transformation rates at the 4 salinity stations in the Scheldt estuary: ammonium and nitrate uptake (U-NH_4+and U-NO_3–), ammonification (R-NH_4+) and nitrification (NIT). nd: not done (Brion et al., 2008)*

v. Nitrogen cycling in Scheldt estuary

However, this apparent conservative behavior of nitrate in the Scheldt estuary in terms of mass balance budgets should not be considered evidence that nitrate turnover is limited. It simply means that nitrate production (regeneration from sediments and nitrification) and nitrate consumption (denitrification and nitrate assimilation) are balanced. To investigate in detail the turnover of nitrogen in the Scheldt estuary we studied sedimentary nitrogen cycling and water column ammonium regeneration, nitrification and uptake of ammonium, nitrate, nitrite, urea and amino acids using ^{15}N as a deliberate tracer (Andersson et al., 2006a, 2006b; Brion et al., 2008). Nitrogen exchange with lateral ecosystems, e.g. tidal fresh-water marshes, have been the subject of another project (see Struyf et al. this volume). Ammonium oxidation by nitrifiers (Archaea and Bacteria) and ammonium uptake by algae and bacteria were of similar magnitude, with nitrification dominating during winter and assimilation processes during the spring bloom. Urea and amino acids constituted up to 43 and 29 % of total nitrogen uptake, respectively, and were of similar importance as inorganic substrates. Through the use of dual-labelled substrates we revealed that amino-acid nitrogen was consumed year-round, while amino-acid carbon was not assimilated during summer. Nitrification was studied in multiple ways: from the transfer of ^{15}N from ammonium to nitrate, from the dark incorporation of ^{13}C and/or ^{14}C into organic matter with and without nitrification inhibitors (N-serve and sodium chlorate) and from oxygen consumption with or without nitrification inhibitors (Andersson et al., 2006a; Gazeau et al., 2005). Our study revealed that nitrifier activity (as measured with ^{15}N technique) and growth (^{14}C incubation) can be uncoupled, complicating the common use of N:C conversion factors. Moreover, nitrification has been identified one of the most important biogeochemical processes in the upper Scheldt, contributing not only to ammonium consumption, but also to carbon fixation, oxygen consumption (Gazeau et al., 2005) and acidification (Hofmann et al., 2009).

vi. Activity-Identity Linking

Through the combination of biomarkers, organic molecules specific to certain groups of organisms, and stable isotopes, it is possible to link the identity, biomass and activity of organisms (Boschker and Middelburg, 2002). We studied planktonic community structure and isotopic composition using compound-specific ^{13}C analysis of phospholipid-derived fatty acids (PLFA) along the Scheldt estuary during a spring bloom (Boschker et al., 2005). Concentrations of algal PLFA and pigments and microscopic identifications of dominant phytoplankton revealed the same trend: a mixed community of green algae and diatoms dominated the freshwater phytoplankton and there was a major diatom bloom at intermediate salinities (Dijkman and Kromkamp, 2006). Bacterial biomass (also based on PLFA) was much lower for the diatom bloom in the lower estuary than in the net heterotrophic upper estuary. Carbon isotopic ratios of a diatom biomarker were mainly related to changes in ^{13}C values of dissolved inorganic carbon. A green algal marker was much more depleted in ^{13}C than the diatom markers, suggesting that these two main phytoplankton groups use a different inorganic carbon source or carbon dioxide fixation mechanism. In the lower, marine side of the estuary, isotope ratios of bacterial and algal PLFA were similar, suggesting a coupling between primary production and bacterial consumption of organic matter. In the upper estuary carbon isotope signatures of dissolved organic carbon (DOC), particulate organic carbon, and bacterial biomass were similar and significantly enriched relative to those of diatoms and green algae, pointing to allochthonous subsidies as an important carbon source for bacteria. The contribution of algae to zooplankton diets as estimated from isotope ratios averaged 41 % and 75 % respectively. Mesozooplankton relies primarily on grazing on phytoplankton and direct consumption of particulate organic matter and appears to receive little of its carbon from DOC via bacteria (Van den Meersche et al., 2009).

Tracer techniques have shown to provide accurate estimates of the transfer from the dissolved to the particulate phase. However, they do not provide any direct information on the organism involved. We have explored stable-isotope labeling of PLFAs as a technique to study group-specific primary production of phytoplankton, as many algal groups possess a specific PLFA composition. After developing and testing the new method (Dijkman et al., 2009), we have investigated the group-specific primary production of a number of phytoplankton groups, including diatoms, green algae, cryptophytes and the combined group of dinoflaggelates/ haptophytes in the Scheldt estuary. Group-specific primary production revealed major differences in contribution of main algal groups. Diatoms, the dominant group along the whole estuary, generally contributed less to the primary production than expected from its standing stock, whereas the dinoflagelates-haptophytes group (mainly consisting of Phaeocystis), was relatively more important in the marine section of the estuary. Our measurement indicated that indicated that estuarine algae are growing at the location –or rather in the water mass- where they are found and are not merely transported from either the freshwater or the marine end. These group-specific primary production measurements will be useful in the next generation of estuarine biogeochemical models.

Integrative models

The joint Flemish-Dutch research program generated a wealth of data: new data on the distrubution of nutrients, particles, organic matter and organisms, a detailed historical reconstruction of nutrients inputs and concentrations and limited data on the linkages between carbon, nitrogen and oxygen cycles and the organisms involved. On the basis of these results we have developed a A new 1-D reactive-transport model of the Scheldt estuary that resolves the major carbon and nitrogen species and oxygen, as well as pH (Hofmann et al., 2008). It is a model based on Occam's razor, i.e. as simple as possible but still able to fit the data well enough to determine the fate and turnover of nutrients entering the estuary and their spatial patterns in the years 2000 to 2004. Nitrification was identified as one of the most important processes consuming comparable amounts of oxygen as respiration and model predicted nitrification rates closely matched measurements. The developed model explicitly resolved the effect of biogeochemical processes on pH. Proton production by nitrification is identified as the principal biological process governing the pH. Its acidifying effect is mainly counteracted by proton consumption due to CO_2 degassing. Overall, CO_2 degassing generates the largest proton turnover in the whole estuary on a yearly basis (Fig. E-2.3; Hofmann et al., 2009).

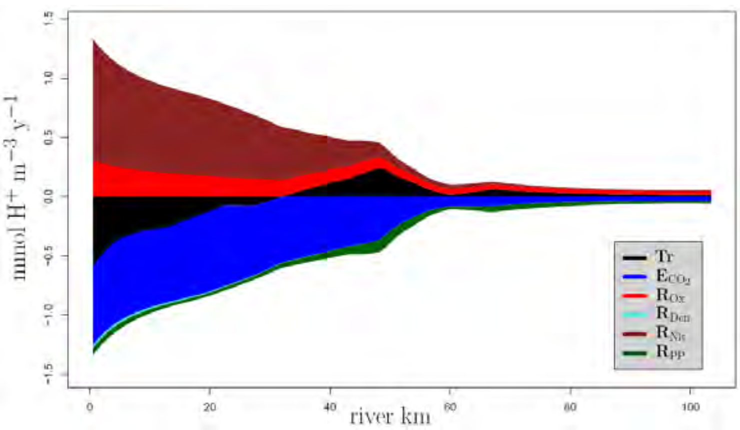

Fig. E-2.3: *The influence of biogeochemical processes on the pH of the Scheldt estuary. Process abbreviations: Tr=advective-dispersive transport, ECO_2=CO_2 degassing, $RO_{x=oxic}$ mineralisation, R_{Den}=denitrification, RNit=nitrification, RPP=primary production.*

vii. Outlook

Future studies will need to focus on a better understanding of the different functional groups in the different biogeochemical processes and ecosystem services. This implies further development of biogeochemical modeling tools that allow projections of Scheldt ecosystem behavior and properties as a result of climate change (changes in river discharge rates and variability, global warming) and human activity (dredging, nutrient loadings). Moreover, there is also a need to develop new methods that allow enhance taxonomic resolution in activity measurements (e.g. combination of stable isotope labeling with RNA extraction or with NanoSIMS for subcellular isotopic measurements).

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3. N and Si cycling in freshwater tidal marshes

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Abstract

Tidal marshes have high sediment surface areas, promoting processes affecting nutrient speciation, transformation and retention. In this project we performed whole-ecosystem $^{15}NH_4^+$ tracer addition experiments to quantify the fate and transport of ammonium through a tidal freshwater marsh. Combined with a mass-balance study, this approach allowed a simultaneous examination of transport and processing of nitrogen. We also performed additional studies on Si cycling in parallel to the N-labeling experiment.

Our work shows that the large reactive surface of the tidal freshwater marsh vegetation is crucial for nitrogen transformation and assimilation. It clearly revealed the dominant role of microbes in initial nitrogen retention in marsh ecosystems. Parallel study of silica cycling revealed that tidal marshes act as biogenic Si recycling surfaces, importing biogenic Si while exporting dissolved Si. Export of dissolved Si is greatest during summer and spring, when dissolved Si concentrations in inundating waters are depleted by diatoms. Tidal marshes thus buffer estuarine dissolved Si in times of limitation. We can conclude that the studied marsh had an increasing effect on the Si:N ratio in flooding waters. Export of DSi and import of total dissolved nitrogen (DIN) contributed about equally to the increase of the Si:N ratio.

i. Problem and aims

Estuaries are well known to modify and attenuate nitrogen (N) transfer from rivers to the coastal sea (Billen et al., 1991). Specifically tidal marshes have been reported to play a major role in nitrogen retention (Van Damme et al., 2009). Marshes have high surface areas of sediment and bio-films in contact with the water, promoting processes that affect nitrogen speciation and remove dissolved inorganic and organic nitrogen while increasing deposition of particulate nitrogen. There is considerable interest in exploiting this nitrogen filtration capacity of wetland ecosystems in order to improve estuarine and coastal marine water quality. However, despite the widely held belief that wetland systems are important nutrient sinks, the literature regarding the influence of tidal freshwater wetlands on water quality is remarkably small (Merrill and Cornwell, 2000).

The importance of freshwater marshes to the estuarine nitrogen budget is most often estimated with a mass-balance approach (e.g., Van Damme et al., 2009). This technique, however, is subject to considerable error and yields little information regarding the role and spatial and temporal distribution of the underlying processes. In this project we performed whole-ecosystem $^{15}NH_4$+ tracer addition experiments to quantify the fate and transport of watershed-derived ammonium through a tidal freshwater marsh system. Combined with a mass-balance study, this approach allowed a simultaneous examination of transport and processing of nitrogen in an intact ecosystem, something that is impossible to achieve in traditional bottle, enclosure, or mesocosm experiments.

The whole-ecosystem ^{15}N labeling experiment was conducted in a tidal freshwater marsh fringing the nutrient-rich Scheldt River (Fig. E-3.1, Belgium). Although many tidal marshes of the Scheldt basin have been reduced to very small size today, they are still a prominent feature of the Scheldt, and the surfaces of the 4.5 km^2 of tidal freshwater marshes could represent important potential N sinks. We defined project goals that were specifically aimed at assessing the role of these marshes as nitrogen sinks and transformers:

- to quantify different processes within the marsh: N-uptake and N-loss, nitrification and denitrification

- to identify the main N-compartiments

- to estimate the retention time of different N-forms and its spatial distribution

It should be emphasized that nitrogen cycling within estuaries cannot be considered independently from the cycle of other nutrients. It is in fact the N-P-Si ratio that eventually reaches coastal waters through estuaries that affects phytoplankton productivity. High anthropogenic inputs of N and P can induce Si limitation in diatoms and cause a succession of the phytoplankton community to non-diatom species, which are less available to higher trophic levels (e.g., Phaeocystis sp). Apart from this negative effect on estuarine and coastal food webs, increased non-diatom phytoplankton production can have several other negative consequences, including increased water turbidity, anoxic conditions, and the appearance of toxic algal blooms (Cloern, 2001).

Especially silica cycling in tidal marshes had so far remained unstudied. Yet both diatoms and reed, both biological silica accumulators, are abundant in tidal freshwater marshes. As such, these areas have a high potential to also affect silica cycling in estuarine ecosystems. Therefore, we performed the most detailed study on Si cycling in a tidal marsh so far in parallel to the N-labeling experiment. Specifically, we aimed to quantify biogenic Si (BSi) stocks in freshwater marsh vegetation and sediment, internal recycling rates of both sediment and vegetation associated BSi and exchange of DSi and BSi between the marsh and adjacent estuarine waters.

***Fig. E-3.1**: A typical Phragmites australis-dominated tidal freshwater marsh (Scheldt estuary, Belgium).*

ii. Results

Nitrogen

In spring (May 2002) and late summer (September 2003), we added ^{15}N-NH4+ to the flood water entering a 3477 m^2 tidal freshwater marsh area, and traced the ammonium processing and retention in four subsequent tide cycles. Changes in concentration and isotopic enrichment of NO3- , NO_2-, N_2O, N_2, NH_4+ and suspended particulate nitrogen (SPN) were measured. All analyzed N-pools were labeled: in May 31 % and in September 49 % of the added ^{15}N-NH_4+ was retained or transformed. The most important pool for ^{15}N was nitrate. The temporal and spatial patterns of ^{15}N transformation in the water phase component of the system were remarkably similar during both periods: however, the absolute ammonium transformation rate was 3 times higher in May. While the marsh surface area was crucial for nitrification in May this was less pronounced in September. Denitrification on the other hand was more intense in September compared to May.

Although the total amount of ^{15}N, and the relative distribution of ^{15}N recovered in the various compartments was quite similar between the two campaigns (Fig. E-3.2a), the corresponding total ammonium processing rates on a marsh surface area basis varied greatly (Fig. E-3.2b). This is mainly due to a combination of a 5 times lower total in situ flood water ammonium pool and a higher relative ^{15}N (4.5 % of the ammonium pool) concentration in September. Thus, the absolute amount of ammonium processed in the marsh was 3 times higher, and >5 times more ammonium was nitrified, in May compared to September. These findings suggest that flood water ammonium concentration is the key determinant for ammonium removal in tidal freshwater marsh ecosystems.

The specific study of the sinks, as in Figure E-3.2, revealed that that leaf litter and ruderal vegetations are more important in nitrogen uptake and retention than the prominent reed (Phragmites australis) meadows. Moreover, short-term nitrogen retention in these nutrient rich marshes occurs mainly via microbial pathways associated with the litter and sediment. Rather than direct uptake by macrophytes, it is the large reactive surface area provided by the tidal freshwater marsh vegetation that is most crucial for nitrogen transformation, assimilation and short term retention in nutrient rich tidal freshwater marshes. Our results clearly revealed the dominant role of microbes in initial nitrogen retention in marsh ecosystems. However, our whole ecosystem labeling study did not allow us to elucidate in detail the dynamics within the microbial compartments; e.g. we do not know whether eukaryotes (benthic algae or fungi) or prokaryotes contribute most to nitrogen retention.

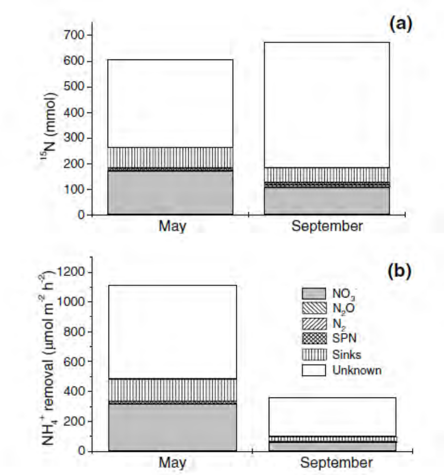

Fig. E-3.2: *(a) Amount of recovered 15N in the various pools after T0 in May and September (not exported as 15NH4+), and (b) average total marsh ammonium transformation rates based on recovery of 15N label after one tide. The "unknown" compartment is probably mainly denitrification and export of dissolved organic N (Gribsholt et al., 2006).*

Silica

Our parallel study of silica cycling revealed that tidal marshes act as significant BSi recycling surfaces, importing BSi while exporting DSi. Nevertheless, BSi is not completely recycled; tidal marshes tend to be net sinks for BSi in estuaries. Higher sedimentation rates result in a more efficient burial of BSi. Export of DSi is greatest during summer and spring, when DSi concentrations in inundating waters are depleted by diatoms. Tidal marshes thus buffer estuarine DSi in times of limitation, when recycling can exceed freshwater runoff. Export of DSi is most strongly connected to the slow advective (horizontal) release of water retained in the marsh after high tide, both from interstitial water and puddles, which contain DSi concentrations of 100–600 µM. The sinks and fluxes of Si in the freshwater tidal marsh (dominated by Phragmites australis) are summarized in Figure E-3.3. Sediment BSi pools are large compared to vegetation. In practice, most export of DSi occurs during only a few months in summer and spring. The vegetation is, in essence, self-sufficient for Si. Nevertheless, the abundant litter layer has an important role in the Si buffering capacity of tidal marshes. The storage of BSi in Phragmites australis in the Scheldt freshwater marshes of Belgium accounts for over 90 % of all ASi in vegetation (although its biomass accounts for only 50 % of total biomass). Decomposition experiments have shown that recycling of reed ASi is very efficient, with over 85 % dissolving within a year after culms collapse. In Scheldt marsh sediment, approximately 80 % of all BSi was diatomaceous in origin, which is consistent with observed rapid recycling of phytoliths.

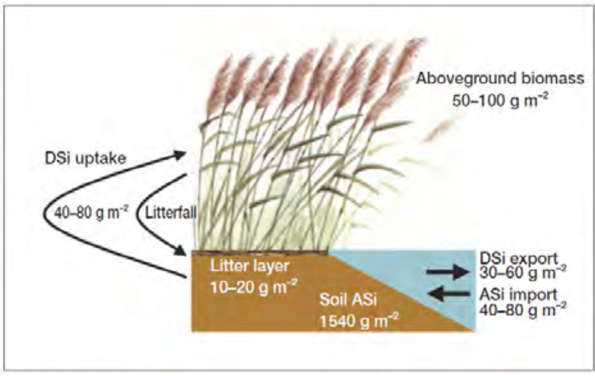

Fig. E-3.3: *Stocks and yearly fluxes of DSi and ASi (amorphous Si ~ BSi) within the 3477 m^2 Belgian freshwater marsh. Sediment stocks are for the upper 30 cm. Litterfall and DSi uptake by vegetation equal each other on an annual time scale (Struyf & Conley, 2009).*

iii. Conclusions and recommendations

Our work has revealed new insights in the cycling of N (Gribsholt et al., 2005, 2006, 2007) and Si (Struyf et al., 2005a,b, 2006, 2007a,b) within freshwater tidal marshes. The studied marsh had an increasing effect on the Si:N ratio in flooding waters. Export of DSi and import of total dissolved nitrogen (DIN) contributed about equally to the increase of the Si:N ratio. The marsh had a counteracting effect on the long term trend of nutrient ratios in the estuary, which could be identified as a positive effect within an estuary that has experienced high N inputs during the past decades. Low Si availability compared to N and P has resulted in frequent occurrence of Si-limitation events within freshwater and saltwater parts of the Scheldt estuary.

However, it should be noted that our results also reveal that tidal freshwater marshes contribute little to the overall yearly N and Si cycling of the Scheldt estuary, which is mainly governed by main-stream water column processes. This is likely due to a combination of the small surface of marshes relative to the overall surface of the estuary, very high nutrient loading, and short water residence time. Still, marshes can play an important role in silica transport through the estuary during specific time-periods when DSi limitation is occurring (especially spring and summer). Moreover, if the large areas of brackish and saltwater marshes in the Scheldt estuary transform N and Si at similar rates compared to our freshwater marsh site, as much as 19 % of the yearly ammonium load to the Scheldt is potentially nitrified in tidal marshes.

We can conclude that coupled research of different element cycles (e.g. N, P, Si) is recommendable for future studies in tidal marshes, as the effect of marshes on estuarine biogeochemical functioning is mainly situated in their interaction. We can also conclude that whole-ecosystem labeling studies are a promising approach to trace importance of internal compartments in nutrient cycling, complementing classical mass-balances. Finally, we recommend research to focus on recently restored tidal marshes. These areas are often implemented to improve estuarine habitat quality, yet especially their role in estuarine nutrient cycling and the evolution of this role with age is poorly quantified.

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4. Diversity-productivity relationships in estuarine microphytobenthos

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Abstract

Field studies at three intertidal mudflat stations within the Scheldt Estuary indicated an inverse relationship between microphytobenthos biomass and species diversity, while the relationship between diversity measures and primary productivity appeared to be site specific, with either a significant positive or a unimodal relationship between both parameters. Species counts and molecular fingerprinting using DGGE were largely congruent and revealed that taxonomic turnover among eukaryotic microbenthos is largely determined by salinity, water content, temperature, irradiance, and tidal elevation. Experimental studies revealed significant cryptic diversity among diatoms and demonstrated that both facilitative and antagonistic interactions play an important role in structuring microphytobenthos communities. Species interactions need to be taken into account when studying critical ecosystem processes such as productivity, stability, sediment stabilization and nutrient cycling in marine and estuarine sediments.

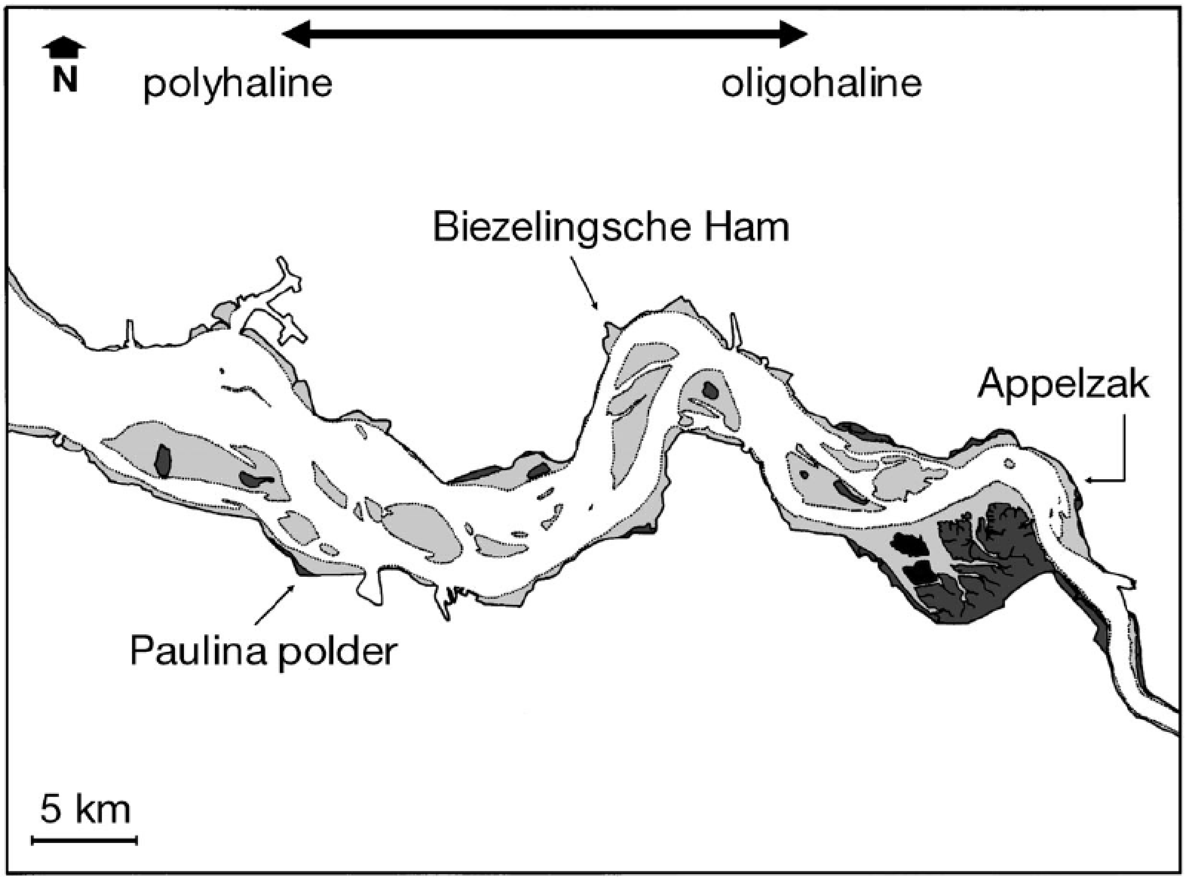
i. Problem

There has been a progressive loss of intertidal mudflats from the main estuaries of the North Sea due to industrial development, dredging activities and land reclamation. This trend may have important consequences for estuarine ecosystem functioning. Indeed, intertidal sediments are characterized by intense carbon and nutrient fluxes due to the primary production (PP) by microalgae, and respiration and remineralization by metazoan grazers and heterotrophic microorganisms. These mudflats often support the growth of dense biofilms of benthic diatoms, which may provide as much as 50 % of the total primary production of estuaries (Underwood & Kromkamp, 1999; Middelburg et al., 2000). While these benthic diatoms migrate into the sediment at high tide, they move to the surface when the sediment is emersed at low tide. Therefore, and in contrast to the turbid water column of estuaries where primary production is strongly limited by the reduced availability of light, high rates of photosynthesis are usually measured in intertidal sediments during daytime emersion. As a result, diatom growth may be unbalanced as nutrients can become limiting in the biofilm, leading to the exudation of copious amounts of extracellular polymeric substances (EPS) that form the biofilm matrix in which the diatoms are embedded (Underwood & Paterson, 2003). In particular, acidic EPS have been suggested to serve as glue, binding the sediment particles (Decho, 2000). In this way, the diatom biofilm may render stability to the sediment, increasing its erosion threshold (de Brouwer et al., 2000). Furthermore, during inundation part of the EPS may be lost ('dissolved') into the water column or biofilms may slough off or be consumed by chemotrophic microorganisms and the diatoms themselves. Clearly, EPS and the diatoms represent an important source of carbon and energy in intertidal foodwebs.

Although these benthic communities of diatoms are very important, not much is known about their diversity and, in turn, how this diversity affects their function. From work on different mainly terrestrial ecosystems it has become increasingly clear that the biodiversity of an ecosystem and its functional features are intricately linked (Loreau, 2010). While much earlier research tried to understand how environmental constraints regulate diversity, the focus has shifted during the last decade to better understand how biodiversity affects ecosystem functioning. Understanding how altered diversity impacts the basic functions of ecosystems is a high priority on the international agenda, as loss in function will inevitably lead to serious consequences for the goods and services provided by these ecosystems.

ii. Aim

The project 'Diversity-productivity relationships in microphytobenthos' (DIVPROD) was launched in 2002 with financial support of FWO and NWO in the framework of the Flemish-Dutch collaboration in coastal sea research. This project addressed the relationship between biodiversity of microphytobenthos and functional aspects of the ecosystem, i.e. primary productivity and stability of tidal sediments along a salinity gradient in the Westerschelde. As traditional diversity assessments of diatoms, like for any other group of microscopical organisms, are fraught with difficulties and usually capture only part of the true diversity, molecular approaches were pioneered in this project to better understand the nature of estuarine diatom diversity and to develop new methods for monitoring it. The project encompassed a combination of a broad-scale seasonal field study as well as mesocosm and laboratory experiments. The field study aimed to quantify the relationships between microphytobenthos species diversity, biomass and activity, and variation in climatic condition, salinity, sediment composition, water content, emersion time and nutrient levels. Experimental studies were designed to better understand diversity effects on biomass accumulation in artificial biofilm communities and to assess intra- and interspecific differences in niche differentiation. The project objectives were realized through a combination of a range of approaches and techniques, including HPLC pigment analysis, 14C uptake and Pulse-Amplitude-Modulated (PAM) fluorescence to estimate biomass and productivity, while microscopical analysis and sequence analysis (18S rRNA, ITS, rbcL) and molecular techniques (PCR-DGGE and q-PCR) were used to assess diversity in field samples and experiments.



iii. Results

Field studies

In situ measurements of diversity and photosynthetic activity of diatom-dominated biofilms were investigated in 6 stations at three locations along the salinity gradient (Fig. E-4.1; Paulina Schor (PS) – salinity = 24, Biezelingse Ham (BH) – S=20 and Appelzak (AZ) – S=8.7).

Fig. E-4.1: *Western Scheldt estuary showing locations of the samoppling sites: Appelzak, Biezelingsche Ham, Paulina polder. After Forster et al. (2005)*

At each location, a high- and low shore station were sampled nine times between March 2002 and September 2003. With the exception of station PS1 which had sandy sediment, all other stations were characterized by low median grain size (mostly between 50-100 µm). Diversity measures were calculated on the basis of relative cell counts down to morphospecies level. Biomass was estimated as chlorophyll a, and primary productivity (Pn) was modeled using a vertically resolved primary production model on the basis of measurements of photosynthetic activity, biomass and abiotic parameters (Forster et al., 2006). Species composition of benthic diatoms differed between sites along the salinity gradient of the estuary. As epipelic species were strongly correlated with photosynthetically active surface biofilm biomass and, hence, also with primary productivity, we focused on the diversity of this functional group. The results indicate that (1) biomass appears to be inversely related to the diversity of the biofilms (periods of low biomass did not show low diversity [as reported for phytoplankton], possibly because these events were driven by grazing pressure and not by nutrient stress) and (2) relationships between diversity (species richness and Shannon index) and Pn appeared to be site specific, with either a significant positive or a unimodal relationship between both parameters (Fig. E-4.2).

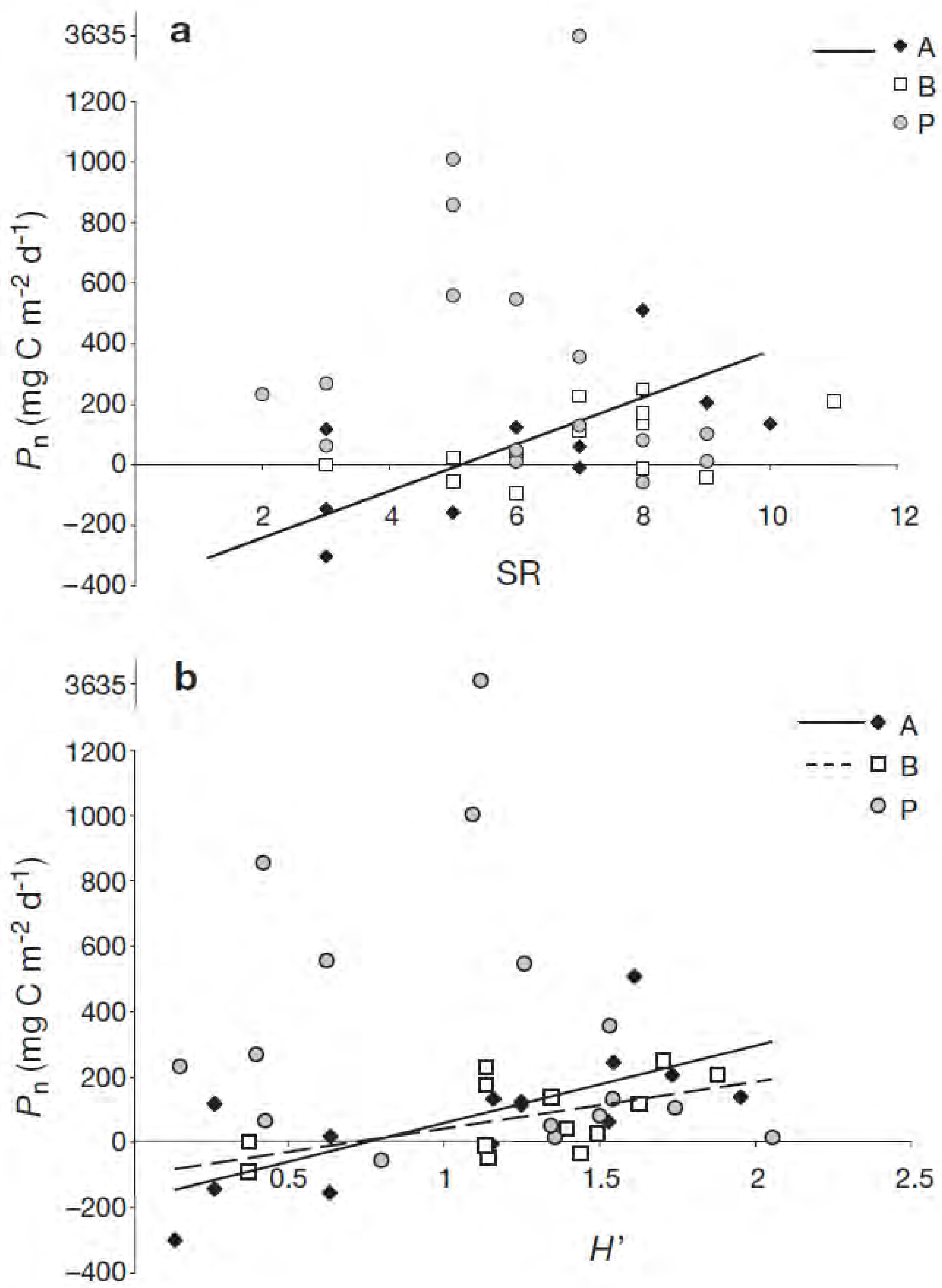


Fig. E-4.2: *Net primary production (Pn: mg C m–2 d–1) as a function of diversity indices: (a) species richness (SR) and (b) Shannon index (H'), for Appelzak (A), Biezelingsche Ham (B) and Paulina polder (P). Linear regression: Panels a & b: R2 = 0.5, p < 0.01, n = 13 for Appelzak; Panel b: R2 = 0.3, p < 0.01, n = 13 for Biezelingsche Ham. After Forster et al. (2006).*

The results confirmed that biomass and primary production were not interchangeable, as they did not show the same relationship with diversity. Changes in standing stock may be impossible to determine for each species, due to the open nature of the ecosystem. Moreover, the biomass represents the standing stock of organic matter, but may not reflect ecosystem metabolism if turnover rates are high. Furthermore, site-specific differences were also found, especially in the relationships of Pn and biodiversity. The causes of this variability in the relationship are multiple. The scale of the study seems to be one of the factors (Chase & Leibold, 2002), due to variability in abiotic parameters along the estuary, such as salinity, sedimentation dynamics and nutrient supply. All these parameters drive the composition of the diatom community, as well as that of associated chemotrophic microbial communities and consumers. Thus, the developmental history of the biofilm will influence the observed rates of ecosystem processes (Fukami & Morin, 2003).

In parallel, the composition and seasonal dynamics of biofilm-associated eukaryotic communities were analysed using microscopy and a genetic fingerprinting technique (PCR-DGGE) (Sahan et al., 2007). In the DGGE data, diatoms, ciliates, amoebae, copepods, nematodes, annelids and platyhelminthes were detected. Ordination analysis of the species counts and DGGE data were largely congruent and indicated that on the scale of the whole estuary (i.e. km scale) salinity, water content and seasonal factors, such as temperature and irradiance, were associated with patterns in the distribution of eukaryotic organisms, including epipelic diatoms and micro- and meiofauna. This is in agreement with earlier reports on the distribution of micro-, meio- and macrobenthic communities in the Westerschelde (e.g. Soetaert et al., 1995, Hamels et al., 2004; Ysebaert et al., 2005). At smaller spatial scales, the position of sampling localities along the tidal exposure gradient appeared to be the main determinant of species turnover, in particular in the brackish reaches of the estuary.

Sequencing of DGGE bands revealed the presence of different types of epipelic diatoms although fewer taxa were identified than by microscopy. This may be due to the fact that PCR-DGGE does not detect genotypes if the abundance is <1 % (e.g. Muyzer et al., 1993) and suggests that microscopic analysis may have a higher resolution. However, it is also possible that microscopical analyses overestimate local diversity as also empty valves (dead cells) are identified. Although it was only possible to identify diatoms to the genus level using sequence similarity due to the poor representation of 18S rRNA gene sequences in the public databases, the diatom count data and the DGGE sequences agreed well. The affiliations obtained from DGGE sequences, Entomoneis (Amphiprora), Pleurosigma and Dickieia, are phylogenetically closely related to Amphora, Gyrosigma and Staurophora respectively. Molecular approaches thus provide a time- and cost-effective method to characterize microbial diversity, in particular for microorganisms that have fewer distinguishing morphological features (e.g. cyanobacteria, green algae). The increase of sequences of 18S rRNA genes in publicly accessible databases would further increase the potential of molecular analyses for micro-algae. The use of multiple primer sets could give a more representative picture of the communities. Although we used the 18S rRNA gene to estimate diversity, more variable regions (e.g., the ribosomal internally transcribed spacer, ITS), group-specific primers, or certain functional genes are needed to obtain a better resolution of the genetic diversity. In addition, expression profiling of functional genes will provide a useful tool to monitor microphytobenthos activity and its response to environmental stresses.

Cryptic diversity

Evidence has accumulated during the last decade showing that many established diatom morpho-species actually consist of several, often sympatrically occurring pseudocryptic or truly cryptic species. This phenomenon raises important questions about niche partitioning between such closely related species. In this project we focused on the benthic diatom morpho-species Navicula phyllepta Kützing sensu lato, which is a widespread and common diatom in the Westerschelde estuary. We used the ribosomal ITS, 18S rRNA gene, and the RUBISCO LSU (rbcL) chloroplast gene sequence data together with cell wall morphology to show that populations of this species consist of several pseudocryptic species. Growth rate measurements in function of salinity showed that N. phyllepta strains assigned to the different species differed in their tolerance to low salinities (<5), which was reflected by their different (but widely overlapping) distribution in the estuary (Vanelslander et al., 2009a). We developed a quantitative real-time PCR (qPCR) assay using TaqMan probes targeted to the internal transcribed spacer 1 (ITS1) to assess the spatial distribution and seasonal dynamics (Creach et al., 2006). Multiple regression analyses of the factors determining the abundance of the different species in field samples revealed that, in addition to salinity, sediment type and ammonium concentrations were probably equally important. Additionally, the seasonal pattern of the two forms of N. phyllepta showed an overlapping, but unique distribution along the estuary. Our results thus show that N. phyllepta sensu lato comprises different species with specialized ecophysiological characteristics, rather than generalists with a broad adaptability to different environmental conditions.

Experimental studies

The potential effect of species diversity on ecosystem functioning was further addressed using microcosm studies (Vanelslander et al., 2009b). Most experimental studies on microorganisms have used randomly assembled communities that do not resemble natural communities. It is therefore difficult to predict the consequences of realistic, non-random diversity loss. Therefore we used naturally co-occurring diatom species from intertidal mudflats to assemble communities with realistically decreasing diversity and analysed the effect of non-random species loss on biomass production. Our results demonstrate a positive biodiversity effect on production, with mixtures outperforming the most productive component species in more than half of the combinations. These strong positive diversity effects could largely be attributed to positive complementarity effects (including both niche complementarity and facilitation), despite the occurrence of negative selection effects which partly counteracted the positive complementarity effects at higher diversities. Facilitative interactions were, at least in part, responsible for the higher biomass production. For one of the species, Cylindrotheca closterium sensu lato, we showed its ability to significantly increase its biomass production in response to substances leaked into the culture medium by other diatom species. In these conditions, the species drastically reduced its pigment concentration, supporting the hypothesis that this species switched to mixotrophic growth in the presence of organic substrates excreted by other species (Fig. E-4.3). Additional studies on this species complex showed a widespread but varying capacity for mixotrophic growth as well as a distinct variation in temperature-dependent growth capacity among the several cryptic and pseudocryptic species (Vanelslander et al., unpubl.).

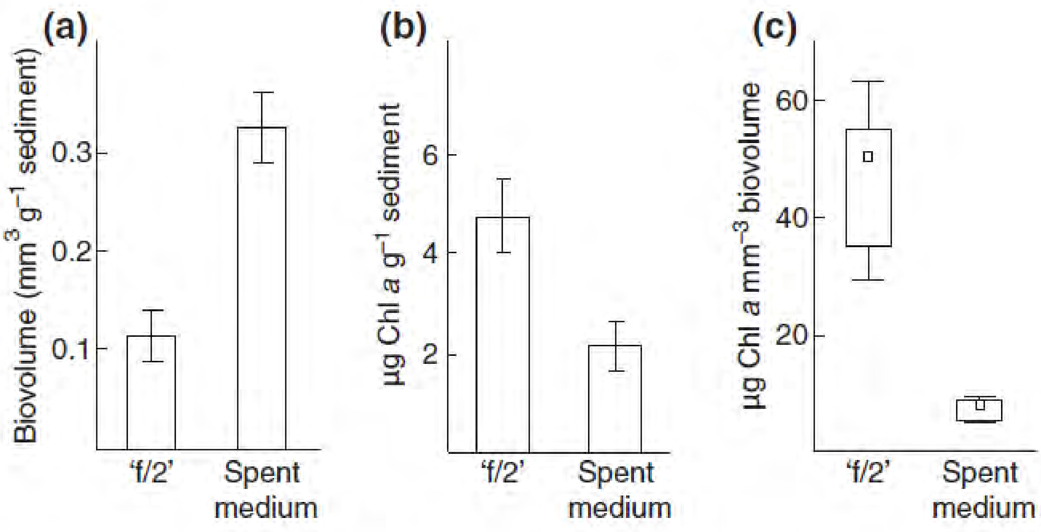


***Fig. D-4.3:** Biovolume yield (a) and chlorophyll a yield (b) of a monoculture of Cylindrotheca closterium when grown in inorganic 'f / 2' medium and in 'f / 2' medium enriched with spent medium of a mixture of Navicula species. (c): boxplot of the chlorophyll a to biovolume ratioin both treatments. After Vanelslander et al. (2009b).*

In conclusion, these experiments demonstrated that both species richness and identity can have strong effects on the biomass production of benthic diatom biofilms and that transgressive overyielding is common in these communities, whereby combinations of species are more productive than the yield of individual species. In addition to providing mechanistic evidence for facilitation, which is partly responsible for enhanced primary production, our results have implications for carbon cycling in sediments. Indeed, mixotrophic uptake of dissolved organic matter by diatoms may compete with carbon utilization by bacteria, further adding to the complexity of carbon cycling in intertidal sediments.

In addition to facilitative interactions, the organization of microphytobenthos communities appears to be strongly affected by antagonistic interactions. In laboratory experiments, we demonstrated allelopathic effects of an – as yet unidentified - Nitzschia species on several common species that occur sympatrically in the Westerschelde estuary. Furthermore, we demonstrated reciprocal, density dependent allelopathic interactions between this species and two other species, suggesting that antagonistic interactions are common among benthic diatoms. It is thus likely that these positive and negative interactions among diatoms contribute to the high spatial and temporal turnover in species composition in estuarine microphytobenthos within the constraints imposed by physical (e.g. Van der Wal et al., 2010) and other biological constraints (e.g., Hamels et al., 2004; De Troch et al., 2006) operating in these dynamic ecosystems.

iv. Conclusions

A general conclusion of this project is that there exists a scale-dependent, positive or unimodal relationship between microphytobenthos diversity and productivity. Micro- and mesocosm experiments further suggest that niche differentiation and facilitation are important mechanisms contributing to this relationship. Mixotrophy is probably one of the main mechanisms in explaining facilitative interactions in diatom biofilms. However, antagonistic interactions also appear to occur commonly in diatom-dominated biofilms and may contribute to spatial and temporal turnover in these communities. The project further demonstrated that cryptic diversity is probably widespread in microphytobenthos, as was found in other functional and taxonomic groups of eukaryotic microorganisms. We showed that distributional patterns of cryptic species were largely overlapping at larger spatial scales, but that at the local scale and over time, niche segregation occurs between the studied gamodemes.

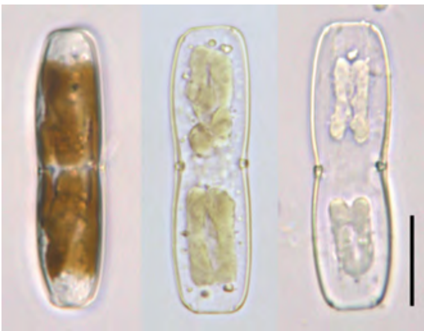


Fig. D-4.4: *LM photographs of Stauronella sp. exposure to the toxic diatom Nitzschia cf pellucid. Left: Healthy cell. Middle: Stauronella cell after 48h. exposure. Right: Stauronella cell after 72h exposure.*

v. Recommendations

The results obtained during the VlaNeZo project have provided deeper insights into the complexity of microphytobenthos communities and have highlighted some important mechanisms contributing to diversity-stability and diversity-productivity relationships in these biofilms. Since the conclusion of the VlaNeZo project, new technologies for rapid and cheap high throughput sequencing of metagenomes and metatranscriptomes have started to revolutionize our understanding of natural microbial communities. It is now becoming possible to link molecular processes occurring in populations of living cells to ecosystem processes. Future work should combine these new tools in field and laboratory-based studies to gain a deeper understanding of the role of environmental controls and various biological processes that determine the taxonomic and functional diversity of microbial communities. In particular, we need a better understanding of the drivers behind site-specific relationships between diversity and productivity. In turn, this will teach us more about the critical controls of important ecosystem processes such as productivity, stability, sediment stabilization and nutrient cycling in marine and estuarine sediments.

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5. The structure and functional roles of tidal flat meiobenthos

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Abstract

Meiofauna comprise the smallest multicellular and largest unicellular metazoans in benthic food webs. They are highly abundant and species-rich, yet essential aspects of the factors driving their community structure and abundance remain poorly understood. Similarly, their functional roles in benthic carbon cycling remain poorly characterized and even more poorly quantified. In the frame of two projects, we addressed questions regarding both the biotic and abiotic factors that drive meiobenthic assemblage structure, and their roles in benthic carbon cycling. Our research involved an intricate combination of manipulative laboratory experiments and field work, the latter mostly focusing on the intertidal flats bordering the Paulina salt marsh in the Scheldt estuary.

The results add considerably to our understanding of the factors that drive meiobenthic assemblage structure. They clearly demonstrate that biotic interactions among different meiofauna, and between meio- and macrofauna, are extremely important and moderate the impacts of prominent abiotic drivers of assemblage structure such as granulometry and oxygen availability.

From a functional point of view, we demonstrated that tidal flat meiofauna rely predominantly on carbon derived from *in situ* primary production by microphytobenthos. Quantification of grazing rates of meiofauna on microphytobenthos and benthic bacteria does not, however, point at an important direct contribution of meiofauna to benthic carbon cycling. The role of meiobenthic species diversity remains to be established, but laboratory experiments into the role of nematodes in OM decomposition reveal that in addition to species identity, species diversity does have a significant, yet largely unpredictable effect on OM decomposition rates.

i. Problem

The past two decades have witnessed an explosive increase in research efforts devoted to the relationship between biological diversity and ecosystem functioning (Loreau et al., 2001, Hooper et al. 2005). A majority of studies have focused on terrestrial systems and on the relationship between plant species diversity and primary productivity. Estuaries, however, are ecosystems which provide an array of 'functions' or 'services' of great importance and economic value to men. Further, in addition to offering food, shelter etc… to impressive numbers of animals and they often present natural gradients of animal diversity (Kaiser et al., 2005). Whether and how both these high abundances and varying diversity levels affect key ecosystem functions in estuaries remains largely unknown.

In terms of density and species diversity, the meiofauna (multicellular and unicellular organisms in the size range between 100 µm and a few mm) are prominent members of sediment communities in all marine and estuarine soft sediments (Heip et al., 1985) (Fig. E-5.1).

Fig. E-5.1: *Picture of meiobenthos elutriated from a small tidal flat sediment subsample, showing nematodes, harpacticoid copepods, polychaetes (large) and a turbellarian.*

The combination of small body size, comparatively short life cycle and limited active mobility, disabling them from escaping local impacts on sediments, renders them highly interesting instruments for biomonitoring of marine sedimentary environments (Bongers and Ferris, 1999, Schratzberger et al., 2000). Their very high abundances (usually > 10^6 individuals m^{-2}) and suspected high metabolic activity per unit body weight, raise questions on their importance in carbon and nutrient fluxes in estuarine sediments (Heip et al., 1985). Moreover, their high species diversity at local scales (usually several tens of species in every m^{-2} of sediment) provides a challenging research model for the study of how species diversity is structured and how it contributes to ecosystem functioning (De Mesel et al., 2006).

Although field studies have shown consistent patterns in meiofaunal assemblage composition, we still lack an understanding of how these patterns are established. More importantly, their actual roles in benthic carbon cycling remain poorly understood and even more poorly quantified.

Meiofauna as a group are generally considered microbial feeders and/or grazers of microalgae; hence, they are likely involved in detritus decomposition and may affect primary production, Since meiofauna are also food to higher animals such as hyperbenthic crustaceans and fish, their importance in channeling carbon and energy from basal to higher trophic levels remains to be established (Gee, 1989). Hence, it is currently hard to describe exactly whether and how a square meter of sediment comprising a million meiofaunal individuals and tens of species function differently from a hypothetical identical sediment completely devoid of meiofauna.

ii. Aims

The aims of the projects were twofold:

1) To elucidate the importance of selected environmental drivers for the structure and activity of meiofaunal communities. We have chosen to focus on a combination of sediment granulometry, organic matter/food availability and sediment oxygenation. These parameters have shown to exert major impacts on benthic fauna in different systems (Heip et al., 1985), They are often subject to fluctuations of anthropogenic origin and they are strongly interrelated. We have further tried to emphasize the role of macrofauna, which, through their burrowing activities, affect sediment oxygenation, while at the same time they may cause meiofaunal mortality through both physical disturbance and direct predation (Olafsson, 2003).

2) To further increase our understanding on the functional roles of meiofauna in benthic metabolism and how these roles relate to taxonomic identity and/or species diversity.

The first goal has been addressed mainly during the first project: Food, oxygen and bioturbation: an experimental study of the structure of meiofaunal communities. Whereas the second goal formed the core of the second project: Functional role of nematodes and foraminifera in benthic metabolism' and derived projects.

The results are based on an intricate interplay between manipulative laboratory experiments and field studies, including an in situ disturbance and recolonization experiment, in the Scheldt estuary during the years 2002 till 2007 (Fig. E-5.2).

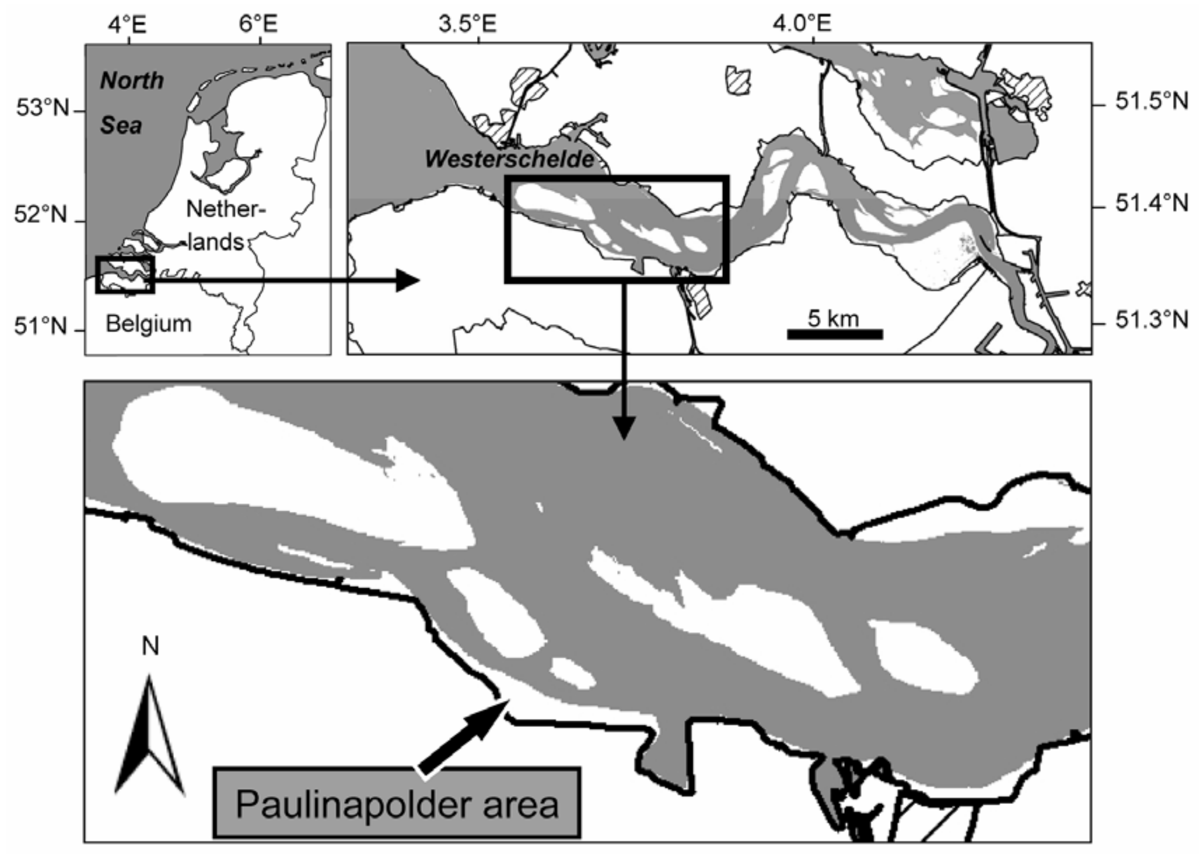

Fig. E-5.2: *Map of the Scheldt Estuary with indication of the Paulinapolder salt marsh and intertidal flat area where most of the field work described in this paper was performed and where most live organisms for lab experiments were collected.*

iii. Results

Project I – Although a considerable body of literature points at the importance of sediment granulometry as the main structuring factor for meiofaunal communities, with oxygenation and organic matter loading as derived factors. However, the results of the project paint a more complex picture in which biological interactions strongly modify these abiotic sedimentary impacts. This is illustrated by the comparison of the vertical profiles of nematode assemblages in sediments with contrasting granulometry. The main differences in nematode assemblages between these sediments are found in the upper 2 cm, while assemblages in deeper layers exhibit substantial similarity (Steyaert et al., 2003). In fine-grained but silt-poor sediments, the upper 2 cm are often characterized by a high prominence of nematodes predacious on other nematodes. Both in terms of biomass and abundance, other nematodes in this sediment horizon are often low, much lower than in nearby silty sediments (Steyaert et al., 2001, 2003). Manipulative laboratory experiments and correlative studies based on field samples clearly indicate that the prey nematode assemblages in this surficial sediment stratum are primarily governed by top-down control in which predation controls prey abundance, species composition and perhaps diversity (Moens et al., 2000, Gallucci et al., 2005). Interestingly, prominent species in deeper sediment strata are often the same as in surface layers of nearby silty sediments. A logical explanation for the segregation between a surface- and a deeper-living assemblage in silt-poor sediments would be that the predatory nematodes are more susceptible to oxygen stress than most of their prey, but this was not confirmed by our lab experiments (Steyaert et al., 2005). We did observe that even minor differences in sediment texture – in particular silt content – and sediment water content (during low-tide exposure on intertidal flats) profoundly impact the predation success of the predatory nematodes: even small amounts of silt create extra refuges for prey and greatly reduce predation rate, which corresponds very well with the in situ distribution pattern of the dominant predatory species (Gallucci et al., 2005) (Fig. E-5.3).

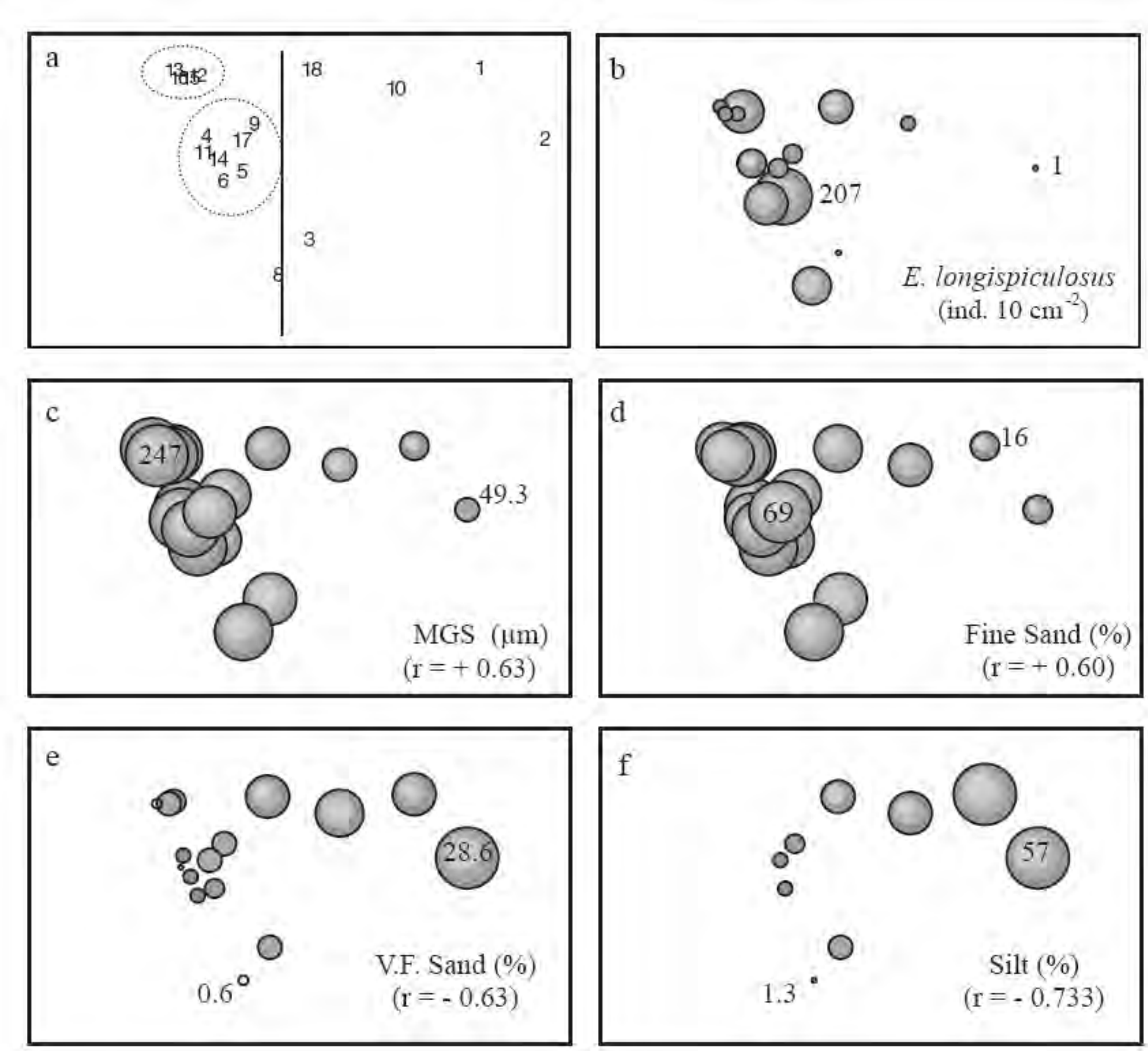

Fig. E-5.3: *Bubble plot of the abundances of Enoploides longispiculosus, a dominant predatory nematode, in 18 stations on the Paulina tidal flat in the Schelde Estuary (b). The data are superimposed on an ordination (PCA) of these same stations based on sediment characteristics (a). Figures (c) - (f) plot mean grain size (MGS), % fine sand (125-250 µm), % very fine sand (63-125 µm) and % silt (< 63 µm) of the 18 stations. The figures clearly show a strong positive correlation between Enoploides abundance, MGS and proportion of fine sand, and a negative correlation between Enoploides abundance and the proportions of very fine sand and silt. Figure taken from Marine Ecology Progress Series 134, p. 172.*

Similarly, drying of surficial sediment during low-tide exposure immobilizes predators, reducing the prey's risk of beying caught (Gallucci et al., 2005). This corresponds remarkably well with observations of tide-induced vertical migrations of different nematode species: as the tide moves out, predatory nematodes tend to burrow deeper to avoid the dryer surface sediment, while several prey species do exactly the opposite, allowing them to feed on the diatom biofilms at the sediment surface (Steyaert et al., 2001). The general net effect, nevertheless, is still such that prey abundances in surface layers remain low (Gallucci et al., 2005). Interestingly, none of the above factors explain the absence of predatory nematodes beneath a depth of 2 cm. Pressure plate experiments suggest that the higher sediment compaction in deeper layers is the main reason for this, as it reduces the available pore space in which predators can forage (Steyaert et al., unpubl.). While mainly of fundamental interest, these results are highly relevant to understand seasonal changes in meiofaunal communities, since intertidal sediments in estuaries are often subject to seasonal siltation-desiltation cycles (Herman et al., 2001). They also have implications for the consequences of any anthropogenic actions that may alter – even to a small extent – the granulometry of intertidal sediments. Since other studies have suggested that the larger predatory nematodes in turn are more susceptible to predation by hyperbenthic predators such as shrimps and fish (Hamerlynck and Vanreusel, 1993), and since predatory nematodes also impact on the microbial loop in sediments through predation on ciliates (which in turn feed on diatoms and bacteria) (Hamels et al., 2001), the current findings may have important implications.

While interactions among meiofaunal species thus appear important in determining meiofaunal assemblage structure, this certainly also holds for interactions between meio- and macrobenthos. This was illustrated by an in situ defaunation experiment at the Paulinapolder tidal flat (Fig. E-5.2) in which silty sediment plots were defaunated by induced hypoxia, and their recolonization followed over a period of 3 years in comparison to neighbouring control spots. The induced hypoxia completely eliminated macrobenthos but not nematodes, several species of which survived, albeit at low abundance (Van Colen et al., 2009). Recovery after hypoxia – even after 3 years – did not result in assemblages identical to those in the surrounding sediments for either meio- or macrobenthos (Van Colen et al., 2008, 2009, 2010). The nematode assemblage changed mainly as a function of microphytobenthos and of abiotic factors such as sediment ammonium content. Both microphytobenthos biomass and several sediment abiotic factors in turn were profoundly affected by the activity of, and changes in, the macrofauna communities which recolonized the disturbed plots. Bioturbation and grazing by macrofauna affect microphytobenthos abundance and sediment accretion (Montserrat et al., 2008, Van Colen et al., 2008), while bio-irrigation impacts nitrification/denitrification processes (D'Andrea and DeWitt, 2009). Hence, the recovering macrobenthos drives the ecosystem changes which in turn control the evolution of the nematode community (Van Colen et al., 2009).

We had rather expected a direct impact of macrobenthos on meiofauna as a result of the deeper oxygen penetration caused by bio-irrigation. We performed several lab experiments in which bio-irrigation of macrofauna was mimicked by flushing artificial tubes with oxygen. These experiments revealed clear species-specific effects on the location and activity of meiofauna (Steyaert et al., 2005). Additional lab experiments documented species-specific survival and recovery rates of nematodes during and after induced hypoxia or anoxia (Steyaert et al., 2007). Even so, the above field experiment illustrates that oxygen in itself is not the sole or even the principal driver of community changes during recovery from hypoxia. Rather, an intricate combination of biological interactions and abiotic drivers, including oxygen, is responsible for the observed structural changes in nematode communities.

Project II – In order to further increase our understanding on the roles and importance of meiofauna in benthic carbon fluxes, an improved insight into their trophodynamics, feeding selectivity and metabolic activity is required. We investigated the relative contributions of different carbon inputs to the diet of nematodes on intertidal flats using stable isotopes. Tidal flats receive a variety of inputs with different quality and palatability (e.g., detritus and algae). The carbon and nitrogen isotopic signatures of these sources often differ. Since isotopic signatures of consumers closely resemble those of their food, natural isotope abundances are good trophic tracers. Using this approach, we demonstrated that nematode assemblages of bare intertidal flats rely predominantly on microphytobenthos-derived carbon. In sediments of salt marshes, which act as traps of suspended particulate (organic) matter and to a lesser extent in bare silty tidal flat sediments, settled phytoplankton also contributes to the diet of nematodes (Moens et al., 2002, 2005). For many nematode species, microphytobenthos carbon uptake is indirect and involves predation on a herbivore which grazes microphytobenthos (Moens et al., 2005) (Fig. E-5.4).

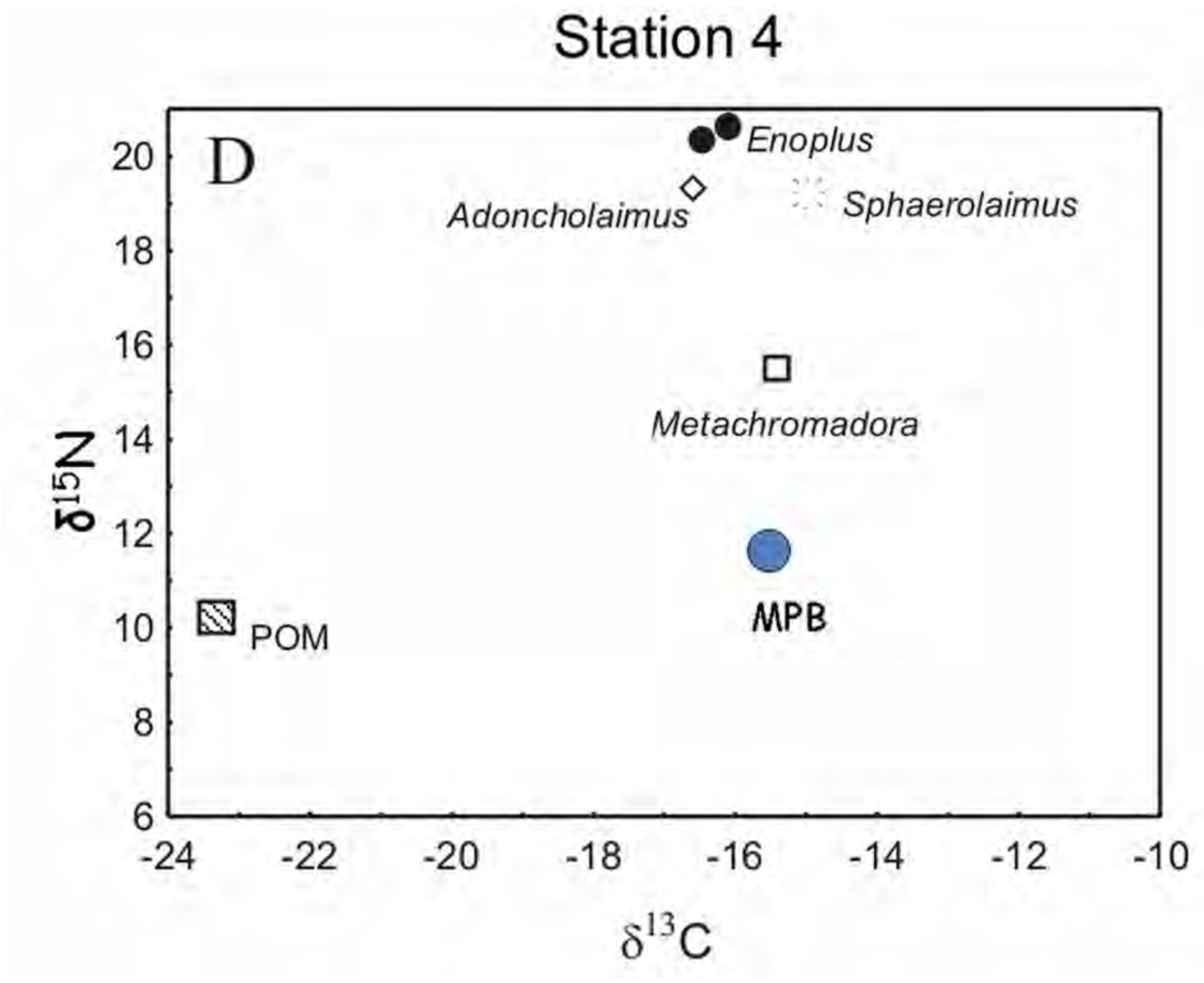

Fig. E-5.4: *Plot of the stable carbon and nitrogen isotope signatures ($\delta^{13}C$ and $\delta^{15}N$) of 4 nematode genera and of microphytobenthos (MPB) and suspended particulate organic matter (POM) at a station on the Paulina tidal flat (Schelde Estuary). The high similarity in $\delta^{13}C$ between MPB and all nematode genera demonstrates that MPB is the predominant carbon source for nematodes on this tidal flat. The offsets between $\delta^{15}N$ of MPB, Metachromadora and other nematode genera illustrates that MPB feeds directly on MPB, while the other nematode genera are predators of herbivores such as Metachromadora. Figure redrawn after Journal of the Marine Biological Association of the United Kingdom 85, p. 143.*

This again illustrates the importance of predation on other meio- and microfauna as a feeding strategy in a variety of nematodes. We further substantiated the link between microphytobenthos (mainly diatoms) and meiobenthos in several tracer experiments in which ^{13}C-labeled diatoms were offered as food, or in which diatoms were labeled *in situ* with ^{13}C and the fate of the freshly produced diatom carbon into different consumers was followed.

Inspite of the importance of diatom carbon to the diet of nematodes, harpacticoid copepods and foraminiferans, none of these meiofaunal groups grazed a significant part of the MPB primary production (Moens et al., 2002, Van Oevelen et al., 2006b). Similarly, while up to 40 % of the carbon requirements of nematodes could be met by their grazing on bacteria, this grazing removed only a marginal portion of the bacterial secondary production (Van Oevelen et al., 2006a). Hence, the direct contribution of meiobenthos to carbon cycling on intertidal flats is probably very small. In addition, our work also revealed that inputs of detrital carbon fuel a major share of bacterial production on intertidal flats. Less than 10 % of this microbial secondary production is consumed and transferred up the food chain, leaving the majority of the bacterial carbon production as a trophic dead end (Van Oevelen et al., 2006b).

In relation to the goals of first project, we also investigated the effects of hypoxia on carbon consumption by meio- and macrobenthos. Since meiobenthos exhibit much better survival under hypoxia than macrobenthos, we hypothesized that meiobenthos could perhaps partly take over the role of macrobenthos in benthic carbon cycling under low-oxygen conditions. However, our results demonstrated that while many nematodes survived episodes of hypoxia, their metabolic activity during hypoxia was severely depressed (Moodley et al., unpubl.).

The two projects also provided the facilities and the impetus for expanding tools and methods to study trophic relations and dynamics in meiofauna. The above-mentioned studies were among the first in which the relative importance of different carbon sources to the diet of meiofauna was studied at genus or even species level, thanks to proper adaptation of existing protocols for larger organisms to the small-sized metazoans. Further, we developed a novel respiration chamber for highly sensitive measurements of oxygen consumption in meiofauna (Moodley et al., 2008). We applied this method to selected species of nematodes, foraminiferans, ostracods and a gastropod. The results demonstrated similar biomass-specific oxygen consumption rates across taxa, averaging 1.5 to 2.5 $\mu lO_2h^{-1}mg^{-1}C$ (Moodley et al., 2008). We also pioneered the use of fatty acid profiles as trophic tracers in meiobenthos, where they provide a complementary method to stable isotope signatures to elucidate the importance of different food sources. We applied both approaches (stable isotopes and fatty acids analyses) to two nematode species, two harpacticoid copepods, a foraminiferan and an ostracod from a muddy tidal flat in the Oosterschelde. The results again highlighted the importance of microphytobenthos as a carbon source for most tidal flat meiofauna. One nematode species and one harpacticoid species clearly relied on chemosynthetic bacteria as food (Moodley et al., unpubl.). That chemoautotrophic prokaryotes are food to some meiobenthos had previously only been documented from deep-sea hydrocarbon seeps (Van Gaever et al., 2006) and from mangrove sediments (Moens et al., unpubl.).

Finally, we also performed closed microcosm experiments into the role of bacterial-feeding nematodes in organic matter decomposition. We found that nematodes can both stimulate and slow down decomposition rates through their interactions with bacteria, but the underlying mechanisms have only partly been elucidated (De Mesel et al., 2003, 2004). Even very closely related nematode species may differentially affect decomposition, and strongly interact – often in an inhibitory way – with eachother. As a result, while we were able to demonstrate highly significant effects of species diversity and identity on decomposition rates, the diversity effect was largely unpredictable (De Mesel et al., 2006).

iv. Conclusions

The results of the Vlanezo projects add considerably to our understanding of the factors that drive meiobenthic assemblage structure. They clearly demonstrate that biotic interactions among different meiofauna, and between meio- and macrofauna, are extremely important and moderate the impacts of prominent abiotic drivers of assemblage structure such as granulometry and oxygen availability.

From a functional point of view, we demonstrated that tidal flat meiofauna rely predominantly on carbon derived from *in situ* primary production by microphytobenthos. Quantification of grazing rates of meiofauna on microphytobenthos and benthic bacteria does not, however, point at an important direct contribution of meiofauna to benthic carbon cycling. The role of meiobenthic species diversity remains to be established. Laboratory experiments into the role of nematodes in OM decomposition reveal that in addition to species identity, species diversity does have a significant yet largely unpredictable effect on OM decomposition rates.

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