Building with Nature

EcoShape

Developing an Interactive Tool for evaluating sand nourishment strategies along the Holland Coast in perspective of benthos, fish nursery and dune quality

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1 Introduction

1.1 Context

In The Netherlands, a significant part of coastal protection is achieved by nourishing sand. At first, this was achieved solely by supplying sand directly onto the beach. Since the nineties, shoreface nourishment became the preferred nourishment technique (Roelse, 2002; Grunnet, 2005; Klein, 2005; Steijn, 2005). Shoreface nourishments supply sand in between the outer breaker bars along the coast, or offshore from the most seaward bar, at water depths of about 4 to 10 metres. The natural action of waves and currents during mild weather conditions transports sand towards the shoreline, re-establishing the original cross-shore profile shape coastline prior to the nourishment. In this way erosion due to storm events can be counter-acted. In other cases, the bar created by nourishments had a stabilising effect on the profile (Ruessink et al., 2012). Since 1997, shoreface nourishments are applied regularly and since 2001 increased volumes of sand have been supplied (Figure 1).

Recently, much larger nourishments (referred to as mega-nourishments) have raised attention in coastal management. The Sand Engine on the South Holland coast is a first pilot project for these mega-nourishments. The cost price per unit of the sand is lower than for small scale nourishments. It is assumed that such a nourishment not only protects the coast at the nourishment location itself, but also functions as a source of sediment for a larger part of the coast. The size of a mega-nourishment, in the order of 20 million m^3 at once, represents a large disturbance of the coast at the time of construction. Due to its size, it is expected to take many years to decades before a new nourishment has to be executed. During this period no other nourishment will disturb the natural processes and the assumption is that this results in a lower environmental impact on the coastal ecosystem.
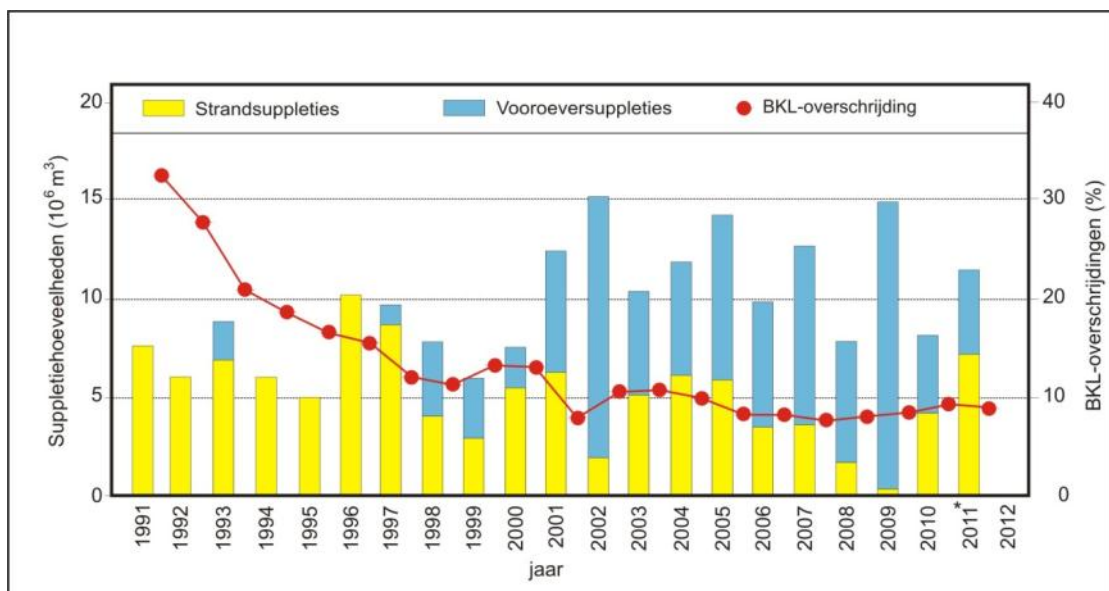
Figure 1. Volumes of sand nourishments per year, subdivided into beach nourishments (yellow) and shoreface nourishments (blue). The red line indicates the percentage exceedence of the basal coastline. Source: Rijkswaterstaat.

Sand nourishments can affect the coastal ecosystem in various ways (Van Dalfsen, 1996; Speybroeck, 2006, Baptist et al., 2008). Direct effects are the burial of benthic species under a layer of sand. In the direct vicinity, suffocation of benthos

can occur due to the settling of a plume of suspended sediment particles. A plume of fine particles may also increase turbidity and thereby affect primary production and the foraging success of filter-feeding benthos and fish. Indirect effects are habitat change, such as altered morphology and sedimentology. This may also change habitat characteristics such as penetrability, compactness, and organic matter and silt content of the seabed.

Sand nourishments may also have an effect on the size and quality of the nursery habitats for juvenile fish. In this study the nursery habitat is delimited by the shallow coastal zone between 0,5 and 10 m water depth, following Glorius et al. (2012). Because of the direct coupling between nursery size and recruitment to the population (Rijnsdorp et al., 1992), enhancing juvenile habitat and nursery grounds can be beneficial to the population size. Moreover, when density-dependence regulates the juvenile phase, management measures aimed at protecting the juvenile habitat may be much more effective than regulating fishing effort on the adults (Van de Wolfshaar et al., 2011). The switch from pelagic to demersal life stages of flatfish may be important to the recruitment success as well (Van der Veer et al. 2000). In this respect grain size at the nursery areas and that of the nourishment may play a role (Tulp et al. 2006). On a broader scale, a recent review showed that 70% of the officially landed fish biomass of species occurring in the north Atlantic region (including the North Sea) use coastal areas during at least a part of their life-history (ICES 2012). It is important to assess the effects of sand nourishments on nursery habitats and juvenile fish in order to establish the nourishment strategy with least effects on the nursery function.

Sand nourishments may also affect the dunes along the coast. They essentially change an eroding coast into a stable or accreting one, through the addition of sand to the system. This may lead to dune growth, both through growth of the existing foredune (i.e. the most seaward dune) and/or the formation of embryonic dunes that may grow out into larger dunes (Stive et al., 2002; Van der Wal, 2004; Arens et al., 2010; Bochev-van der Burgh et al., 2011). Although the situation is unprecedented on the Holland Coast in recent history, based on natural bar welding on the Dutch Frisian Islands, large influxes of sand may lead to the formation of green beaches, new foredunes and primary dune slacks. Such landscapes are considered very valuable for biodiversity, as they contain pioneer communities that have become very rare along the coast of The Netherlands and abroad. Therefore, high expectations exist for the ecological potential of mega-nourishments, which through their large size might allow repeated new formation of these habitats.

1.2 Objective and approach

The objective of Building with Nature is to provide guidance on ecologically optimized design of sand nourishments, in terms of frequency, season, location and configuration. Nourishing the coast may be detrimental for many organisms but also yield favoured habitats and ecosystems like new foredunes. In this Building with Nature Holland Coast project we initiated the development of such a tool. Using the data available a first preliminary tool was developed. It was tested by investigating whether it is possible to optimise nourishment configuration, location and timing, to:
- minimise the impact on benthos,
- increase nursery area and/or quality, and
- enhance dune quality.

By applying the tool, it becomes clear what are the strong points and where the tool needs improvement. A list of improvements will be postulated. This guides the programming and design of future research in order to improve both the understanding of the processes associated with nourishment and yielding the necessary data for the improvement of the guidance tool.

1.2.1 Approach

For this purpose several tasks were carried out. First an assessment was made of available knowledge on habitat factors (depth, grain size, sediment stability, water temperature, presence of food, etc.) in relation to seasonal patterns, mapping larval settlements habitats and juvenile nursery habitats. This has been reported in Teal & Van Keeken (2011). Next, additional data on the use of the shallow coastal zone by juvenile fish was collected through surveys. This has been reported in Van Keeken (2011). Subsequently, habitat maps for six fish species in the shallow coastal zone of the Netherlands have been developed. This has been reported in Glorius et al. (2012). The overall conclusion from these studies is that the coast is inhabited by many (commercial) fish species, with individual distributions and preferences. Plaice and dab are most common in the Wadden Coast area, while sole and gobies inhabit mainly the Voordelta coast. Gobies have the highest densities, especially in the more brackish waters in the Voordelta coast. Whiting densities are lowest in the Holland coast, whereas flounder has highest densities in this region. Flounder generally has the lowest densities.

The focus of this report is the last step in this assessment. We describe the set-up and execution of a model for long-term predictions of habitat change due to sand nourishments. For this, we extended the already existing Interactive Design Tool for the Holland Coast (ITHC). This tool has been developed for predicting long-term shoreline changes as a result of different nourishment strategies with the UNIBEST model (Deltares, 2012). Two ecological modules have been implemented into the ITHC. The first module considers the direct impact of burial on benthic species and subsequent population recovery. The second module considers the impact of nourishments on the available habitat for juvenile fish, based on the decrease (or increase) of foreshore area as a result of a prograding or retreating coast. Additionally, results from an independently developed dune module of the ITHC are presented (De Groot, 2012 as part of BwN HK4.1). The expanded ITHC model was applied to a number of coastal nourishment strategies. The results of the combined model were used to formulate guidelines for the application of ecologically optimized nourishments.

The ITHC has been developed for use during stakeholder sessions, for rapidly giving a first impression of the consequences of envisaged management scenarios. Knowledge is still limited on many of the consequences of nourishments on ecology. Therefore, the presented set of models represent a first, global, attempt to integrate and visualise several effects of nourishments. This is done as far as possible within the constraints put by process knowledge, available data and technical aspects concerning modelling.

This study is carried out as work package HK3.8 in the Building with Nature (BwN) programme and has been carried out in close collaboration with work package HK4.1. The latter aims at "Developing a strategy for the long-term, sustainable development of the Holland Coast through extrapolation of findings from projects and pilots to the scale of the entire Holland Coast". The strategy will be based on the design philosophy of BwN which aims at maximizing the potential of the eco-morphodynamic system. The original ITHC model without benthos, fish and dunes, was developed as part of work package HK4.1.

2 Methods

2.1 Interactive Tool for the Holland Coast (ITHC)

The Interactive Design Tool for the Holland Coast consists of a user interface (web based front-end), a set of models that forecast the long-term coastline changes as a result of nourishment strategies and post processing routines for several (ecological) indicators. Simulations with the ITHC were performed for a period of about 100 years. The ITHC is intended for use in stakeholder sessions, where nourishment strategies can be designed and evaluated on the spot. The model is computationally efficient (i.e. several minutes processing time for 100 years of simulation for the entire Holland coast). The core of the model consists of the UNIBEST module that simulates coastline changes. The impacts on ecological indicators are calculated separately in post-processing modules, based on the outcomes of the UNIBEST model. These post-processing modules consider benthos (this report), juvenile fish (this report), and dunes (De Groot et al., 2012 in prep.). The results can be exported to Google Earth, in which the users can visualise the results in time and space. Next to the predictions, an important aspect of the tool is to visualise aspects related to nourishments that are little known by most stakeholders. In this case that includes the alongshore effect of nourishments (UNIBEST) and the possible contrasting effects on parts of the ecosystem.

Technical information on the implementation of the benthos and fish modules in the code and code structure can be found in Deltares (2012). Initial test cases that were used to tune the parameters, different from the scenarios shown in this report, are described there as well.

2.2 Coastline schematization of the Holland Coast in the ITHC

The ITHC includes a UNIBEST-CL+[1] coastline model that has been set up for the Holland coast (i.e. from Hoek van Holland in the south to Den Helder in the north). The model has a length of 118 km and includes 113 cross-shore profile transects. The harbour moles of Scheveningen and IJmuiden are included as hard structures. The model computes alongshore sediment transport from location-specific but fixed profiles, shoreline orientation and a wave climate conditions. The output consists of the alongshore sediment transport gradients, which are translated into a landward or seaward shift of the profiles along the coast. The shape of the cross-shore profile is fixed in the model, as the cross-shore profile adjustments in the surfzone are expected to take place at shorter time scales than the model time step of 1 year. An overview of the computed alongshore sediment transport in the model is provided in Figure 2. A detailed description of this tool is provided in the memo 'Evaluation of nourishment strategies Cycle 1: HK4.1: Long-term sustainable strategies for the Holland Coast' (Deltares, 2010). In this study, the ITHC was extended with a module for benthos and a module for the nursery habitat for juvenile fish.

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[1] The Unibest-CL+ model is a shoreline model that computes wave driven longshore sediment transport for beaches with uniform cross-shore profiles. Coastline changes are then computed on the basis of gradients in the computed transports. The model computes the longshore current on the basis of obliquely incoming waves. Model transport has been compared to a reference (Van Rijn, 2004). The UNIBEST model uses long-term averaged wave climates. Consequently, the model computes net long-term averaged sediment transports. In practice, this approach is very suitable for assessments of large scale and long term coastline changes (i.e. decades and multiple kilometres).
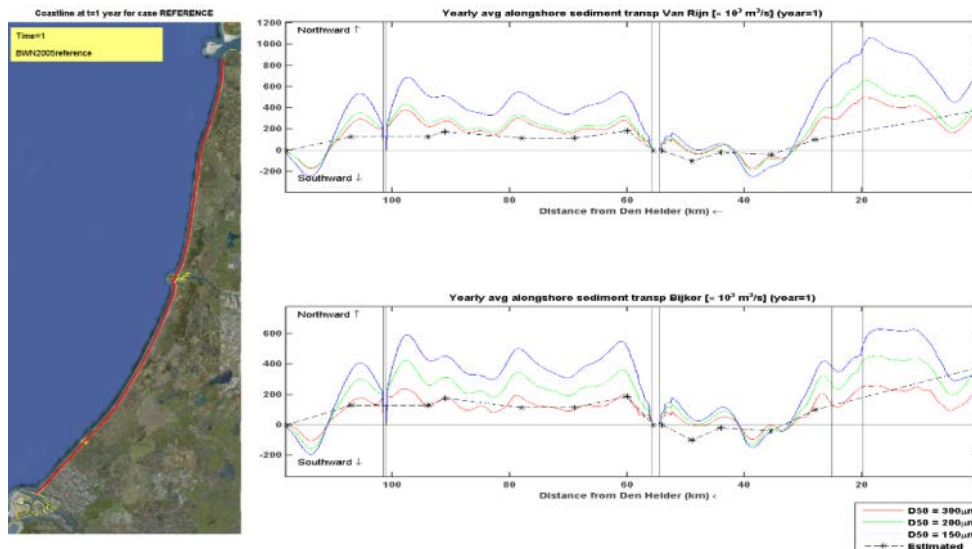
Figure 2. Computed sediment transport along the Holland coast for 3 sediment diameters (D50=150, 200 and 300 μm) and two sediment transport formulae (Top: Van Rijn, 2004, Bottom: Bijker, 1977) (Deltares, 2010)

2.3 The module for benthos in the ITHC

2.3.1 Model description

The first new ITHC module considers the direct impact of individual nourishments, i.e. the local burial of benthic species under a large amount of sand at the nourishment site. The indicator used for this is the relative change in population size of a benthic species. The impact of a nourishment consists of a change in local environmental conditions, leading to a reduction in local carrying capacity and population size.

The carrying capacity for a species is defined as the maximum possible population density *under certain habitat conditions*. The carrying capacity is reached when the per capita population growth rate is zero. After a nourishment, the habitat conditions need time to recover to its former state. In our approach this means that the carrying capacity will, in time, recover to its former state to reach the final equilibrium carrying capacity. This means that the carrying capacity is time varying and not a stable end state. When the habitat conditions have recovered fully in time, a population will be able to recover to its maximum population size. The speed of recovery does not only depend on the speed of the carrying capacity recovery, but also on the (logistic) growth rate of the population. In summary, population recovery after nourishing depends on:
1. the initial reduction in population size;
2. the initial reduction in time-varying carrying capacity;
3. the recovery rate of the time-varying carrying capacity;
4. the regrowth rate of the population.

The model describing the changes in benthic species population was kept simple. This was done as limitations were imposed by the coarseness of the ITHC model (such as a yearly time step, a fixed depth profile, no two-dimensional data, no modelling of nutrients or water clarity, etc.), and limited insight on the response of benthic species to nourishment treatments used in the scenarios (e.g. the effects of frequency and sand volumes). The benthos module must therefore be viewed as a first step in including benthos in the ITHC. The primary goal is to raise awareness

among managers on the possible effects of coastal defence measures on part of the organisms inhabiting the coast.

Given these limitations, a logistic growth function that allows for a time varying carrying capacity was used to model the response of a benthic population (Shepherd & Stojkov, 2007) (for a mathematical description see the Appendix). This time varying carrying capacity is suitable to model an instantaneous decrease in carrying capacity due to a nourishment. It is assumed that only at the moment of nourishing, i.e. the actual construction, population density and carrying capacity are affected negatively. Afterwards, recovery of both population density and carrying capacity starts. Frequency, location and magnitude of the nourishment are assumed to determine the reduction in population density and carrying capacity. All calculations, including reduction and recovery, are carried out in the transects used in the UNIBEST module of the ITHC. Migration (predominantly larval transport) of benthic organisms between transects is not accounted for. The mathematical specifics are described in the appendix.

2.3.2 Nourishment types and carrying-capacity recovery rates

Three types of nourishments for coastal protection were distinguished in the ITHC. Values for the recovery rate of the carrying capacity and the % reduction of the carrying capacity are given in Table 1.
- A beach nourishment is defined as a nourishment of less than 500 m^3 m^{-1}, where it is assumed that the sand is deposited on the beach and surf zone. Consequently, it has limited effects on benthic organisms as the species living in these zones are already adapted to highly energetic conditions.
- A foreshore nourishment assumes a nourished volume between 500 m^3 m^{-1} and 2000 m^3 m^{-1}, deposited onto the foreshore (-4 to -10 m deep). Hence it has a larger impact than a beach nourishment, as the species present at the sand bars are somewhat more sensitive to disturbances of their habitats.
- A mega-nourishment assumes a nourishment volume over 2000 m^3 m^{-1}, deposited onto the foreshore. A mega-nourishment will result in a very strong decrease of depth (actually, it will likely change the nourished area from a subtidal into a temporal terrestrial or intertidal area) and due to that, it will lead to a longer recovery time in terms of recovery of a subtidal population and with that affecting the recovery of a subtidal benthic community. The mega nourishment in the tool is set to 4.000 m^3 m^{-1} and a 10 years cycle. This is considerably less than the Zandmotor deposited at Monster, with 8000 to 10.000 m^3 m^{-1} and a proposed cycle of 20 years.

Table 1. Values per nourishment type for the benthic population carrying-capacity recovery rate (ε) and the percentage reduction in carrying capacity (CC) due to a single nourishment as currently included in the tool, based on a fixed cross shore profile transect.

Type:	Beach	Foreshore	Mega	Revetment
ε (CC recovery rate)	5	4	1	0
CC % reduction	30	80	90	100

Besides sand nourishments, revetments may be used as a means of coastal defence. Because a revetment is permanent and stationary, we assume that the carrying capacity of soft substrate benthic organisms (as considered here) does not recover from such a measure. However, other species may benefit from revetments as they provided shelter for certain fish or crab species in crevices, and may serve as substrate for mussels, polyps or cold water corals to grow on. The latter was not included in the model.

Currently the effect of the nourishments are considered for a fixed cross shore profile. This implies that changes in density are an interpretation of changes for a whole transect rather than a per surface area unit. Ideally a two-dimensional grid is

to be used instead of a fixed profile, allowing for changes per surface area along the transect depending on the magnitude. In this manner the thickness of the deposited sand layer could be taken into account explicitly and habitat changes can be represented spatially.

The effect of nourishments on the benthic population is only considered locally, and independently for each cell along the coast. Consequently, a slowed-down recovery of the benthic population as a result of the lack of benthos from adjacent areas along the shore is not included. This is a valid approach, as there is a fast recovery of the benthic population over large distance in reality, due to mobile life-stages such as swimming larvae that move over tens of kilometres in their pelagic phase (Rozemeijer, 2009). Only very large scale nourishments can have a reducing effect on larval availability. Further, the effect of alongshore transport of nourished sand on benthic populations is not taken into account. However, this effect is thought to be small, as the cross-shore transport is much larger than the long-shore transport (Baptist et al., 2008).

2.3.3   Benthic population growth strategies

Next to the recovery rate of carrying capacity, population size depends on population growth rate r and equilibrium carrying capacity $K*$. Opportunistic, smaller, fast-reproducing and fast-growing species are often denoted as r-strategists, whereas long-living, slow reproducing and larger species are K-strategists. Estimates of both parameters r and K for the benthic species of the North Sea are needed to model the effects along the Holland coast. We used data provided by Tom Brey[2] and MWTL-Noordzee data from the Dutch government (Rijkswaterstaat, www.waterbase.nl). These data include estimates of biomass (B) and P/B, the production-to-biomass ratio. It is assumed that K^* ~ biomass and r ~ P/B, and therefore values of biomasses and P/B can be used in the growth function of our model.

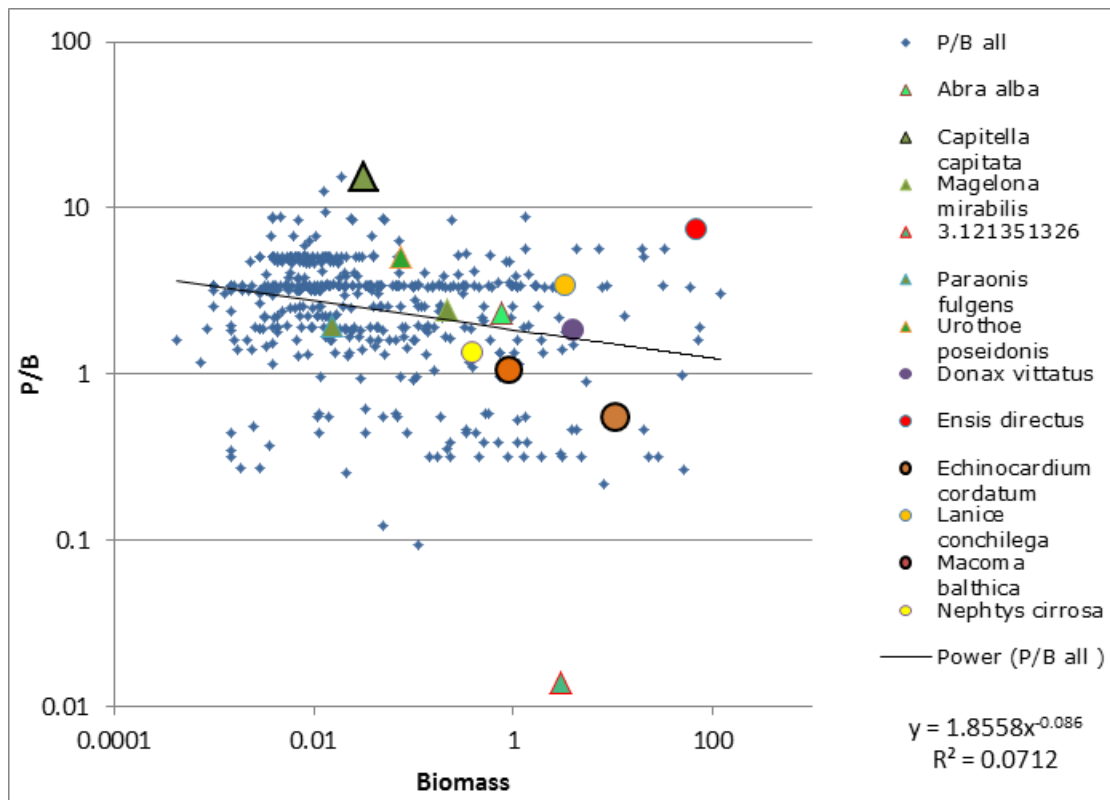[2] http://www.thomas-brey.de/science/virtualhandbook/navlog/index.html

Figure 3. Biomon data on biomass and P/B averaged per species, of a total of 476 species. Species indicated as r-strategist (triangle) and as K-strategist (circle) in Rijkswaterstaat (2007) are given explicitly (see also Table 2). For reference, a number of commonly occurring species were added: Donax vittatus (K-strategist GONZ), Abra alba (r-strategist pers. com. J. Craeymeersch), and Crangon crangon.

Biomass and production estimates differ considerably between locations, population structure, temperature regions, etc. The data used here is derived for individuals rather than populations, but gives the best available estimate. Generally, the species indicated as r-strategist plot more to the left in the graph, towards low biomass and higher *P/B*, and K-strategists plot more to the right, towards higher biomass and lower *P/B* (Figure 3). However, the classification of species into r and K strategists, while abandoned by ecologist yet embraced by managers, is debatable. We use the K and r strategists therefore mostly as indication of the extremes in species response.

Table 2. List of r- and K-strategists provided in Rijkswaterstaat (2007) for the 'Voordelta'.

r	K
Capitella capitata	*Lanice conchilega*
Magelona mirabilis	*Macoma balthica*
Paraonis fulgens	*Ensis directus*
Abludomelita obtusata[*]	*Nephtys cirrosa*
Urothoe poseidonis	*Echinocardium cordatum*

[*] no data available in the BIOMON data set.

Three species were selected for the ITHC tool: *Capitella capitata* (polychaeta) representing a species with a relatively low biomass, yet a relatively high population growth rate (defined as an r-strategist in Rijkswaterstaat 2007), *Echinocardium cordatum* (sea urchin) representing a species with a relatively high biomass and a relatively low population growth rate (defined as a K-strategist in Rijkswaterstaat 2007), and *Macoma balthica* (bivalve) as intermediate species (defined as a K-strategist in Rijkswaterstaat 2007) (Table 3, Figure 3). *Capitella*

capitata is a polychaete worm that can reach 10 cm in length and occupies the sandy to muddy seafloor. *Macoma balthica* is a small bivalve (maximum length around 2.5 cm) that lives buried in the sand in the intertidal and sublitoral zone. *Echinocardium cordatum* is a sea urchin that buries itself to a depth of 15 cm in sandy bottoms and is commonly found north of the Wadden islands. These three species represent different groups commonly occurring in the Dutch coastal zone, represent different strategies, and are listed in governmental documents concerning the Dutch coast. However, it is stressed that the variety is high both within and among species, and only 3 out of numerous species are included in the benthos module.

A generalized response of a population to a reduction in carrying capacity is given in the appendix.

Table 3. Species used in the benthos module of the ITHC, parameter values are taken from BIOMON data and T. Brey.

Species	K^*(Biomass)	r (P/B)	Strategy
Capitella capitata	0.03	15.3	r
Macoma balthica	0.9	1.0	intermediate
Echinocardium cordatum	10.6	0.5	K

2.4 The module for fish nursery area in the ITHC

The nursery area module considers the impact of nourishments related to the change of the foreshore area as a result of a prograding or retreating coast. The foreshore surface area is considered a proxy for the available habitat for juvenile fish along the coast (the so-called nursery area for juvenile fish). Foreshore area may vary as the direct result of a nourishment, but also through alongshore transport of (nourishment) sand. We assume that a reduction in foreshore area has a negative impact on the nursery function of the coast. Any effects of changes in light conditions, grain size, salinity etc. are not included in the ITHC, nor does the benthos module provide food availability estimates. These limitations currently exclude the use of a more detailed approach for modelling the nursery function.

It is assumed that the area of each depth range decreases linearly with a reduction in foreshore area. The UNIBEST model does not adapt the shape of the cross-shore profile, as it shifts the cross-shore position of the profiles. Hence, a differentiation in depth ranges and their changes in area due to nourishments (which are valuable for the assessment of the impacts in the nursery function) cannot be derived directly from the model results. The available foreshore area along the Dutch coast up to the -20 m NAP contour was therefore estimated in a very basic way, by using the cross-shore position of the shoreline from the UNIBEST model and an average width of 10 km of the foreshore for the whole of the Holland coast. The relative reduction in available foreshore width (ψ) is then evaluated over time for each transect along the coast:

$$\psi(x,t) = \frac{B_{ref}(x) - \Delta B(x,t)}{B_{ref}(x)}$$

(6)

With:
B_{ref} Reference width of the foreshore [m] (default = 10 km)
ΔB Coastline change [m]

ψ Relative change of foreshore area
x   Alongshore distance [m]

Note that due to the fixed profile in UNIBEST any increase in shallow zones, such as those resulting from the sand engine, are not included. This module therefore only provides a general indication of the impacts of nourishment strategies on the nursery area of juvenile fish.

2.5 The module for dune formation in the ITHC

The dune-formation module is described in detail in a separate report (De Groot, 2012 in prep), from which also the dune results in the next section are taken. Here we give a short description of the module. The model gives the development of the most seaward dunes with respect to the current situation, and the potential biodiversity associated with that. It is a combination of data-driven and expert-judgement rules, but the approach gives room for including more process-based approaches in future.

The module starts with the volume changes per coastal cell that UNIBEST calculates (Figure 4). Those volume changes are then distributed over parts of the profile: offshore, subtidal beach, subaerial beach (i.e. the intertidal and dry beach), and dunes. This distribution is based on a Bayesian Network model that is constructed from JARKUS data of the Holland Coast (De Vries & De Groot, 2012). The JARKUS database consists of yearly elevation/bathymetry measurements of the coast, from underwater to the first dune row, one transect every 200 – 250 m along the coast. For a given change in profile volume from UNIBEST, the Bayesian Network model gives the corresponding distribution over the parts of the profile, according to the observed changes in the JARKUS database. Subsequently, the cumulative dune volume with respect to the initial situation is calculated.

The cumulative dune volume is then classified into dune classes. These are:
1. Erosive (cumulative dune volume < -30 $m^3 m^{-1}$);
2. Stable (cumulative dune volume between -30 and 100 $m^3 m^{-1}$);
3. Slightly prograding (cumulative dune volume between 100 and 400 $m^3 m^{-1}$);
4. Prograding with new, unvegetated (mobile) dune field on beach ('Sahara-like') (cumulative dune volume larger than 400 $m^3 m^{-1}$);
5. Prograding with partly vegetated new dunes, with possibly green beach (cumulative dune volume larger than 400 $m^3 m^{-1}$ for at least 10 consecutive years)

A green beach is defined here as a mosaic of dune, salt-marsh and dune-slack vegetation, in an area that is occasionally flooded by the sea. It is mostly sandy, but may also have some mud deposition. It may contain dunes but this is not necessary. More details on dune shape are not considered.
The threshold values are based on expert judgement, observations from Schiermonnikoog and Ameland (but increased because foredune height on Holland coast is generally larger, giving more accommodation space), estimations from simulations (De Groot et al., 2012 in prep.), and trials with test scenarios.

The ecological richness (biodiversity) of the dune area is a crude interpretation of how many habitat types each dune class can potentially support. Dune classes 1 and 2 are considered to have normal (i.e. relatively low) biodiversity, classes 3 and 4 are considered intermediate, and class 5 is considered relatively rich.
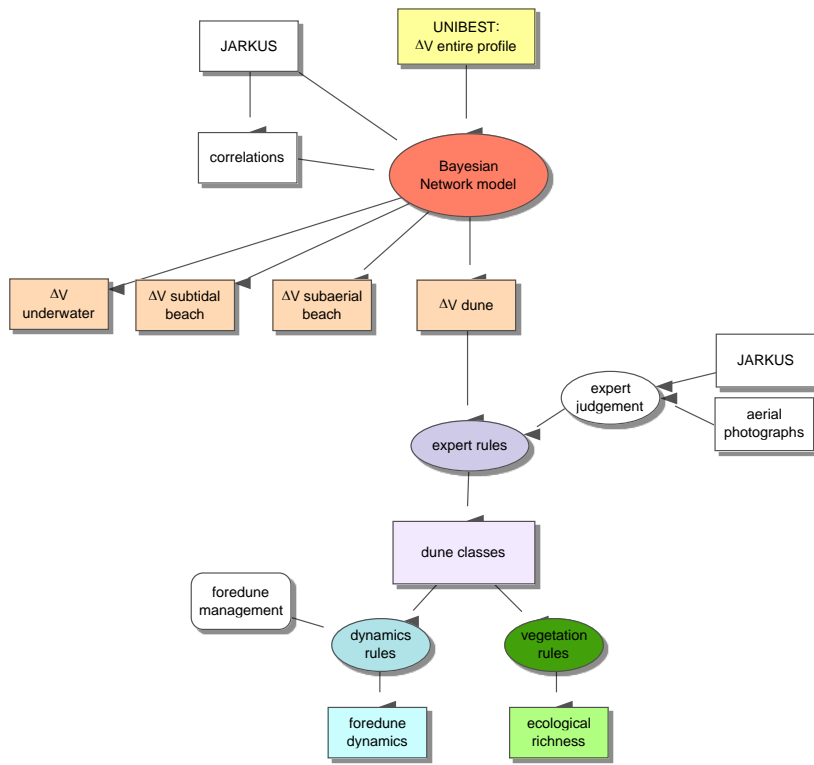
Figure 4. Schematic outline of the dune formation module.

2.6 Management scenarios

Five coastal-defence scenarios were applied in the ITHC to test their impact on benthos, nursery habitat for juvenile fish, and dunes.

1. **Autonomous**
    Autonomous development without any measures.
2. **Minimal continuous consolidation**
    Specific settlements and other risk areas are protected against erosion by continuous beach and surf zone nourishments of 5.0 million m^3 per year, whereas other locations do not receive nourishments.
3. **Minimal five-yearly consolidation**
4. Minimal protection of the entire coast at coastal settlements with shoreface nourishments of 12.5 million m^3 every 5 years. **Seaward** Extending the coastline gradually seawards with the help of mega-nourishments of 20 million m^3 each, that are applied every ten years at five locations along the coast (Vlugtenburg, Katwijk, Zandvoort, Egmond and at the Hondsbossche zeewering).
5. **Revetments**
    Revetments protecting the coastal settlements (no additional nourishments)

The model simulations cover a period of 95 years until the year 2100. A moderate sea-level rise (2 mm y^{-1}) is included for all scenarios, by means of an additional coastal retreat that was computed for a profile with an average slope of 1:500. For none of the scenarios any 'normal' nourishments are carried out. In reality, the coastline is evaluated every year for compliance to the Basal Coast Line, and nourishments are carried out if the Basal Coast Line is exceeded (see Figure 1). Such management response is not included here, showing how the coast and its

ecology develop when regular nourishments would be stopped and only the ones in the scenarios are carried out.

The computed impact on each of the indicators (fish nursery and benthos, for each transect and each time step) was aggregated to a smaller number of 60 alongshore coastal cells with a length of about 2 km and 20 output time steps for the purpose of presentation on the map.

3 Results

3.1 General

For each of the five management scenarios, the Interactive Tool for the Holland Coast has been run to compute long-term changes in coastline positions and evaluate the impacts on the indicators for benthos populations, nursery area and dunes. The results are presented in a set of figures for each scenario. The upper panel of each of these figures shows a Google Earth image of the southern part of the Holland coast with a visualisation of the considered coastal indicators. The coastline position is shown as a yellow line on the coast and the change in coastline position is depicted with red and green bars (which improve the visibility of the coastline changes). Plotted in offshore waters the indicator for benthos is shown in three green bars where Benthos 1 is *Capitella capitata* (the r-strategist), Benthos 2 is *Macoma balthica* (intermediate strategist) and Benthos 3 is *Echinocardium cordatum* (the K-strategist). The nursery area for juvenile fish is presented in blue bars. The blue bars, in fact, presents the relative change in foreshore area, which is considered a proxy for the size of the nursery area that is available for juvenile fish. The initial state for the green and blue bars is presented by a grey box, so relative changes in benthic population size and nursery area are visualised as difference with respect to the grey box. For the dunes, the status of the dunes for a specific moment of time (after about 90 years) is visualised with icons on the Google Earth plot. These icons are similar to the classes defined in Section 2.5 and explained in Table 4.

Next, a number of plots are provided that show the development of the benthic populations. The recovery rate for the three selected species is shown in a first graph, for a typical nourishment location showing the response over a period of 20 years. Subsequently, the response of the benthic populations is presented in separate figures that show relative population density (in %) over a period of 100 years (horizontal axis) for each position along the 118 km long Holland Coast (vertical axis). Figures are shown for the *Capitella capitata* (r-strategist), *Macoma balthica* (intermediate strategist) and the *Echinocardium cordatum* (K-strategist).

A separate graph shows the development in time and space of the habitat for juvenile fish, in a similar way as the benthos. Finally, the response of the dunes in space and time is presented in two graphs, one showing the development of the morphology expressed as dune classes, and the other showing the development of the three biodiversity classes.

Table 4. Explanation of the icons used in the Google Earth plots to display the status of the dune class and dune habitat richness (see definition in Section 2.5).

Indicator	Improvement	Similar	Worsening
Dunes classes	Class 3 : Wide beach + potential for new dunes Class 4 : Extremely wide beach + potential for new dunes Class 5 : Extremely wide beach + potential for new dunes and green beach	Class 2 : Normal + slight progradation	Class 1 : Erosive dune front
Dunes habitat richness	Intermediate habitat richness (class 3 and 4) Rich habitat (class 5)	Low / Normal habitat richness (class 1 and 2)	

3.2   Scenario 1: Autonomous

In the autonomous scenario (Figure 5), there is considerable erosion along the coast. Consequently, the foreshore area increases slightly, which results in a larger area for juvenile fish (panel A, blue bars, and panel F) than initially. There is no effect on the benthic populations expected, as there are no measures taken in this scenario, i.e. the population size stays at 100% (panels B, C, D and E).

Some parts of the coast will erode and others will gain sediment. In general, the dunes are expected to be more or less stable. Hard structures such as the harbour of IJmuiden (around y = 55 km) clearly affect the local budget and consequently also the dune volume. With time, the accreting areas updrift of the harbour moles at the Holland coast will develop into dune fields and possibly into green beaches (panels G and H).
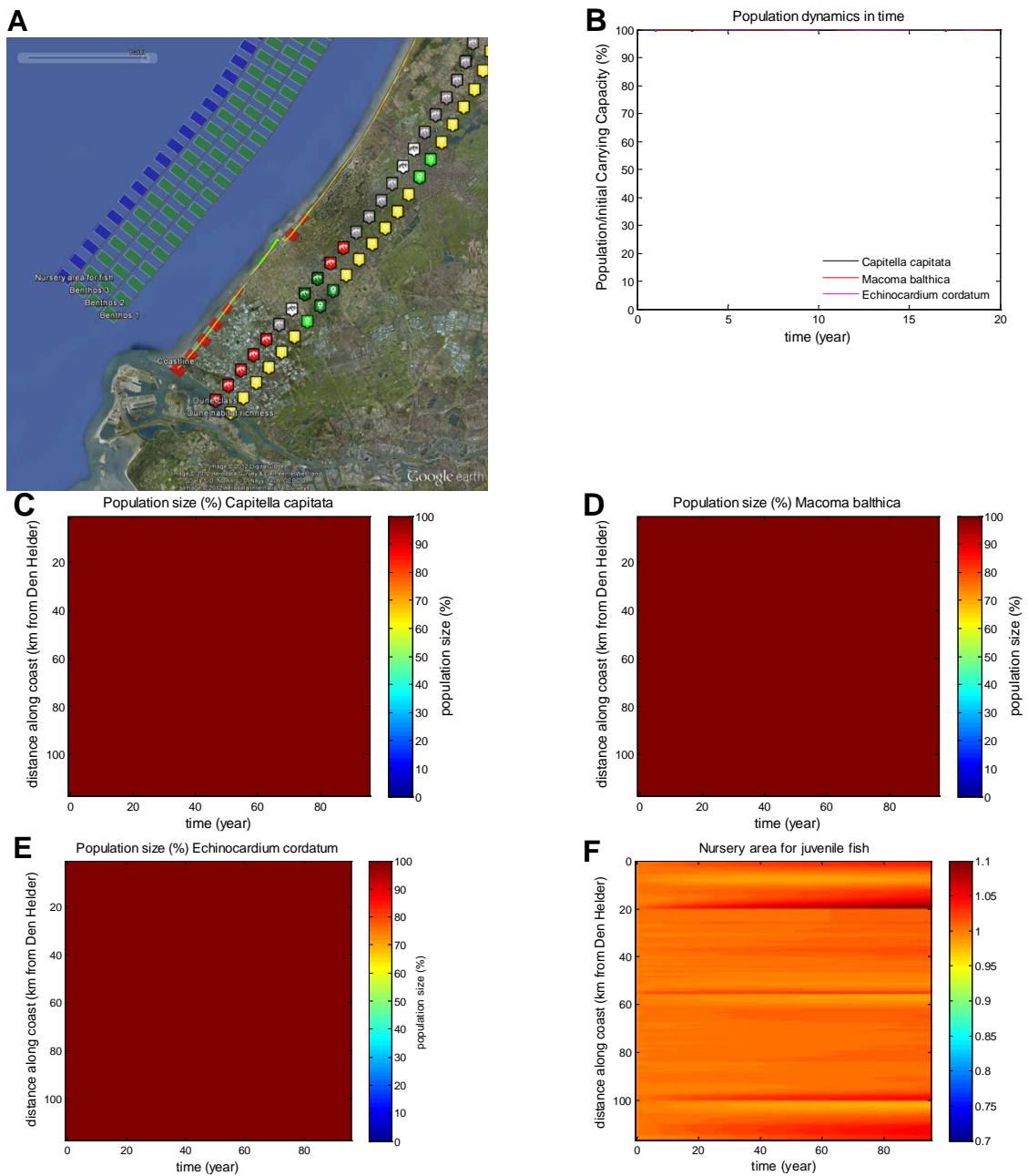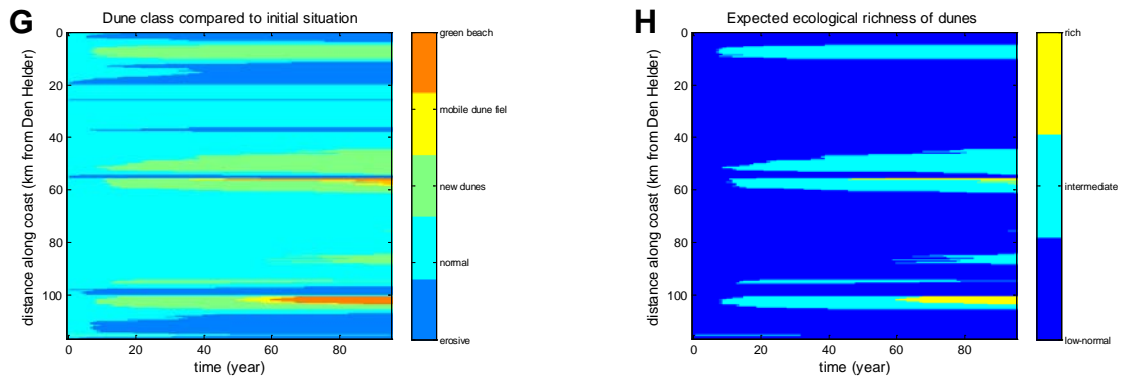
Figure 5. Coastal development and coastal indicators for reference scenario 1: autonomous. Panel A: screenshot from a part of the visualisation of the ITHC. The yellow line gives the position of the coastline, the green and red bars give its change relative to the starting situation. The two rows of green bars, plotted in the sea, visualise the indicators for the population of three types of benthos (Benthos 1 is Capitella capitata (an r-strategist), Benthos 2 is Macoma balthica (an intermediate strategist) and Benthos 3 is Echinocardium cordatum (a K-strategist) at each location along the coast. Each bar is filled with colour for as far as the population size reaches the original (i.e. maximum) size. The blue bars, plotted in the sea, visualise the indicator for the nursery area for juvenile fish. The status of the dunes is visualised with icons (see Table 4 for explanation). Panel B: the response of the three species for one nourishment location in time, by population size relative to original carrying capacity. Panels C, D and E: the response in time and space of Capitella capitata (C), Macoma balthica (D) and Echinocardium cordatum (E). The horizontal axis gives time in years and the vertical axis distance along the coast running from north (Den Helder) to south (Hoek van Holland). Colours represent relative population size as percentage of the original carrying capacity. Panel F: development of the nursery area for juvenile fish in space and time. Colours represent nursery area relative to the initial situation (standardized to 1), axes as in panels C – E. Panels G and H: dune development in five dune classes (G) and biodiversity in three classes (H), axes as in panels C – E.

3.3 Scenario 2: Minimal continuous consolidation

The impact of continuous (i.e. yearly) nourishments on the benthic populations in Scenario 2 was found to be considerable at the location of the nourishments, even though the nourished volumes are relatively small. Due to the first, initial nourishment the carrying capacity of the populations is reduced to 30% of its original, but because the nourishment continues yearly, the populations do not have time to recover before the next nourishment takes place (Figure 6). In fact, only the r-strategist *Capitella capitata* locally does not decline to zero as long as the nourishments are carried out (panel B, C, D and E). The relative coastline changes, on the other hand, are not that large that they affect the size of the fish nursery area significantly (panel F).

On the largest part of the coast, dunes show steady growth: more nourishment sand is blown into the dunes than is taken away by structural erosion. This excess of sand creates room for new dune development and locally the development of a species-rich green beach. Further, the sand is transported to adjacent areas, leading to additional dune growth (panels G and H). Dune growth as a result of nourishments has indeed been observed in recent years along parts of the Dutch coast (Arens et al., 2010), but the actual dune growth along the Dutch coast is expected to be smaller than indicated in Figure 6.
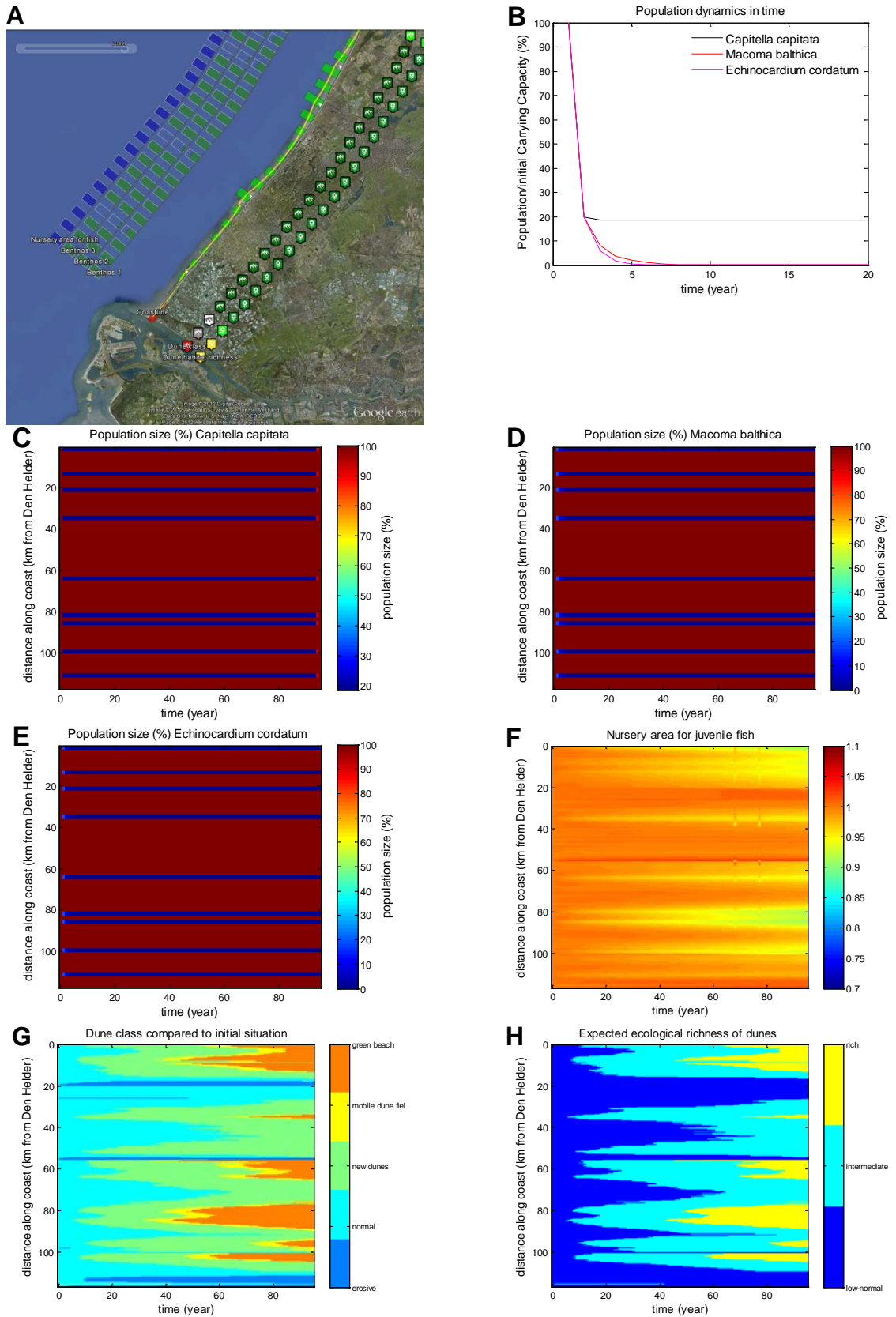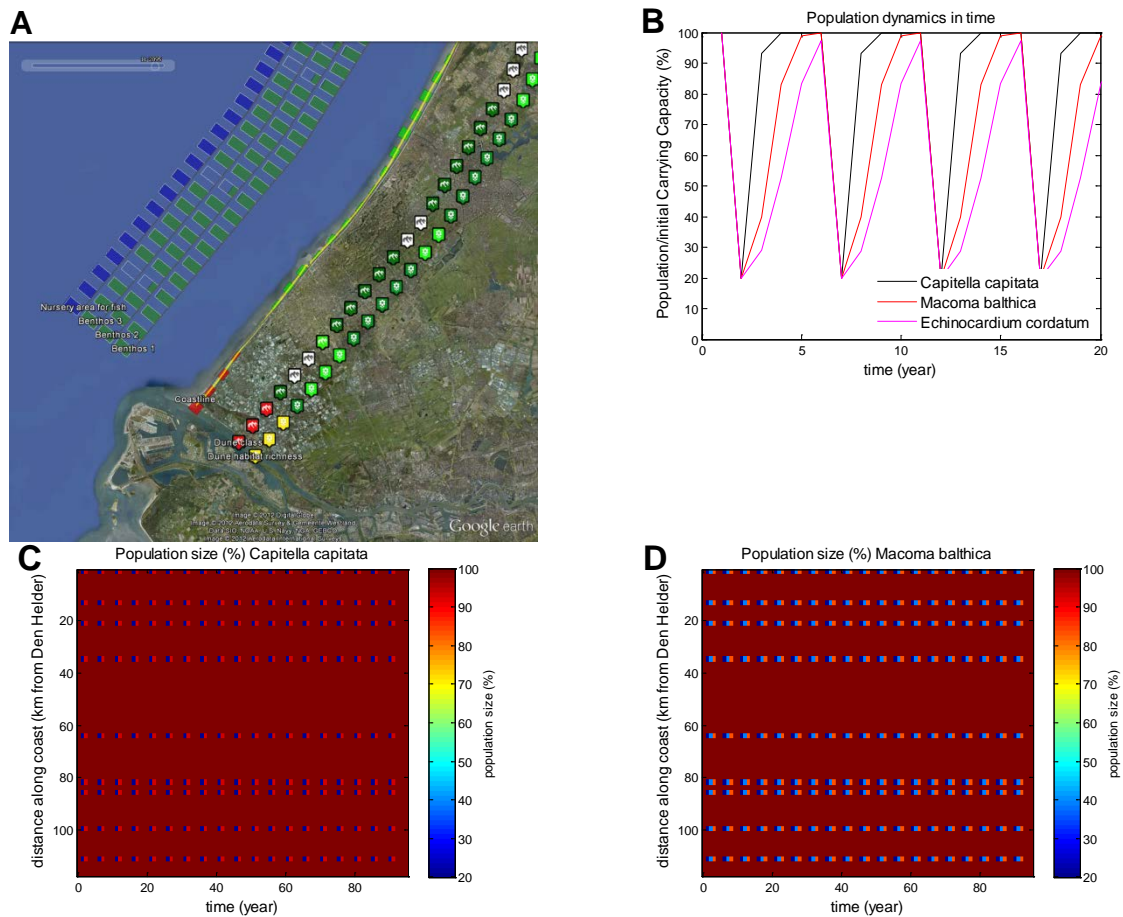
Figure 6. Coastal development and coastal indicators for scenario 2: 'minimal consolidation'. Panels as in Figure 5.

3.4 Scenario 3: Minimal five-yearly consolidation

The scenarios with nourishments with a regular interval of five years also shows a local effect on the benthic population at the nourishment sites. The three populations show a different recovery after the nourishment (Figure 7). *Capitella capitata* recovers for more than 90% after one year and completely in two years, *Macoma balthica* shows complete recovery after four years and *Echinocardium cordatum* shows 95% recovery after five years (panel B). Within years following (near-)complete recovery the next nourishment is carried out, resulting again in a drop in population density and subsequent recovery. This eventually leads to a locally intermittent presence of populations (panels C, D and E). The relative change in foreshore area is not large, leading to very minor changes to the size of the nursery area for juvenile fish (panel F).

The nourishment sand is spread out less than in the scenario 2, leading to more variation in dune shape along the Dutch coast. Compared to the scenario 2, green beaches develop earlier as a result of the nourishments (panels G and H). This is related to the wider beaches that develop at the nourishment locations, which function as a source of sediment for the dunes (De Groot et al., 2012 in prep.). Further, there are slight differences in the alongshore location of spots with dune formation due to the different locations of the nourishments.
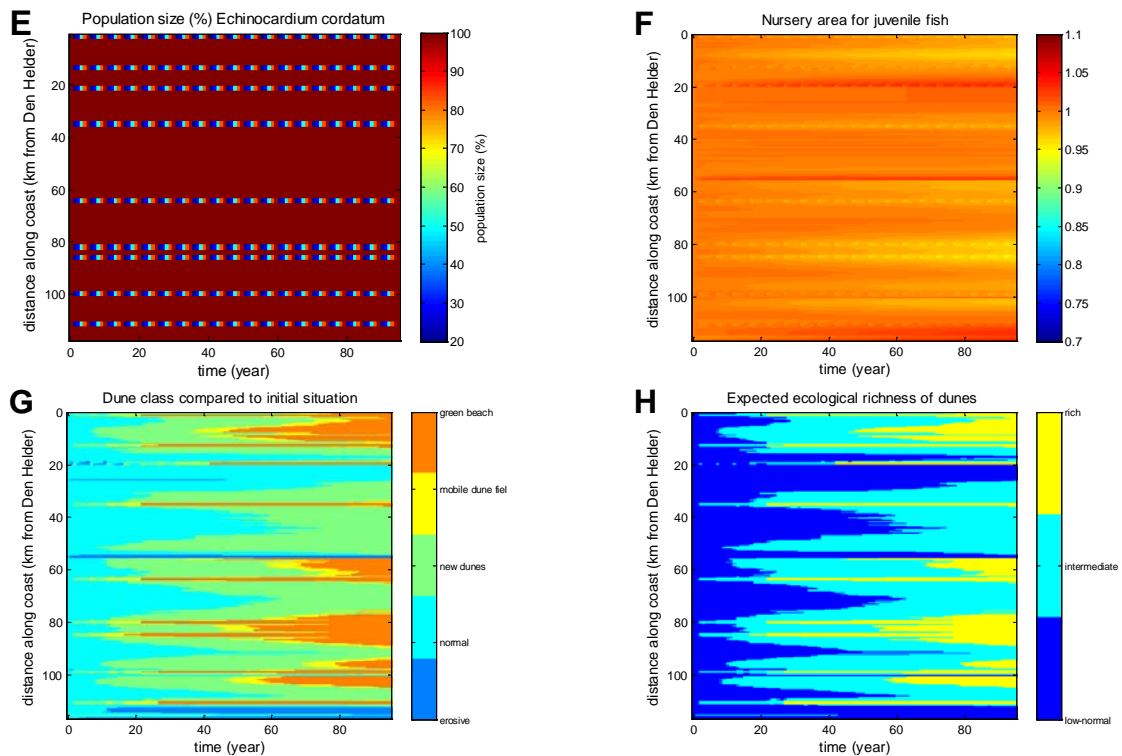
Figure 7. Coastal development and coastal indicators for scenario 3: 'Minimal consolidation with five yearly nourishments'. Panels as in Figure 5. Panel A gives the situation just before a nourishment.

3.5 Scenario 4: Seaward

The fourth scenario concerns the 'sand engine' approach with a 10-year nourishment interval at different and less locations than scenarios 2 and 3. Directly after the nourishment, the impact on the benthic species is very large, but all populations can now recover in-between nourishments (Figure 8). With a long enough time interval between nourishments, even the slower *Echinocardium cordatum* can recover fully (panel B). However, placing the nourishments at the same location leads to an intermittent presence of benthic populations (panels C, D and E).

The coast is built out considerably in the considered period. Consequently, there is a reduction of the foreshore area as habitat for juvenile fish (blue bars and their grey contours in panel A and bluish colours in panel F). It is, however, noted that the positive impact of a possible increase in shallow zones in mega-nourishments is not included in the results, as this is not evaluated with the ITHC.

Because the mega-nourishments are local, in the beginning some non-nourished dune areas will be eroded. With time, the sand of the sand engines spreads along the coast. As there is an excess of sand nourished, virtually the entire coast builds permanently seaward, giving rise to extensive dune formation. After about 60 years, green beaches, and thus new dune rows, have established everywhere (panels G and H). It has to be noted, though, that with such strong seaward building, other functions will undoubtedly make use of the new land. Any ecological expectations then may have to be tempered.
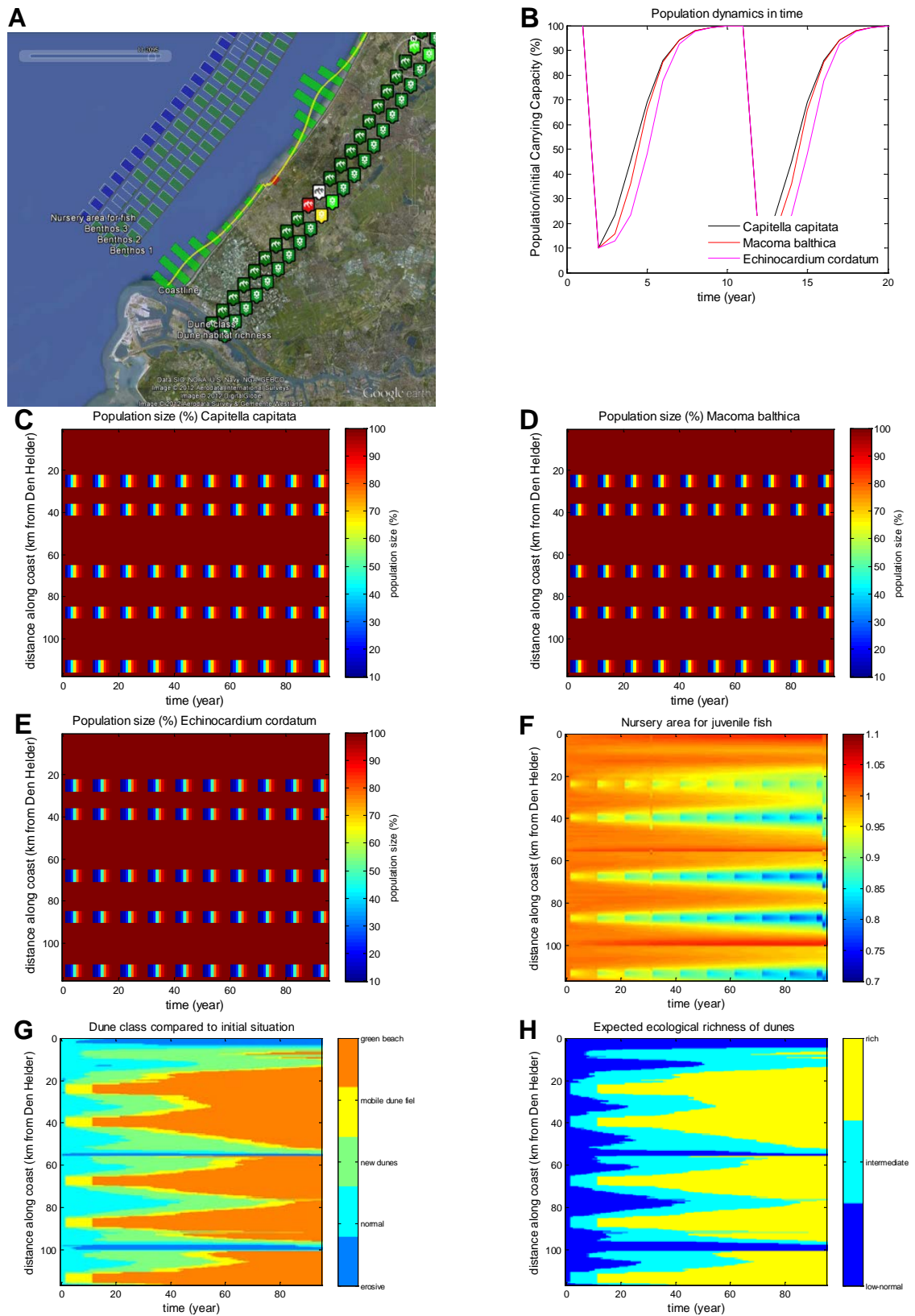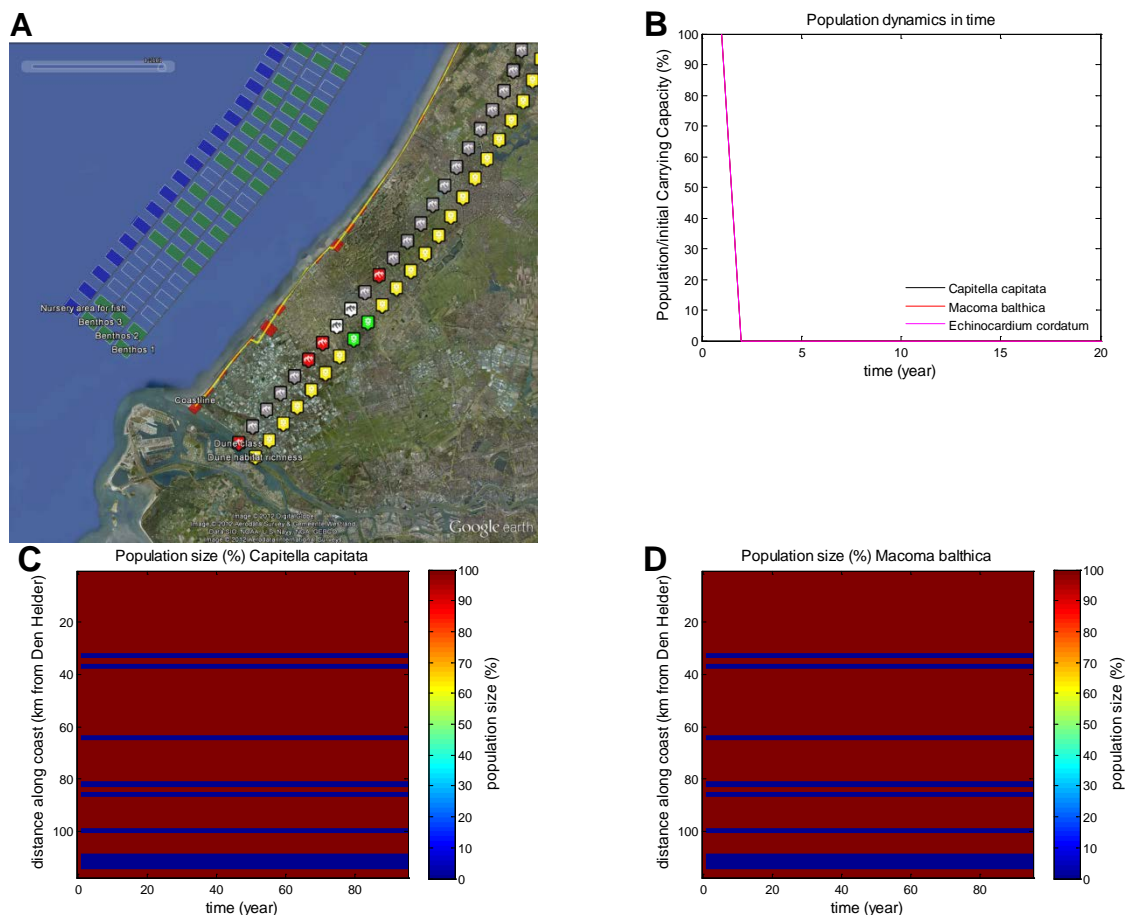
Figure 8. Coastal development and coastal indicators for scenario 4: 'seaward'. Panels as in Figure 5. Panel A gives the situation just before a nourishment.

3.6 Scenario 5: Revetments

The fifth scenario aims at preserving the coastline position by means of revetments (thus without additional sand nourishments). For the soft substrate benthic species living on and in a sandy and muddy seafloor, the use of revetments is assumed detrimental in case the revetment covers their natural habitat (Figure 9). However, revetments do serve as habitat to other species that use the revetment for shelter (such as the North sea crab, fish), or for attachment (such as polyps, mussels). Moreover, the width of the revetments in the ITHC is much wider than in reality, so the effect on the benthic population is exaggerated in the results presented here (panels B, C, D and E).

Revetments can be considered a small local decrease in nursery size for species that occupy sandy bottoms, based on the seafloor surface area covered by the revetment (panel F). The revetment itself however could serve as a shelter for other fish species. From that perspective the net effect of a revetment (as compared to the autonomous situation) on fish habitat size is considered zero.

For the dunes, scenario 5 leads to a situation comparable to scenario one, but with less new dune formation. Because no sand is brought to the coast, new dune development is limited and most dune areas are stable or eroding. Species richness is therefore lower than for the other scenarios (panels G and H).
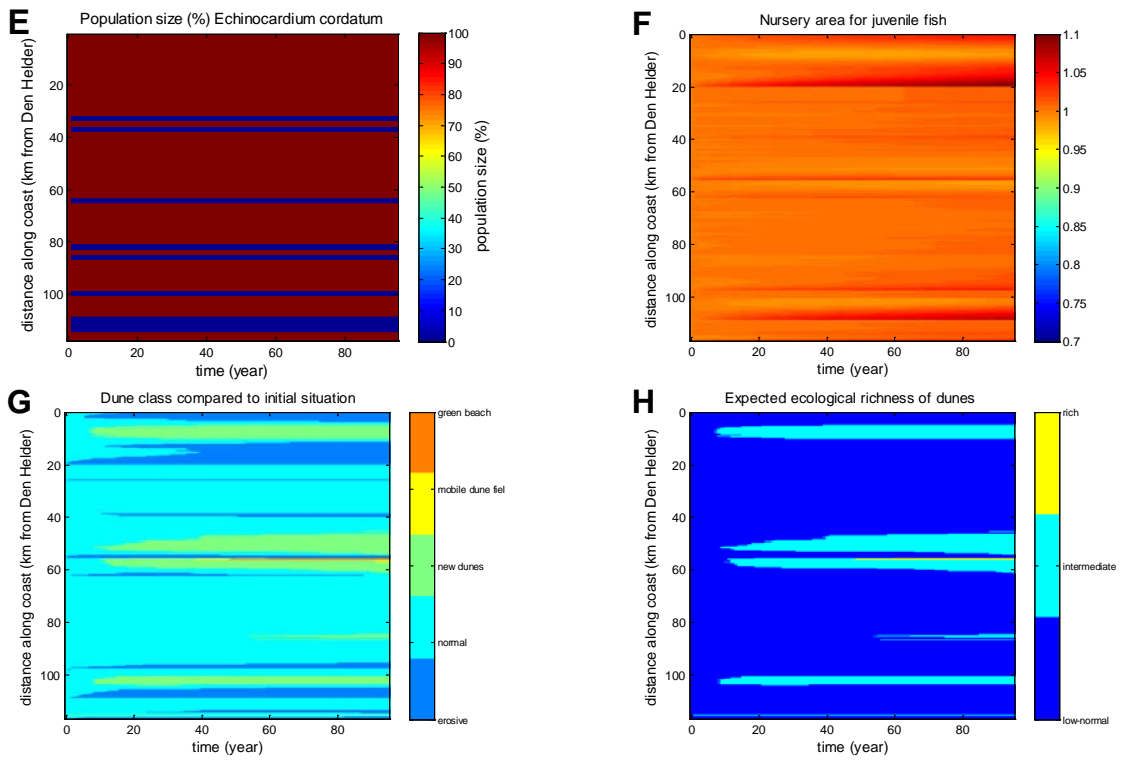
Figure 9. Coastal development and coastal indicators for scenario 5: 'revetments'. Panels as in Figure 5.

4 Discussion

4.1 Model discussion

The modules for benthic species, fish nursery area and dune development have been added to the Interactive Design Tool for the Holland Coast to visualize the possible effects of nourishments on ecological aspects of the system. This is a significant addition to the ITHC, as until now the tool had a focus on abiotic responses to coastline measures. The benthos module provides information on possible effects of nourishments on benthic species, represented by slow, intermediate and fast responding species. The nursery area module provides information on the size of the shallow coastal habitats that are used by juvenile fish. The dune development module provides information on the development and diversity of dune types. The extended ITHC is considered as a first step for the inclusion of ecology into a coastal management tool. It should therefore be treated as such. Yet, the ITHC will help to raise awareness on ecological effects of measures when the tool is used in workshops organized for water managers, local and national governments, nature organisations etc.

The benthos module uses a simple function to describe the response of the carrying capacity to disturbances such as nourishments and the related population dynamics. The uncertainties in the parameter values are large. There are large gaps in knowledge on benthic species in the coastal zone. In particularly the values used for describing (the recovery of) the carrying capacity are educated guesses. To improve the reliability of the outcomes, it is imperative to do monitoring studies on the range of recovery rates, and reduction in carrying capacity and population response. The parameter values used for the species characteristics (r- and K-values) are highly variable among individuals, populations and communities. In addition, we selected only three species as representatives out of 476, not spanning the total range of values possible. Finally, processes such as migration, (re)colonization, changes in suitability due to other reasons than nourishments, food-web interactions, etc. are not taken into account when describing the population dynamics. Future models of benthic organisms can include a more mechanistic approach that could include physiological parameters (maintenance, feeding rates, growth), size and/or age structure, predation and a time step based on the biology of the species (e.g. within generations). Such an approach, requires the inclusion of more knowledge, more parameters and more detailed input from the abiotic part of the ITHC. In the meanwhile, monitoring responses of the benthic species on nourishment activities should continue to feed the module with better parameter estimates. The simple approach used here is therefore a good first-step solution for including a benthic response in the Interactive Design Tool for the Holland Coast, bearing its caveats in mind.

The nursery area module uses an even simpler approach than the one for benthos. The assumption is made that a prograding shoreline leads to loss of shallow water, by steepening the shoreface profile. Since the shallow sea is the most suitable habitat for juvenile fish, loss of shallow water leads to a quantitative loss of nursery area. Reality, however, is much more complex. Firstly, there are large differences in environmental preferences between species. Turbot and brill, for instance, favour shallow water, but sole favours deeper water. Secondly, other environmental factors play an important role such as water turbidity, water temperature, salinity and sediment grain size (Teal & Van Keeken, 2011). Thirdly, there are large seasonal differences (Teal & Van Keeken, 2011; Van de Wolfshaar et al. 2012). More complicated environmental effects resulting from sand nourishments, such as changes in the morphology of breaker bars and changes in water turbidity and grain size would require the application of additional cross-shore profile models in

the ITHC. Therefore, the very simple approach used here is considered to be a first step for including the response on juvenile fish habitat from nourishments, and should therefore be assessed with great care.

For a detailed discussion on the dune module, see De Groot (2012 in prep.).

4.2 Synthesis of ecological effects of nourishment strategies

The results of the scenario computations with the ITHC can be used to derive guidelines for ecologically optimised nourishments. These guidelines consist of recommendations on design of sand nourishments, in terms of frequency, location and size. The focus of such strategies in the context of this report is to improve the nursery function of the Dutch coast for commercial and non-commercial fish species, while minimising impacts on benthic populations and enhancing dune quality.

From the benthos and dune modules it follows that large nourishments with large nourishment intervals show the best potential for benthos and dunes. They allow benthic populations to recover fully from the impact and leads to, at least temporarily, new dune formation. The dynamics in growth and erosion of the dunes in such situation gives rise to repeated pioneer habitats, which is considered beneficial for the currently rather stabilised dune area. However, the potential for juvenile fish nursery areas depends on foreshore width, and thus on overall nourished volume rather than nourishment frequency, given the current fixed profile. Building the coast seaward, thereby steepening the profile, has detrimental effects on the size of the nursery habitat for juvenile fish.

The results further show that 'continuous' nourishments prevent full recovery of the benthic population, even if the reduction in carrying capacity may be small. Only opportunistic species such as *Capitella* are able to fully recover to their carrying capacity. It is plausible that due to frequent nourishment more opportunistic species will dominate. These can potentially provide good prey and feeding conditions for juvenile fish.

The autonomous scenario, without nourishments, shows considerable erosion along the coast. Consequently, the foreshore area increases slightly, which results in a larger nursery area for juvenile fish.

Sand nourishments reduce the carrying capacity locally and temporarily. Revetments, however, are of a more permanent nature and are assumed to result in a complete local loss of habitat for bottom dwelling organisms of sandy habitat. Despite this loss, revetments do provide habitat for other species and communities that prefer hard substrate (e.g. polyps) or use crevices for shelter (e.g. crabs, fish). The net effect of a revetment may therefore be considered zero for benthos and fish, but because they stabilise the dunes completely, revetments score less on that aspect.

This version of the tool is a first developers version. At the moment the actually calculated differences are not certain enough to be used and discussed on their merits. The true gain of this exercise is that an easy to use prediction tool is conceptualised, developed and applied. By applying it, it becomes clear what the next steps are to strengthen both the underlying knowledge and the model definitions.

5 Conclusions & Recommendations

5.1 Conclusions

In The Netherlands, a significant part of coastal protection is achieved by nourishing sand. At first, this was achieved by nourishing sand directly onto the beach but later shoreface nourishment have increased in importance. Recently, mega-nourishments have become a new focus in coastal management, with the Sand Engine on the South-Holland coast as first pilot project.

Sand nourishments can affect the ecosystem in various ways. Direct effects are the burial of benthic species under a layer of sand. Sand nourishments may also affect the size and quality of the nursery habitats for juvenile fish due to changes in depth ranges, grain size of the sand and food availability. And, last but not least, nourishments lead to changes in dune ecosystems. Although nourishments may be detrimental for many species, perhaps it is possible to find ecologically optimised nourishment strategies.

The Interactive Design Tool for the Holland Coast (ITHC) was applied to predict long-term shoreline changes as a result of several nourishment strategies using UNIBEST. Three ecological modules have been implemented into the ITHC. The first module considers the direct impact of burial of benthos and the subsequent benthic species recovery. The second module considers the impact of measures on the fish nursery size, related to the change of foreshore area as a result of a prograding or retreating coast. Nursery quality, however, could not be studied as the variation in impact over the cross-shore profile is not resolved yet by the current ITHC model. The third module results from an independently developed dune module of the ITHC (De Groot 2012). The expanded ITHC model was applied to five coastal nourishment strategies. Of these strategies, nourishments with large time intervals appear to be most optimal concerning benthos, fish nursery size and dune development. It should be noted that the reliability of results reduces when predictions are done increasingly further away in time. In addition, the reliability of the results especially for benthos and nursery area can be improved when better parameter estimates can be given. Furthermore, it would be favourable if the ITHC could be extended with means to assess the influence of nourishments on the cross-shore profile development.

Using the results of this first developers version of the extended ITHC, it appears that the ecologically most optimised nourishment strategy are at least ten year nourishment intervals with nourishments that keep the minimum coastline in place instead of building the coast permanently seaward. This gives time for benthic communities to recover, allows pioneer dune habitats to develop and does not reduce the nursery habitat area for juvenile fish.

5.2 Lessons learned

- A lack of knowledge and data on an ecosystem or parts of it (e.g. the process of benthic recolonisation) poses limitations to model development. Even if the mechanisms can be translated into model equations, poor parameterisation will most probably result in outcomes that are less reliable than wished for.

- It is important to clearly communicate the possibilities and limitations of existing models, when these models are used as input for new models. This is especially the case when working together with people from different fields, as they may not be aware of the common assumptions or methods of the other fields. In this specific case, the assumptions and output of UNIBEST, for

example, imposed boundary conditions to the modules that build further upon it. It was not feasible to develop special means for the evaluation of cross-shore profile changes within the framework of the current project. A number of times during development of this model, the expectations researchers had of the models were not in line with the capabilities of the models. It needs time to sort this out and to get fully acquainted with each other's models.

- Application of the ITHC shows that relatively simple models are valuable to users when combined and presented in such a way that also non-experts can work with the results. Good visualisation tools are essential for this, and are worth spending time on. In addition the model should not be used without moderation by an expert, who can clarify the results if necessary and explain model limitations.

- When working with the ITHC, stakeholders tend to over-interpret the spatial precision and (temporal) reliability of the model outcomes. To avoid this, in the visualisation in Google Earth the alongshore spacing of the indicators was increased, and for the dune model classes rather than volumes were used.

5.3 Potential future improvements

To improve the reliability of the ITHC model outcomes, additions to the benthos and fish nursery modules would involve:
- Include a benthos model that allows for a size and/or age approach based on physiological processes (for instance a DEB approach).
- Improve parameter values on benthic population reduction and recovery. This should be done through monitoring studies on the effects of nourishments on benthic populations.
- Include a coupling between benthic recovery and fish recovery since benthos forms the food of juvenile fish inhabiting the coastal zone.
- Include more detailed information on bathymetric and sedimentologic changes within the cross-shore profile.
- Include more detailed information on water quality parameters such as turbidity and temperature, and sediment grain size since these affect juvenile fish and benthic organism distributions.
- Include seasonal effects of nourishing, i.e. nourishments in spring and summer may hamper juvenile fish and benthic organisms more than in autumn and winter.
- Include more detailed information on the magnitude in combination with duration of nourishments, for instance expressed as effects on the turbidity of the water.

The dune module could be improved by:
- Include feedback between the UNIBEST module and dune formation, so that the profile adapts if the system changes. There are developments to include more detail on profile development in UNIBEST. This might partly replace the division of volumes used here, so that more attention could be given to the processes that directly act on the dunes. This would also include a better estimate for beach width than the current profile movement.
- Include the type of nourishment and its consequences for the calculations of dune volume.
- The Bayesian Network Model is now used in a very simple way. The method however gives the opportunity to do e.g. Monte-Carlo modelling or uncertainty

estimates. With the current setup of the model, such things should be straightforward to add in a later phase.

- Include storm scenarios. This could be done by adding a table to Netica (the software where the dune module gets information from, see De Groot, in prep.): add years with large storms to category 'storms', and select during runs for whether it is a storm year or not.
- Include the available sub-module for 'foredune dynamics' and include more foredune management options. The absence and presence of vehicles, beach raking and cleaning, and tourist pressure has similar implications for the development of a green beach.
- Allow tracking of dune dynamics through time. This requires more parameterisation.

For improved information for stakeholders, a separate module on nourishment costs is being implemented in the ITHC (not covered in this report).

5.4 Recommendations

The Interactive Design Tool for the Holland Coast has already been used in workshops, in which various stakeholders make plans for the future of the Dutch coast. It is a great tool for visualising the impact of management measures (nourishments and revetments) in both time and space. This is of great value because the individual processes have different temporal and spatial scales, and respond differently to the measures. This model should not be used without moderation by an expert, who can clarify the results if necessary and explain model limitations. The tool is most suited in the beginning of the design process, when all possible scenarios are being explored. For more reliability on the local scale, more detailed models and knowledge should be gathered and applied.

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7 Appendix

7.1 Logistic growth model

To model the response of a benthic population, a logistic growth function was used that allows for time-varying adaptation of the carrying capacity (Shepherd & Stojkov, 2007). In this model, both population density and carrying capacity are a function of time. This approach was used assuming that sand nourishments in the coastal zone not only bury and kill the resident population, but also reduce the carrying capacity by affecting the environmental conditions. It subsequently takes time for the new substrate to become as suitable as the undisturbed substrate to allow for the pre-nourishment carrying capacity, which is represented as a time-varying carrying capacity. The logistic growth function is as follows:

$$\frac{dP}{dt} = rP\left(1-\left(\frac{P}{K(t)}\right)^{\sigma}\right)$$

$$(1)$$

With P denoting the population density (AFDW/m^2), t denoting time in years, r denoting the population growth rate, K(t) denoting the time-varying carrying capacity and σ denoting the power of the logistic growth function.

The time-varying carrying capacity $K(t)$ in equation 1 is modelled with the following equation, based on equation 17 in Shepherd & Stojkov (2007):

$$K(\varepsilon t) = \frac{K^*}{\left(1+\left(\left(\frac{K^*}{K(0)}\right)^{\sigma}-1\right)e^{-\sigma\varepsilon(t-t0)}\right)^{1/\sigma}}$$

$$(2)$$

Where $K(\varepsilon t)$ is the time-dependent carrying capacity, $K(0)$ the value of $K(\varepsilon t)$ at the time of nourishment, K^* is the limiting value as time (t) approaches infinity (the equilibrium carrying capacity). ε scales the recovery rate for the carrying capacity $K(\varepsilon t)$: when it is small the recovery of $K(\varepsilon t)$ is slow, and when large the recovery is fast.

To use the differential equation for logistic growth (Eq. 1) directly in the model, it needs to be translated into an explicit form. This can be resolved by setting σ equal to 1. Shephard & Stojkov (2007) found such an explicit form for the logistic growth function. The equations used in our model read as follows:

$$P(t + 1) = \frac{K^*}{(1+\alpha e^{-\varepsilon \cdot dt}+(\beta-\alpha)e^{-r\cdot dt})}$$

$$(3)$$

Where P(t) is the population at time step t, P(t+1) is the population at time step t+1, and dt is the duration of the time step between time instance t and t+1.

$$\alpha = \frac{r}{r-\varepsilon}\left[\left(\frac{K*}{K(t)}\right)-1\right], \beta = \left(\frac{K*}{K(t)}\right)-1$$

Note that the equation for β used here contains a correction for the one written in Shepherd & Stojkov (see eq. 18 in their paper).

Specific parameters that are required to resolve the considered explicit logistic growth function (Eq. 3) are the initial value of P, the growth rate r and equilibrium carrying capacity (K^*).

$$P(t+1, \varepsilon) = \frac{K(\varepsilon t) * P(t) * e^{r(t-t0)}}{(K(\varepsilon t) + P(t) * (e^{r(t-t0)} - 1))}$$

Where r is the population growth rate of the logistic function, and K(εt) the carrying capacity at time *t*.

When at time *t* a nourishment takes place, $K(\varepsilon t)$ equals K(0) and thereafter slowly increases towards K* following equation 3. In addition, at time *t* the population density is set to a lower value and thereafter the population regrows following a logistic curve (eq. 3), limited by the recovering carrying capacity ($K(\varepsilon t)$).

7.2 Nourishment types

The influence of nourishments and hard structures such as revetments on a benthic population is simulated by applying a nourishment-dependent reduction factor for the population density *P* and carrying capacity *K*. These reduction factors are only applied at the moment of construction of a measure, as the effect of the construction of nourishments on the population is expected to be much larger than throughout the nourishments lifetime. In addition, the assumption is made that the size of the nourishment affects the recovery time of the carrying capacity. For a lack of data these parameters (reduction and recovery) are assumed identical for all species (Table 1, main text).

It is assumed that the type of nourishment (based on magnitude, location and frequency combinations) determines the reduction in population and carrying capacity at the time of construction of the nourishment. Typical values for the reductions in *P* and *K* can be applied for different nourishment types (e.g. mega, foreshore or beach nourishments).

$$P(t)_{red} = P(t) \cdot (1 - R_{meas})$$

$$K(t)_{red} = K(t) \cdot (1 - R_{meas})$$

With:
$P(t)_{red}$ Reduced population as a result of a measure
$K(t)_{red}$ Reduced carrying capacity as a result of a measure
R_{meas} Reduction factor for a measure

7.3 General response

The recovery of a benthic population after a nourishment is depicted in Figure A1. Population size (*P*) is expressed as a percentage of the maximum population size. The maximum population size equals the equilibrium carrying capacity (K*). The response of the population size varies between species and between nourishment types. Following from the species-specific parameter value for *r*, the population growth rate, *Capitalla capitata* (r-strategist) (black line) recovers faster than *Macoma balthica* (intermediate species) (red line) and *Echinocardium cordatum* (K-strategist) (pink line). Figure A1 shows that with increasing reduction of the carrying capacity, the recovery time of the population increases. It simply takes longer to recover from a heavier impact. It is noteworthy that the difference between species response decreases with increasing reduction of the carrying capacity. Therefore, after a heavy impact, there is no difference in recovery time between the species. This is due to the model assumption that population recovery is not dependent on population growth, but on recovery of habitat conditions and therefore recovery of the time-dependent carrying capacity.
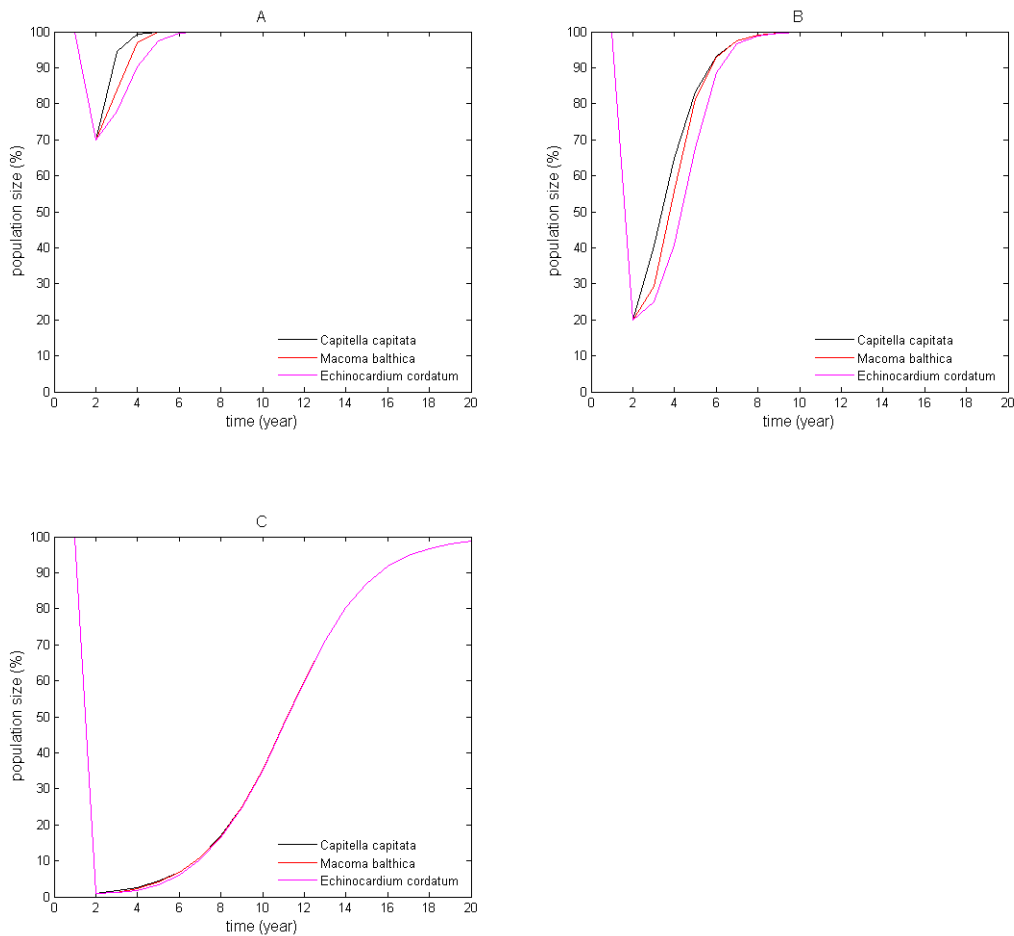
Figure A1. Population response presented as the population density at time t as fraction of the initial carrying capacity, of the three selected species to a single nourishment in year 2. The beach and surf zone nourishment causes a reduction of 30% of the population (A), the foreshore nourishment a 80 % reduction (B) and the mega nourishment a 99 % reduction (C).

More generally, the effect of the carrying capacity recovery rate on the population density is shown for two values of the recovery rate in Figure A2. The top row shows the change and recovery of the carrying capacity only. The carrying capacity is initially reduced to a certain percentage as shown on the vertical axis. Then it recovers through time (the horizontal axis), finally up to 100%, as shown in the colours. Of course, the larger the initial reduction in carrying capacity, the longer the recovery takes. Likewise, the lower the recovery rate ε, the slower the recovery will be (compare the left with the right column).

The middle and lower rows show the recovery of population size (expressed in % of maximum size), which is a combination of recovery of the carrying capacity and the growth strategy of the benthic population. The middle row shows the population response of *Capitella capitata*, an r-strategist whereas the lower row shows the response of *Echinocardium cordatum,* a K-strategist. The population response to the reduction in carrying capacity and the recovery rate of the population density follow a similar pattern to the carrying capacity (top row), but additionally depend on species characteristics. An r-strategist responses quickly and follows the carrying capacity directly (middle row), whereas a K-strategist is slower in its response and lags behind the recovery of the carrying capacity (bottom row).
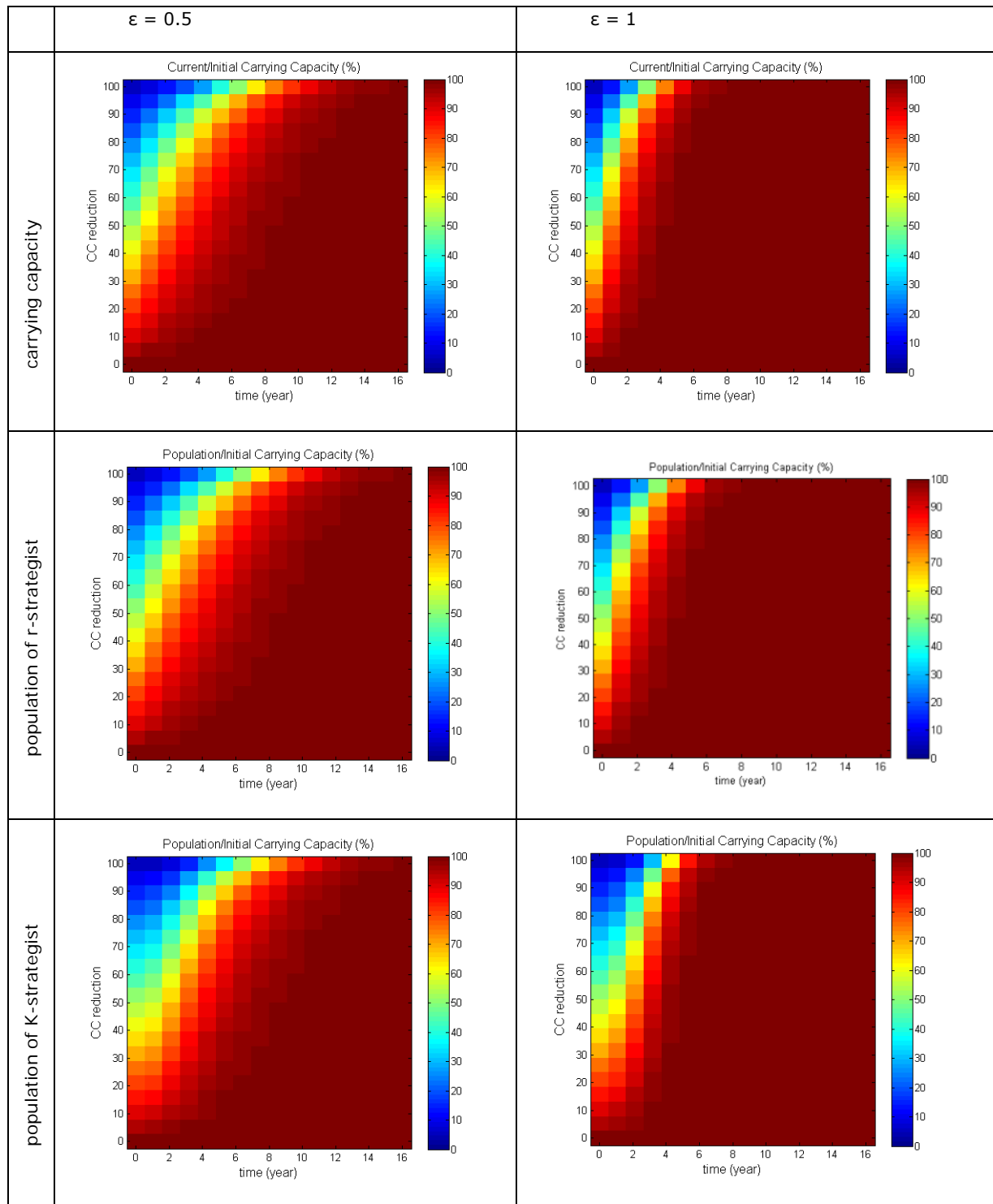
Figure A2. Top row: Carrying capacity recovery as a function of reduction (vertical axes) and time (horizontal axes), for different recovery rates (Left ε = 0.5; Right ε = 1). Middle row: Population recovery of an r-strategist (Capitella capitata). Bottom row: Population recovery of a K-strategist (Echinocardium cordatum).

It is important to know that the values for the recovery rate of carrying capacity are not validated with field data. Would for example the recovery rate (ε) be lower in reality than suggested here, then recovery time will increase. The benthic module in the ITHC needs validation with field data to determine typical recovery rates of populations and/or communities. For now, the estimates of recovery rates of benthic populations used in the simulations yield recovery times that are in line

with field studies results on sand extractions. Those indicate that the recovery times vary from 1 year for opportunistic r-strategist, to 4 to 6 years for K-strategists, based on the change in sediment and dredging intensity (Rozemeijer, 2009). The response of the benthic species living in the coastal zone in the North Sea to nourishments may show a different response than presented by the model results here, but are likely within the same order of magnitude.
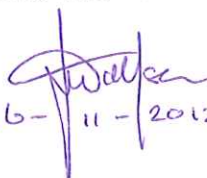
8 Justification

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The scientific quality of this report has been peer reviewed by colleague scientists and the head of the department ecosystems of IMARES.

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