Evaluating coastal multifunctionality: Sand nourishment strategies at decadal scales

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Keywords

Multifunctionality; sand nourishment; climate change adaptation; interdisciplinary; nature-based solutions; strategy; indicators

Abstract

Globally, there is a growing societal need for multifunctional coastal climate adaptation of sandy shores in the coming decades. Sand nourishment strategies are increasingly regarded as promising nature-based approaches to adaptation. They may increase flood safety and mitigate coastal erosion while enhancing recreational and ecological functioning. However, their multifunctional potential has not yet been assessed under diverse climate impacts at decadal scales. This study analysed the effects of beach, shoreface and mega-nourishment strategies on the physical capacity of sandy shores to supply coastal multifunctionality, using a systems-based approach. Through a structured literature review, we identified eight indicators for recreational (2 indicators), ecological (3) and flood safety (3) functions. We integrated these indicators into a process-based sand distribution model for dissipative coastal profiles. We simulated indicator states as the coastal profile responded to the nourishment strategies under five sea-level rise scenarios and three erosion rates. Next, we calculated the extent to which the physical capacity for coastal functions and multifunctionality were supplied over six decades. Our results indicate that all three nourishment strategies can highly supply the capacity for coastal multifunctionality, although the drivers of this potential differed per strategy. These findings imply that sand nourishment strategies are viable approaches for multifunctional coastal climate adaptation in the coming decades. However, they require prioritising specific coastal features and functions. Although sand nourishment strategies remain high-impact interventions, they also allow for intentionally creating coastal landscapes. These landscapes may not only provide flood protection but also enhance the specific environmental and societal functions valued in dissipative sandy shores. Prioritising among these functions requires explicit political choices.

1. Introduction

Globally, there is a strong societal need to understand the impacts of sand nourishment for coastal climate adaptation. Coasts deliver multiple functions, but sea-level rise may disrupt this delivery, intensifying from the coming decades onwards (IPCC, 2022b). Nourishing sandy coasts with sand not only mitigates erosion and increases the volume of the coastal fundament, but can also increase recreational opportunities, expand and improve ecological habitats, and support dune development through aeolian transport (de Vriend et al., 2015; Hanson et al., 2002). Thereby, sand nourishments can simultaneously provide flood protection against increased sea-level rise while delivering recreational, economic and ecological benefits. As such, they can deliver the physical capacity for multifunctionality (as defined by Manning et al. (2018)). Because of this multifunctional promise, sand nourishments are increasingly called for to adapt coasts to the sea-level rise of the coming decades and onwards. However, it remains poorly understood whether and when they impact multiple coastal functions simultaneously (De Schipper et al., 2021; IPCC, 2022b).

Different nourishment strategies lead to diverse impacts on coastal functions and multifunctionality. To adapt coasts to rising sea levels, these strategies vary primarily in their placement location, volume and frequency (Brand et al., 2022; Cooke et al., 2012; De Schipper et al., 2021; Hanson et al., 2002). Such variations affect the coastal profile, leading to different impacts on coastal ecology, recreation and

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flood safety. For instance, compared to more frequent nourishments, larger nourishments may benefit and reduce harm to ecological features, such as the abundance and diversity of intertidal macrofauna (van Egmond et al., 2018) and increase dune development (Luijendijk et al., 2019). However, the recreational potential of these larger beaches may decrease as their width increases beyond desired dimensions (Bax et al., 2024; Cabezas-Rabadán et al., 2019). The diverse cross-shore profiles of sandy shores following the application of the main sand nourishment strategies have been simulated at decadal scales, under diverse sea-level rise scenarios and erosion rates (Kettler et al., 2024). Choosing the right nourishment strategy to adapt coasts to increased sea-level rise requires insights into the effects that nourishments have on different coastal functions (Cooke et al., 2012; De Schipper et al., 2021; Singhvi et al., 2022). To inform decision-making on such effects, it is essential that the right indicators are identified. Such indicators can effectively and credibly inform decision-making on changes in those aspects of coastal functions that are most important to stakeholders (Geukes, van Bodegom, et al., 2024; Hinkel, 2011; Manning et al., 2018; van Oudenhoven et al., 2018).

However, it remains unclear how changes in the cross-shore profile of sandy shores resulting from the different nourishment strategies affect their physical capacity to deliver multifunctionality at decadal scales. Specifically, it has not yet been assessed how the morphological responses of sandy shores to the main nourishment strategies impact the societal and environmental benefits these coasts can provide. Additionally, it is not yet known how these responses quantitatively affect coastal multifunctionality at decadal timescales. This follows the general trend that assessing the wider and integrated benefits of sand nourishments has not followed the development of physical models at decadal timescales (Kindeberg et al., 2023; Stronkhorst et al., 2018; Temmerman et al., 2013).

This study aimed to identify the physical capacity of key nourishment strategies for delivering multifunctionality on sandy shores at decadal timescales. We identified the morphological responses of sandy coasts to nourishment strategies and related these to function-specific indicators. We then assessed how these morphological responses, under diverse sea-level rise scenarios and erosion rates, affect the capacity to supply coastal functions and the resulting multifunctionality of sandy shores. We expected differences between the strategies in their capacity to supply coastal functions and multifunctionality, as each strategy leads to different morphological responses. We also expected these capacities to decrease under increased climate impacts (i.e., through increased erosion and sea-level rise), as these would lead to more frequent nourishing, which increases the sand volumes required and the frequency of ecological disruption.

2. Methods

We assessed the physical capacity of nourishment strategies to supply coastal multifunctionality at decadal scales in three steps. Firstly, we simulated cross-shore coastal profiles after applying the main nourishment strategies. Secondly, we identified the indicators of the functions of sandy shores that may be affected by such cross-shore sand distribution. Thirdly, we calculated and analysed the state of these indicators, and the extent to which coastal functions and multifunctionality can be supplied for applying the main nourishment strategies at decadal timescales.

2.1. Simulating coastal profile response to nourishment strategies at decadal timescales

We simulated the responses of the cross-shore profile of sandy coasts to nourishment strategies under diverse sea-level rise scenarios and erosion rates at decadal scales. To simulate dissipative sandy shore

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profiles following nourishment strategies, we applied the Cross-shore Coastal Diffusion Long-term Evolution (Crocodile) model of Kettler et al. (2024) (Fig. 1). This is a diffusion-based numerical model designed to simulate the effects of nourishment strategies on coastal profile evolution over multiple decades. In this model, nourishments are regarded as perturbations to the coastal profile. Thus, after nourishment, sediment is redistributed cross-shore and longshore, by which the coast gradually adjusts towards a dynamic equilibrium profile. The model does, therefore, not simulate autonomous (nourishment-independent) profile development, such as storm and recovery cycles, cyclic bar behaviour and passing alongshore shoreline undulations. The model was calibrated to the dissipative Holland coast of the Netherlands, as this area has a well-documented nourishing history spanning multiple decades. This documentation includes yearly altimetric and bathymetric profile data available for model calibration and validation (Wijnberg & Terwindt, 1995). At the start of the simulation, the mean water level is set at 0 m from the local Dutch vertical datum (NAP), which approximates mean sea level. The model was validated using three Dutch case study locations, accurately simulating decadal changes in beach width, shoreline position and coastal volume under different nourishment strategies (Kettler et al., 2024). We followed the simulation method described in Kettler et al. (2024), unless stated otherwise. Per simulation, the model calculated the instantaneous bed level per horizontal coordinate, for 2153 timesteps of around 10 days per timestep, simulating the coastal profile for 59 years. Per timestep, the bed level is translated to the beach width, coastal volume change and shoreline location change.

Applying Crocodile, we simulated three main nourishment strategies: beach, shoreface and mega-nourishment. When simulating a shoreface nourishment strategy, 450 m^3/m (cubic meters of sand per meter of coastline) was placed offshore at the horizontal position where the cross-shore bed level intersects with the -5 meters isobath, for each nourishment. In a beach nourishment strategy, 200 m^3/m sand was placed where the cross-shore bed level intersects with the +2 meters isobath, thus landward from the intertidal waterline. For mega-nourishment, 2000 m^3/m sand was placed where the bed level intersects the +5 meters isobath. We simulated these strategies as responsive hold-the-line strategies, which is a main nourishment approach, commonly applied in e.g., Italy and France (Hanson et al., 2002). If the current coastline nearly crossed the initial coastline in a landward direction, a new nourishment with the same volume was placed. These strategies were followed consistently.

We simulated the effects of these three nourishment strategies for five sea-level rise scenarios and at three erosion rates using Crocodile. We applied a global mean sea-level rise rate of previous decades (2 mm/year), the current rate (4 mm/yr), rates representing increased sea-level rise in the coming decades (8, 16 mm/yr) and a low likelihood, high-impact rate (32 mm/yr) (IPCC, 2022c, 2023; Kopp et al., 2023). We applied erosion rates of 10, 40 and 70 m^3 per meter shoreline per year. Simulating these relatively high erosion rates enabled us to explore how coastal profiles respond to varying erosivity and to increased climate impacts that accelerate erosion rates by, e.g., increased rainfall intensity, storm frequency and intensity, and vegetation loss (Masselink & Russell, 2013; Pang et al., 2023).

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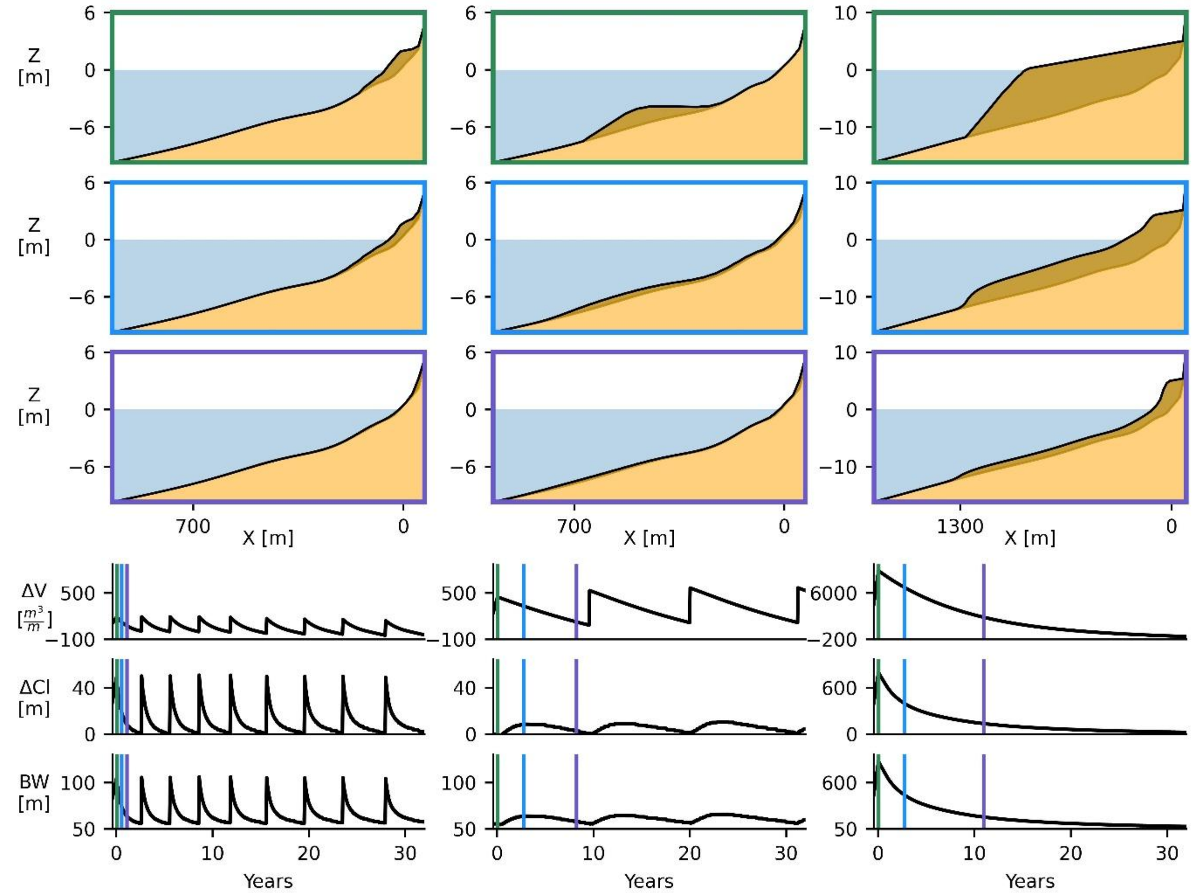

Fig. 1. Visualisation of simulating coastal profile development following beach, shoreface and mega-nourishment strategies at decadal scales with the Crocodile model by Kettler et al. (2024). The model calculates the instantaneous bed level (Z) per horizontal coordinate (x) and timestep, and returns per timestep. ΔV: the change in coastal cross-shore profile volume (in the vertically constrained section between -20 m NAP and the dune top per meter coastline), ΔCl: the change of the coastline position (as the average, intertidal coastline) and BW: the beach width (as the horizontal distance between the coastline position and the dune foot at +3 m NAP). The columns show the profile development per nourishment strategy. The upper three rows show the cross-shore profile progression at the timesteps indicated by the colours. The lower three rows show model outcomes over time.

2.2. Identifying indicators of the functions of sandy shores

We define an indicator as a tool for operationalising a concept that cannot be directly observed, by approximating it by a logically connected, observable variable. This variable can reflect the concept's status, cause or outcome (Geukes, van Bodegom et al., 2024; Hinkel, 2011). In this study, we use indicators based on model outcomes to estimate the physical capacity to supply the functions and their multifunctionality. As we simulate changes in the physical capacity for providing coastal functions, these indicators reflect the physical requirements for delivering coastal functions (cf. Liquete et al., 2013; Villamagna et al., 2013). The final delivery of these functions and the overall multifunctionality can additionally depend on social, economic, cultural or ecological factors, which differs per indicator and function.

The status of an indicator can relate to a function in different ways (Hinkel, 2011; Manning et al., 2018). We identified four relationship types to capture these relations (Table 1). We use the three types defined by Manning et al. (2018): (1) a linear relation between the indicator status and the potential to

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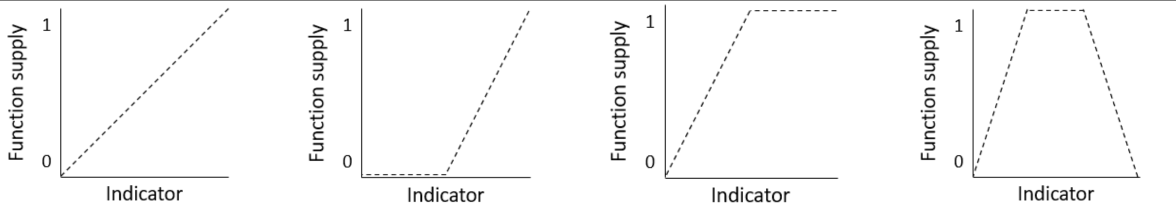
provide the benefit, (2) a threshold value of the indicator status before which no benefit is provided and after which the benefit is fully provided, and (3) a ‘threshold-plus’, where the benefit increases linearly before or after a certain threshold. Additionally, we identified (4) a ‘combined threshold-plus’ relationship. This relation has two thresholds with a linear increase or decrease before and after the thresholds, in between which the benefit is fully provided. These four types can also be applied to decreasing relationships, as the directionality of the benefit provided depends on the definitions of the function and the indicator.

Table 1

Relationship types between an indicator status and coastal function supply. The first three types were defined by Manning et al. (2018), the Combined threshold-plus was added for this study.

Linear	Threshold	Threshold-plus	Combined threshold-plus



We identified indicators for the functions of sandy shores by performing a structured literature review. We searched in the Web of Science database for “coast* AND beach* AND indicator* AND (sand OR sandy) AND (ecosystem service OR ecosystem services)” up until 09-01-2024. We searched for ecosystem services as these connect the physical state of the coast to the functions it can deliver. Of the resulting 33 papers, we screened their titles and abstracts. We excluded those not concerned with indicators of functions of sandy coastal beaches, or that only presented indicators whose state would not be affected by cross-shore sand distribution. Of the remaining papers, we read the full text to identify the functions provided by sandy coasts and their indicators that could be affected by cross-shore sand distribution on dissipative coasts in general. This resulted in an overview of 24 indicators, of which we selected those that could credibly be simulated at decadal scales with Crocodile, as well as affected by cross-shore sand distribution and nourishment. See Appendix A for the papers we found, the indicators and functions they provided and our rationale for including or excluding them, following these steps.

We combined indicators that presented overlapping information into indicators that reflect unique information. Following these steps, we identified seven indicators of the capacity to supply three functions: recreation, ecology and flood safety (Table 2). We included the total volume nourished as an additional indicator of flood safety. This indicator demonstrates the feasibility and efficiency of sand use in maintaining a strategy, which is regarded as central to the safety that nourishment strategies can provide for adaptation, and a main reason for potentially switching nourishment or coastal adaptation strategies (Haasnoot et al., 2020; Hanson et al., 2002; Stronkhorst et al., 2018; UNEP, 2022b). These indicators could be determined based on five model outcomes, of which we calculated the status per timestep with Crocodile (Fig. 2).

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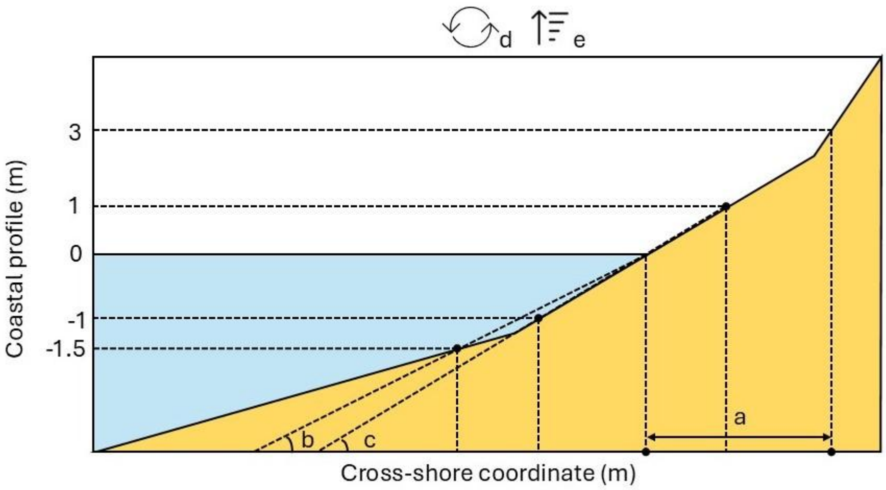
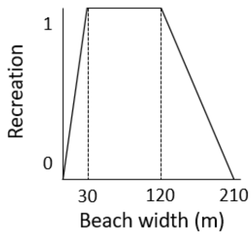


Fig. 2. Visualisation of the model outcomes in a cross-shore profile calculated with the Crocodile model developed by Kettler et al. (2024), used for indicating coastal function supply: a) beach width, b) beach face angle, c) intertidal area angle, d) nourishment frequency and e) total volume nourished per meter coastline.

For each identified indicator, we studied additional literature to identify the most appropriate relationship and, if applicable, the threshold value or values. We selected the relationship type that followed the consensus in the literature on the relation's directionality and form. As thresholds, we selected those values that were most generically applicable. If there were multiple options, we selected the thresholds most applicable to the hydrodynamic conditions used for calibrating the morphological model. For the volume nourished for flood safety indicator, no credible threshold could be identified that allowed for comparability with other studies or with sand budgets in general, as the global sand supply is not known, nor is its demand for coastal protection or other potential uses (UNEP, 2022b). To allow for comparability between strategies, we applied the largest volume used in our simulations as threshold. See Table 2 for the relations per indicator and function, and Appendix A for a more detailed description of the steps taken to identify these relations and values.

Table 2

Overview of the functions of sandy shores, indicators and their relationships. All indicator states can be calculated per timestep by applying the Crocodile model developed by Kettler et al. (2024). The indicators, functions and relationships were identified through a structured literature review (Appendix A, see references in the footnotes).

Function	Indicator	Range	Description	Relationship between the indicator status and the benefit provided
Recreation	Beach width to support recreation. The width between the average waterline and dune foot (+3 m NAP)	30-120 meters	Beach width indicates the physical carrying capacity of the dry beach for standard sunbathing recreation. A minimal width is required to provide optimal carrying capacity for recreationists. There is a maximum distance from the seashore for recreationists. The optimal beach width thus benefits recreation by providing sufficient space for recreationists, while limiting the cross-shore distance to the sea. The optimal width is locality-dependent and often depends on the	

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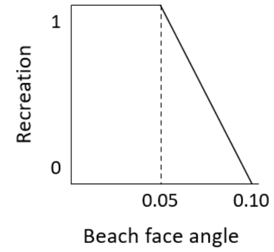
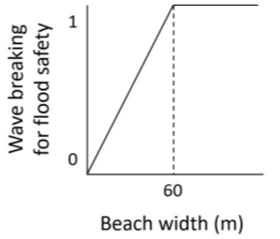
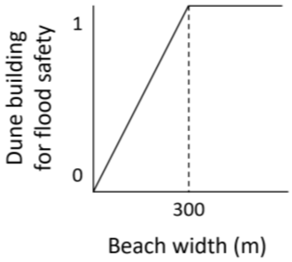
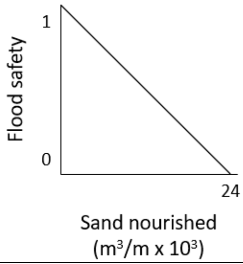
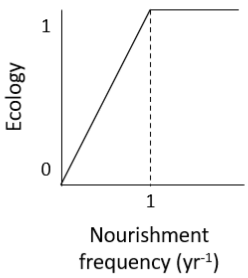
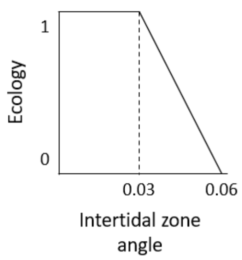
			initial beach width and cultural preferences. We selected the beach width considered optimal for Dutch beaches, to which the morphological model was calibrated.[1]	
	Beach face angle. Slope of high waterline to 1.5 m depth	0-5%	The beach face's angle indicates the beach's safety for sunbathing and swimming. The safer the beach, the more it supplies recreational benefits. Beyond the threshold, the beach is considered increasingly unsafe, as mentioned in case studies over multiple continents. Below the threshold, the safety is considered sufficient for standard recreation.[2]	
Flood safety	Beach width for wave breaking. The width between the average waterline and the dune foot	>Initial beach width	More beach width allows for reducing wave energy, reducing erosion, wave setup and overtopping. Maintaining at least the current beach width delivers substantial flood protection benefits. We therefore applied the initial beach width as a threshold. The optimal threshold depends on local hydrodynamic conditions.[3]	
	Beach width for dune building. The width between the average waterline and the dune foot	>300 meters	The beach can offer aeolian sand transport, necessary for dune building. Increased dune height and width protect coasts by reducing surges and overtopping, increasing sand-trapping by vegetation and stabilising the shoreline. This all prevents flooding. Beach width and dune volume generally positively correlate up to 300 meters, after which sufficient sand is available for aeolian transport.[4]	
	Total volume sand nourished per meter coastline	<24 * 10^3 m^3/m	The volume nourished demonstrates the feasibility and efficiency of sand use, which are central and often-used indicators of the ability to provide flood safety. To calculate the score for comparing strategies, we contrast the volume nourished to the highest amount of sand nourished in this model, by any strategy.[5]	
Ecology	Nourishment frequency	0-1 nourishment/year	The intertidal macroinvertebrates are killed by sand nourishment. Intertidal macrofauna benefit coastal ecology by providing food for the rest of the food web and cycling nutrients, connecting the marine and coastal ecosystems. Recolonisation can start immediately after nourishment and is generally back to initial abundance levels after one year.[6]	
	Intertidal zone angle. The angle of the high waterline (+1 m) to the low waterline (-1 m)	0-3%	The intertidal zone angle indicates the suitability of the local intertidal habitat for intertidal macrofauna. The intertidal macrofauna is key for cycling nutrients and organic content from the sea to the rest of the coastal ecosystem. Dissipative slopes are globally found to be optimal, after which the favourability of the intertidal area	

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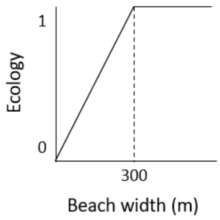
			decreases with steepness. The threshold indicates the threshold of dissipative slopes.[7]	
	Beach width for dune building. The width between the average waterline and the dune foot (+3 m NAP)	>300 meters	The beach width allows for aeolian transport, for marram grass growth. This can bind sand, which increases dune growth. Dune growth supports stable and varied habitats and microhabitats that are essential to coastal biodiversity. Marram grass presence and dune volume relate positively with beach width until 300 meters. To potentially supply all ecological functions, this is therefore considered the minimal optimal beach width.[8]	

Sources:

[1] (Ariza et al., 2010; Broer et al., 2011; Cabezas-Rabadán et al., 2019; De Souza Filho et al., 2014; García-Morales et al., 2017; González & Holtmann-Ahumada, 2017; Ocaña et al., 2022)

[2] (Ariza et al., 2010; Chen et al., 2022; De Souza Filho et al., 2014; García-Morales et al., 2017; González & Holtmann-Ahumada, 2017; Lucrezi et al., 2016; Rijkswaterstaat, 2020; Van Ettinger & De Zeeuw, 2010; Wienhoven et al., 2020)

[3] (Ariza et al., 2010; González & Holtmann-Ahumada, 2017; Larson & Kraus, 1989; Toimil et al., 2023; Venkatachalam et al., 2012)

[4] (Galiforni Silva et al., 2019; González & Holtmann-Ahumada, 2017; Hanley et al., 2014; Van der Biest et al., 2017; Venkatachalam et al., 2012)

[5] (Haasnoot et al., 2020; Hanson et al., 2002; Stronkhorst et al., 2018; UNEP, 2022b)

[6] (González & Holtmann-Ahumada, 2017; Hanley et al., 2014; Leewis et al., 2012; Ocaña et al., 2022)

[7] (Bosboom & Stive, 2023; González & Holtmann-Ahumada, 2017; Kelly, 2016; Mclachlan, 1990; Ocaña et al., 2022; Short & Wright, 1983)

[8] (Galiforni Silva et al., 2019; González & Holtmann-Ahumada, 2017; Hanley et al., 2014; Keijsers et al., 2014; Kelly, 2016; Ocaña et al., 2022; Van der Biest et al., 2017; van Puijenbroek et al., 2017; Venkatachalam et al., 2012)

2.3. Calculating the extent to which functions and multifunctionality are supplied

Based on the identified indicators, functions and their relationships, we calculated the extent to which the physical requirements for supplying the functions were met simultaneously. We calculated this supply for the cross-shore profiles corresponding to the different nourishment strategies, sea-level rise and erosion rates, per timestep. We define coastal multifunctionality as the extent to which multiple coastal functions are supplied simultaneously. By calculating the extent to which individual indicators supply different functions and by grouping these, we calculate multifunctionality as a single aggregate indicator, following the definition and operationalisation by Manning et al. (2018). Firstly, we calculated the model outcomes and the associated indicators per nourishment strategy, sea-level rise scenario and erosion rate, at each timestep. Then, per indicator, we calculated the extent to which the morphological state of the profile corresponded to the optimal state of this indicator, applying the indicator-function relationships identified (Table 2). Thus, we ascribed an indicator a 100% score if the morphological state was in the optimal range. Otherwise, the score was (1 – distance of the indicator value to the closest threshold / the range wherein the function is supplied optimally) * 100%. Secondly, we calculated the extent to which the coastal functions could be supplied, expressed in percentages of the optimal score. We calculated these scores as the average of the indicator scores per function, per nourishment strategy, timestep, sea-level rise scenario and erosion rate. We thus assumed that all

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indicators are equally important to supplying a function. However, different stakeholders will likely prioritise different system properties and weigh indicators differently. Identifying these weights requires further research. Thirdly, per nourishment strategy, sea-level rise scenario and erosion rate, at each timestep, we averaged the function scores to calculate the extent to which the physical capacity for coastal multifunctionality was supplied. We refer to these as the multifunctionality scores. Here, we applied equal weights again. We then calculated the relative difference between the functions' scores per nourishment strategy. Additionally, we tested the sensitivity of the model outcomes to varying the indicator threshold values and initial starting conditions.

We simulated the indicators temporally but assessed the functions and multifunctionality scores as averages over time. The time between the change in the status of an indicator and a change in its benefit to a function varies per indicator. Therefore, an analysis of these scores per timestep would not credibly show what benefits they could bring. This would limit us in comparing strategies' potential for doing so. Therefore, instead, we followed Manning et al. (2018) and averaged the scores over time, to compare strategies' benefits to functions and multifunctionality. This proved feasible, as the dynamics of the indicator values and the scores did not vary drastically over time. Identifying the temporal relations between indicator values and benefits provided by sandy coasts remains a direction for further research.

3. Results

3.1. Indicators of coastal functions' responses to nourishment strategies

Beach nourishments provide sufficient beach width and a sufficiently low angle of the beach face for recreation, while not becoming too wide, under each sea-level rise scenario (Fig. 3). The angle of the intertidal zone remains low enough to accommodate the intertidal macrofauna. However, the nourishment frequency is relatively high compared to other strategies, especially in the higher sea-level rise scenarios. Under the lowest sea-level rise scenarios, the maximum time for re-nourishing is 4 years, and under the highest sea-level rise scenarios, every other year, a new nourishment is placed. The potential for dune growth for ecological and flood safety concerns is never optimal, as the 300-meter width is never reached.

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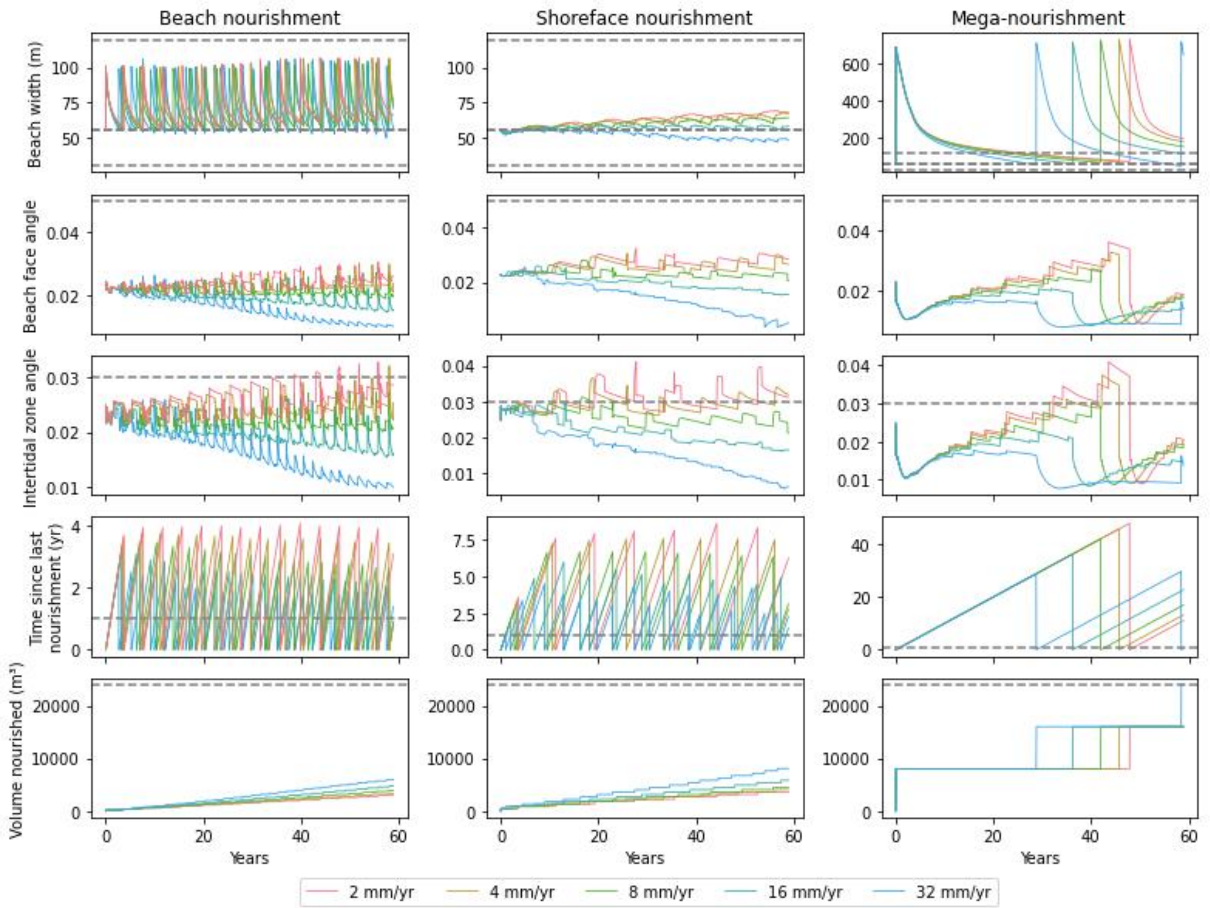

Fig. 3. Overview of the temporal coastal profile responses to three nourishment strategies under diverse sea-level rise scenarios. Graphs present indicator values of coastal functions over time, per nourishment strategy and rate of sea-level rise, with an erosion rate of 40 m^3/m/yr. The three columns show the three nourishment strategies. Each row shows an indicator's development. Colours indicate simulation outcomes per sea-level rise scenario. The grey dotted lines demonstrate indicator thresholds (Table 2). Note that y-axis scales can differ between subplots, as they are adjusted to the range of indicator values per strategy. Outcomes for background erosion rates of 10 and 70 m^3/m/yr are presented in similar graphs in Appendix B.

Shoreface nourishments also deliver sufficient carrying capacity for recreation, while the beach more upslope does not become too wide or too steep to create unsafe recreational conditions. The angle of the intertidal zone is generally suitable for intertidal macrofauna under sea-level rise scenarios of 8 mm/yr or higher. However, this angle may become too steep under lower sea-level rise scenarios. The nourishment frequency is relatively low compared to beach nourishment and increases with sea-level rise. Under the lowest sea-level rise scenarios, a new nourishment must be placed every 7.5 years, and under the highest sea-level rise scenarios, this is the case every 4 years. The longer it takes for new nourishment to be placed, the more the coast is exposed to erosion and the steeper the angle can become. The optimal beach width for dune growth is not reached and is substantially lower than for beach nourishment. The amount of sand used is approximately equal to that of beach nourishment and increases with sea-level rise.

Mega-nourishments are often wider than the maximal width for recreational preferences, as the distance between the start of the beach and the waterline can reach over 600 meters. The angle of the beach face stays sufficiently low to provide recreational safety for swimming and entering the water. After more than 30 years, the intertidal zone may become too steep for the intertidal macrofauna

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under sea-level rise scenarios of 8 mm/yr and lower, as the profile is more exposed to erosion over this period, increasing its steepness. Placement frequencies are much lower than for beach and shoreface nourishments, allowing the intertidal macrofauna and the associated food web to recover well, as the periods between the nourishments range between 30 and 50 years. The beach is often sufficiently wide for dune growth for flood safety and ecology, especially compared to the beach width delivered by beach and shoreface nourishments. However, after placement, the width decreases quickly, as the wider the beach is, the quicker it erodes. Regarding their efficiency and feasibility as flood safety strategies, mega-nourishments utilise much more sand than beach and shoreface nourishment, limiting the sand budget and thereby the feasibility of continuing that strategy, especially for higher sea-level rise rates.

These results, i.e., the relationships between the indicator values of the strategies, do not differ notably between the erosion rates. Exceptions are the increasing steepness of the profile, especially for shoreface nourishments, and increasing nourishment frequency as erosion rates increase. See those outcomes in detail in Appendix B.

3.2. Functions supplied per nourishment strategy

Beach and shoreface nourishment supply coastal functions almost equally. They provide optimal recreational capacity, whereas mega-nourishments better supply ecological functions compared to these other strategies (Fig. 4, Appendix C). Beach and shoreface nourishments optimally provide the physical requirements for recreational use. Mega-nourishments score lower and are more volatile in supplying coastal recreation functions. However, compared to beach and shoreface nourishments, mega-nourishments score relatively high on providing the capacity for ecological benefits. All three strategies supply flood safety almost equally well.

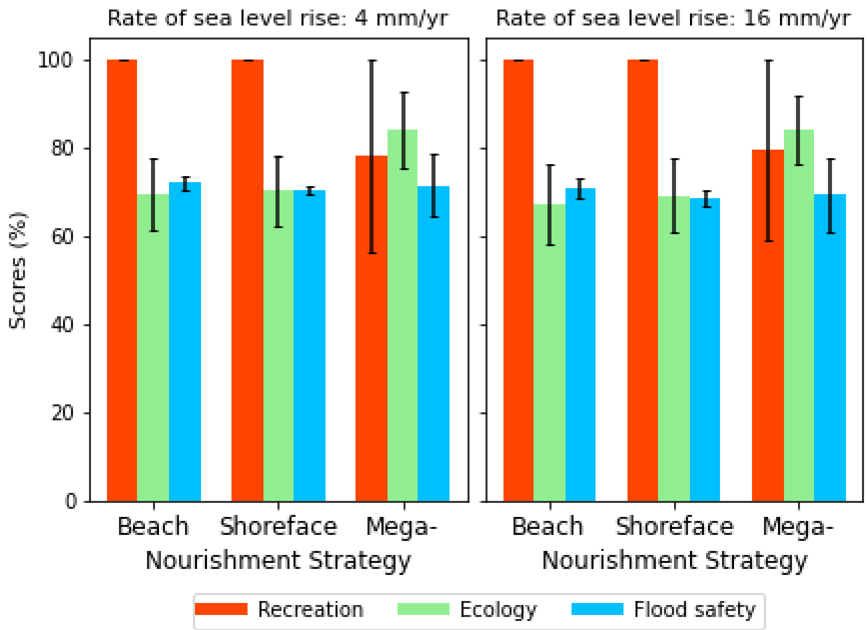

Fig. 4. Function supply capacity per nourishment strategy for two sea-level rise scenarios, as scores in percentages. Each column shows the outcomes per sea-level rise scenario. The bar groups show the outcomes per nourishment strategy. Bar colours show the outcomes per function. These scores were calculated for an

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erosion rate of 40 m^3/m/yr for 60 years in 2153 timesteps and averaged over time. The error bars indicate the scores' standard deviations. See Appendix C for the outcomes for all erosion rates and sea-level rise scenarios.

Beach and shoreface nourishment strategies score almost equally on providing the physical requirements for delivering ecological benefits, but these scores result from different indicators that balance each other. For beach nourishments, the angle of the intertidal zone remains low, but the nourishment frequency is relatively high. While for shoreface nourishments, the angle of the intertidal zone can become too steep to accommodate intertidal macrofauna, their nourishment frequency is lower than for beach nourishments. The increase and decrease in these indicators balance each other out, leading to almost equal ecology scores.

Similarly, the equal flood safety scores of the three strategies follow different indicators that balance each other. Mega-nourishments provide more beach width to allow for dune building for flood safety but utilise a lot of sand, compared to beach and shoreface nourishments. These benefits balance each other, leading to almost equal flood safety scores between the three strategies.

In general, these results are robust to changing the sea-level rise scenarios and erosion rates (Fig. C1). Recreational scores remain similar under all sea-level rise scenarios. Generally, ecology scores decrease slightly as sea-level rise increases (the maximum absolute effect is -3.5%, over all scenarios). However, at higher erosion rates, shoreface and mega-nourishment's scores on ecology generally rise with increased sea-level rise scenarios (up to 10%, as absolute score), due to flattening the profile and increasing beach width by increased nourishment. Flood safety scores generally decrease slightly as sea-level rise increases (a maximum absolute effect of -5.7%). Increased erosion rates and sea-level rise require additional nourishment, but each nourishment expands and flattens the coastal profile, resulting in relatively robust coastal functions. See the detailed outcomes per function, sea-level rise scenario and erosion rate in Appendix C.

3.3. Multifunctionality per nourishment strategy

The multifunctionality scores are almost equal per strategy but have different drivers. Averaged over time with 4 mm/yr sea-level rise and an erosion rate of 40 m^3/m/yr, the multifunctionality score of beach nourishment is 80.5%, of shoreface nourishment 80.2% and of mega-nourishment 77.9%. The multifunctionality scores per erosion rate and sea-level rise scenario do not differ substantially. These are shown in detail over time and per erosion and sea-level rise rate in Appendix C. Additionally, they are generally robust to varying indicator threshold values (Appendix D). However, the multifunctionality scores follow from different contributions by the coastal functions (Fig. 5). Choosing a mega-nourishment strategy over a beach nourishment strategy results in a 28.0% relative decrease in recreation scores and almost equal flood safety scores (-0.73%), but 17.4% higher scores for ecology. Beach and shoreface nourishments, however, score equally well on recreation, and differ slightly on flood safety (-2.45%) and ecology scores (1.24%). Thus, choosing a shoreface nourishment strategy over a mega-nourishment strategy leads to 21.9% relatively increased recreation scores, roughly equal flood safety scores (-1.70%), but 19.6% lower ecology scores. Similarly, the multifunctionality scores and preferred nourishment strategy depend on how the functions and indicators are prioritised (Appendix F).

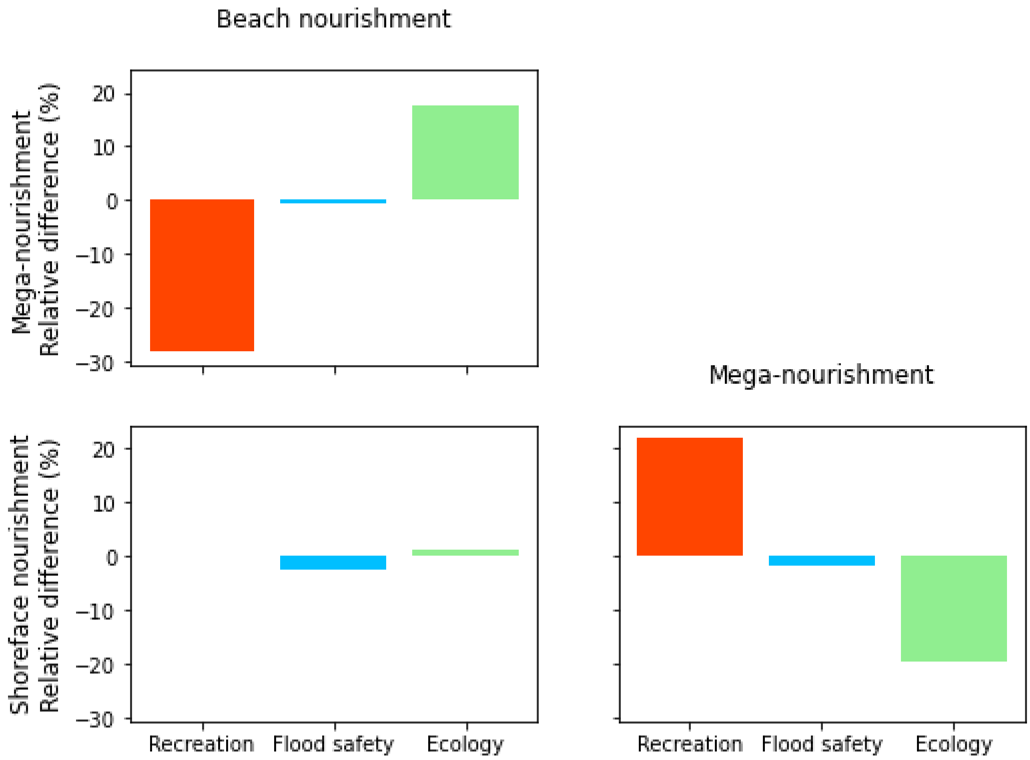

Fig. 5. Relative difference in the capacity to supply coastal functions between nourishment strategies. The figure shows the comparison between the contributions of an individual function to the multifunctionality scores. The scores are calculated for a sea-level rise rate of 4 mm/yr and averaged over 60 years in 2153 timesteps, under an erosion rate of 40 m^3/m/yr. For the multifunctionality and function scores in detail, per erosion and sea-level rise rate, see Appendix C. The multifunctionality scores of the three nourishment strategies are around 80% under all sea-level rise scenarios and erosion rates considered. Even though the multifunctionality scores of the nourishment strategies are approximately equal, the functions within them differ.

4. Discussion

4.1. Sand nourishment strategies can supply the capacity for coastal multifunctionality that is robust for diverse sea-level rise scenarios and erosion rates.

Sand nourishment strategies can substantially provide the physical capacity required for coastal multifunctionality. This capacity is generally robust across sea-level rise scenarios and erosion rates (Appendix B and C). Also, it proved robust to adjusting the relationships between indicators and functions supplied (Appendix D for this sensitivity analysis), and adjusting the starting conditions towards more dissipative profiles. This robustness suggests generalisability towards diverse hydrodynamic conditions and indicator-function relationships. The multifunctionality scores do, however, decrease when we set the initial conditions to be much steeper (Appendix E), which is in line with the general trend of our indicators and the increased biodiversity and safety benefits that more dissipative beaches allow for (Defeo & McLachlan, 2013; Toimil et al., 2023).

The consistently high capacity for coastal multifunctionality suggests that sand nourishment may be a viable and multifunctional approach towards coastal climate adaptation of sandy shores. This finding underscores the positive contribution that nature-based solutions could make to multifunctional adaptation (Seddon, 2022; UNEP, 2022a). The robustness of our findings implies that our outcomes may be generalizable to other dissipative sandy shores. For reflective or sheltered low-energy beaches,

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morphodynamic responses and indicator thresholds may differ substantially (e.g., McLachlan et al., 2013). Even though the morphological model was calibrated to a Dutch coast, it represents a general dissipative beach, and the indicators used are broadly applicable. However, the outcomes were relatively sensitive to adjusting the optimal range for beach width for recreation (Appendix D), for which we found diverse locality-specific values. Thus, in assessing sand nourishments at other localities, optimal indicator ranges for beach width may be adjusted accordingly. Moreover, our morphological simulation did not include nourishment-independent profile developments and short-term fluctuations, such as storm events and bar dynamics. These would likely affect the profiles' short-term multifunctional capacity. The results presented here present estimates of multifunctionality capacity on decadal scales. For shorter-term responses, more detailed morphological models can be integrated, as discussed in Section 4.3.

To simulate local effects in more detail, the functions, indicators and thresholds can be adjusted to fit the coastal system. We applied the Crocodile model by Kettler et al. (2024) as the morphological basis of our simulations. This model is considered to be generalizable to sandy coasts with varying profiles and hydrodynamic conditions, but this requires further validation (Kettler et al., 2024). The thresholds of our flood safety indicators (Table 2) are generally applicable to beaches with similar hydrodynamic conditions (Appendix A). However, a detailed overview of the availability of sand resources for nourishment and their future distribution among and within countries is currently lacking. We therefore did not identify a generally applicable indicator for sand volume nourished for flood safety. The threshold for this flood safety indicator must be defined in the local economic and morphological context, depending on the sand availability, price and financial budget through further morphological and economic studies (Coelho et al., 2022; Qiu et al., 2020; UNEP, 2022b). For the purposes of this study, our simulation was robust to changes in this flood safety indicator. The thresholds for ecological indicators were generally applicable, including to non-dissipative beaches (Defeo & McLachlan, 2013; McLachlan & Dorvlo, 2005). The suitable beach angle for recreational safety was derived from case studies in Asia and Europe, which also suggests broad applicability (Ariza et al., 2010; Chen et al., 2022; Rijkswaterstaat, 2020; Van Ettinger & De Zeeuw, 2010). This recreational threshold might be adjusted depending on other factors that affect safety, such as the presence of lifeguards, the number of visitors and the local regime of waves and currents (Chen et al., 2022; Fletemeyer et al., 2018; Radermacher, 2018; Rijkswaterstaat, 2020). The optimal beach width for recreation depends on the number of visitors and cultural preferences (Broer et al., 2011; Cabezas-Rabadán et al., 2019; de Paula et al., 2022), and should be adapted to these local conditions.

Despite the highly viable and robust multifunctionality of all sand nourishment strategies, the strategies call for further considerations in decision-making. In choosing between adaptation strategies, there are major implications for the required governance and management structures. These relate mainly to conducting either one major engineering project over several decades or nourishing regularly. Also, the amount of sand that is suitable and available for nourishment will decrease, which may increasingly become a main criterion in choosing between nourishment and other adaptation strategies, such as hard defences or coastal realignment (IPCC, 2022a; UNEP, 2022b). Moreover, the costs of nourishment strategies can be volatile and will likely increase as sand budgets shrink, which must be weighed against nourishments' high capacity for multifunctionality. Additionally, the extent of sea-level rise in the coming decades is deeply uncertain and can vary highly (Bakker et al., 2017). For the highest projections of sea-level rise, nourishment may not be feasible, and the lead time for switching to other adaptation strategies can take several decades (Haasnoot et al., 2021). Therefore, decision-makers on coastal climate adaptation strategies are presented with the dilemma of how long to invest in potentially highly multifunctional nourishment strategies before switching to other adaptation strategies.

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4.2. The desirability of distinct nourishment strategies depends on conflicting outcomes related to different interests and functions.

Despite the similar multifunctionality outcomes for diverse strategies, sea-level rise scenarios and erosion rates, the underlying functions strongly diverge. Across all simulated sea-level rise scenarios and erosion rates, beach and shoreface nourishments generally allowed for more recreational capacity, while mega-nourishments led to more ecological benefits. Under the highest erosion rates, responsive sand nourishment strategies can increasingly offer recreational and ecological benefits by increasing beach width, even under the highest sea-level rise scenarios, but at the cost of flood safety benefits, as the feasibility of these strategies decreases in the longer term.

These differences in functions underscore the need for explicating conflicting functions, understanding their drivers and how diverse stakeholders relate to these benefits. Even when applying highly multifunctional nature-based solutions, human and ecological interests can still misalign (e.g., Schlacher et al., 2007). The optimal nourishment strategy depends on what functions are prioritised. To inform decision-makers on the desirability of such multifunctional nourishment strategies, it is crucial to consider the decision-making stage during which the information is required (Geukes, van Bodegom, et al., 2024). For instance, researchers can focus on the high multifunctionality scores when a project requires broad stakeholder support, on how the supply of diverse functions differs between the strategies for political decision-making, and on how indicators drive these scores differently in evaluation and in informing coastal managers.

Additionally, our findings underscore the call by Manning et al. (2018) to study the diverse perspectives on the desired weight of the contribution of indicators and functions to calculate multifunctionality. Such studies require research on how stakeholders understand and prioritise coastal values. As this entails identifying societal phenomena, instead of primarily ecological or physical processes, they should be rooted in the social sciences (Jacobs et al., 2018). These different perspectives can be integrated into a multicriteria decision-making framework (Ruangpan et al., 2021). This approach allows considering both qualitative and quantitative data, and enables stakeholder participation in analysing trade-offs to support decision-making (Belton & Stewart, 2002). To increase the legitimacy and fairness of the weights, perspectives can be included from stakeholders that have (historically) been underrepresented in decision-making on nature-based solutions (Cousins, 2021), or from the interests of future generations (Reed et al., 2009; Taebi et al., 2020). This would align with the call by Jacobs et al. (2018) to identify and integrate diverse valuations of nature in assessing the value of natural systems.

Even when coastal function scores are similar, their physical drivers might differ and promote different aspects of a function. This calls for researching which aspects of coastal functions can and must be prioritised (Geukes, Kettler, et al., 2024). Strategies could show similar scores for flood safety but differ in the extent to which this was due to using little sand or allowing for dune building. Similarly, they could show similar ecology scores but promote either habitat for intertidal macrofauna or dune development. Ecology scores did therefore not necessarily decrease as nourishment frequencies were increased, due to the additional intertidal and dune habitat created. This contrasts with suggestions that increased application of nourishments would decrease the ecological values of coasts (e.g., Speybroeck et al., 2006) or would lower their flood safety or multifunctional benefits.

The ecological benefits that can result from both frequently and infrequently nourishing have implications for the current dichotomy in the thinking on managing natural areas (e.g., Maniatakou et

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al., 2020) and the necessity of applying nature-based solutions. Some consider it best practice to actively promote specific natural functions of the landscape, while others argue that the most natural landscape is the one that develops without human intervention (Curry, 2011; Fairweather & Swaffield, 2003). Our study shows that these perceptions of what constitutes naturalness shape the extent to which the benefits to the landscape are perceived as such, determining, e.g., to what extent cultural and regulatory functions might benefit simultaneously. Further research could explore the physical drivers of such cultural perceptions of the right 'natural' landscape.

4.3. *Towards assessing the coastal multifunctionality of sand nourishment strategies at decadal timescales*

We assessed the coastal capacity to deliver multiple benefits simultaneously at decadal timescales by extending the cross-shore sand distribution process model developed by Kettler et al. (2024) with diverse indicators of societal and ecological function supply. The need to assess the multifunctionality of coastal climate adaptation strategies over time and under different environmental conditions will increase (IPCC, 2022a). For this, our approach of combining morphological process-based models with multifunctionality assessment is a viable starting point. It allowed us to assess the physical supply of multiple functions simultaneously and the temporal development of supplying multiple functions. Moreover, we showed how these factors varied over diverse abiotic environmental conditions, including increased climate impacts such as sea-level rise scenarios and erosion rates. Combining a physical sand distribution process model with indicators of supplying coastal functions expands the scope of current assessments of the multifunctional potential of sand nourishment strategies for coastal climate adaptation (Brown et al., 2016; De Schipper et al., 2021; Kindeberg et al., 2023; Stronkhorst et al., 2018).

Our approach of applying a physical process-based model with indicators of coastal functions allows further assessment of sand nourishment effects on coastal multifunctionality. For instance, more detailed morphological behaviour can be integrated in future models. This includes simulating diverse storm frequencies and impacts, and foreshore sandbar dynamics, which could affect the capacity for providing multiple coastal functions simultaneously (Hanley et al., 2014; Kettler et al., 2024; Marshall et al., 2014; van Puijenbroek et al., 2017). Additional multifunctional assessment includes investigating interactions within and between wider environmental variables and coastal functions (Bakhshianlamouki et al., 2023). For instance, by adjusting aeolian transport parameters and indicator ranges, the effects of a wide range of changed abiotic conditions on coastal functions may be included, such as changed precipitation and temperature on the potential for dune vegetation to grow and bind sand, intertidal macrofauna to recolonise and visitors' recreational preferences. Also, the effects of coastal functions on the morphological potential for supplying other functions can similarly be extended to our combined model, integrating, e.g., how recreational activities by infrastructure, cars and visitors affect aeolian transport potential, intertidal macrofauna habitat quality and dune building. Moreover, by simultaneously modelling different morphological developments, indicator behaviours and diverse outcome weightings, our model allows for the integrated scenario planning that is recommended for decision-making on climate adaptation under deep uncertainty (Kwakkel et al., 2016; Lempert et al., 2003; Marchau et al., 2019).

Combining these models from a cross-shore perspective is a starting point for researching multifunctionality at landscape scale and considering spatially explicit variations in function demands. Nourishments may interact with neighbouring coastal areas, increasing erosion or deposition, affecting the functions delivered there. This calls for also identifying strategies' effects on multifunctionality at a

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landscape scale (De Schipper et al., 2021; Luijendijk et al., 2019). Our combined cross-shore model could be integrated into one with a dissipative coastal landscape scope, by regarding these profiles as adjoining sections of the longshore coast (Ferreira et al., 2024). In such sections, indicator ranges can be adjusted to local contexts, and longshore morphological, social and ecological factors can be included, such as differing sediment supply and transport, and visitor movement. As macrofauna recolonisation depends on longshore recolonisation, further studies can identify how repeated nourishment at a landscape scale affects their recolonisation and the coastal ecological system under diverse climatic impacts, even though Leewis et al. (2012) suggest that the impacts may be limited under current conditions. At a landscape scale, locality-specific demands and political priorities can be included. For instance, higher weights can be given to recreational functions for areas with high population densities nearby, weights can be adjusted to meet local juridical demands for nature conservation, or flood safety standards can be adjusted based on the vulnerability of the hinterland. Translating our cross-shore model to a landscape perspective will allow decision-makers to better align coastal function supply to locality-dependent policy goals and specific stakeholder demands and interests. This would improve the legitimacy and support for these strategies. Moreover, it would allow for a better understanding of what and how policy goals might be achieved with a certain sand budget, which improves informed decision-making on long-term coastal climate adaptation.

Overall, our findings suggest that if coastal managers aim to provide multifunctionality (de Vriend et al., 2015; Fuchs et al., 2025; Seddon, 2022), sand nourishment strategies could be the right approach, regardless of the strategy. However, if specific functions are strived for (De Schipper et al., 2021; Dolšak & Prakash, 2018), the appropriate strategy must be chosen. For instance, if more ecological functioning is required, mega-nourishment might be considered. If more recreational opportunities are desired, beach or shoreface nourishment might be considered, depending on the ecological functioning that is considered more important. Beach nourishment leads to more aeolian sand availability for dune growth and habitat for the intertidal macrofauna compared to shoreface nourishment, but also disturbs the ecological system more frequently. In addition to the considerations on the physical long-term changes, as investigated in this study, coastal managers should also consider local social and ecological demands (Manning et al., 2018; Speybroeck et al., 2006), short-term morphological dynamics (Cooke et al., 2012; Kettler et al., 2024), the social (Gopalakrishnan et al., 2017; Martinich et al., 2013), cultural (Geukes, Kettler, et al., 2024) and economic (Pendleton et al., 2012; Qiu et al., 2020) effects of nourishments, and the overall sand availability to maintain a strategy (UNEP, 2022b) in their final selection of the optimal nourishment strategy.

Conclusion

We assessed sand nourishment strategies for multifunctional climate adaptation at decadal scales by evaluating the impacts of changes in the coastal profile on the physical capacity to supply specific indicators, individual coastal functions and overall multifunctionality. Our study shows that all three main nourishment strategies can substantially provide the physical capacity for coastal multifunctionality at decadal timescales and are thus viable approaches for coastal climate adaptation, each with multifunctionality scores around 80%. We found no strong decline in the strategies' capacities to provide coastal multifunctionality as climate impacts increased. Even when comparing the lowest to the highest simulated erosion (10 vs. 70 m^3/m/yr, respectively) and sea-level rise scenarios (2 vs. 32 mm/yr), the multifunctionality scores decreased by only 4-5%. However, under all scenarios, the coastal functions varied strongly (up to >40% in one scenario), depending on the strategy. We present a robust and adaptable methodology for assessing coastal multifunctionality based on

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morphological modelling, applicable to different coastal systems. It allows for further evaluating nourishment strategies' effects on societal and ecological functions, such as economic and social impacts, consequences for decision-making and political trade-offs. Our outcomes suggest that we can regard sand nourishment for multifunctional coastal climate adaptation in the coming decades as a balancing act. They remain high-impact interventions that pressure the coastal ecological and socio-economic environment considerably, but they also allow us to create coastal landscapes. If we do so carefully and consider societal and ecological demands, these landscapes have the physical potential to fulfil the specific environmental and societal functions we desire, even in the face of increased climate change impacts.

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