Evaluating coastal multifunctionality: sand nourishment strategies at decadal timescales

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Keywords

Multifunctionality; sand nourishment; climate 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, as they may increase flood safety and mitigate 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 aimed to identify the effects of beach, shoreface and mega-nourishment strategies on coastal multifunctionality using a systems-based approach. We identified indicators for recreational, ecological and flood safety functions through a structured literature review, and integrated these 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, and calculated the extent to which coastal functions and multifunctionality were supplied over six decades. We found that all three nourishment strategies could supply coastal multifunctionality to a high extent, although the drivers of this potential differed per strategy. These findings imply that sand nourishment strategies are viable approaches for multifunctional coastal climate adaption in the coming decades, that require prioritising specific coastal features and functions. While sand nourishment strategies remain high-impact interventions, they also allow for creating coastal landscapes that may not only prevent floods but also enhance the environmental and societal functions and features we desire of sandy shores worldwide.

1. Introduction

There is a strong societal need to understand the impacts of sand nourishment as coastal climate adaptation globally. 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 it can also increase opportunities for recreation, the size and quality of ecological habitats, and support dune systems through aeolian transport (de Vriend et al., 2015; Hanson et al., 2002). Thereby, sand nourishments can simultaneously provide flood protection to increased sea level rise and support recreational, economic and ecological benefits, delivering 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). These variations affect the coastal profile, leading to different impacts on coastal ecology, recreation and flood safety. For instance, compared to more frequent nourishments, larger nourishments may benefit or 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), but the recreational potential of 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 timescales 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 decisions to be made between these diverse effects nourishments have on coastal functions (Cooke et al., 2012; De Schipper et al., 2021; Singhvi et al., 2022).

However, it remains unclear how changes in the cross-shore profile of sandy shores following the different nourishment strategies affect their potential to deliver multifunctionality at decadal timescales. 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 quantitively 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 aims to identify the main nourishment strategies' potential for delivering multifunctionality on sandy shores at decadal timescales. We, therefore, identify the morphological responses of sandy coasts to the application of the main nourishment strategies and the effects of these morphological responses under diverse sea level rise scenarios and erosion rates on the supply of coastal functions and the subsequent multifunctionality of sandy shores.

2. Methods

We assessed the potential to deliver multifunctionality of the main nourishment strategies at decadal timescales 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 timescales. To simulate dissipative sandy shore 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. We therefore did not model 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 decadal well-documented nourishing history, including yearly altimetric and bathymetric profile data available for model calibration and validation. Per simulation, the model calculates 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. The model was tested using three Dutch case study locations, accurately simulating decadal changes in beach width, shoreline position and coastal volume under different nourishment strategies (see Kettler et al. (2024) for the outcomes in detail).

We simulated three main nourishment strategies: beach, shoreface and mega-nourishment. When simulating a shoreface nourishment strategy, 450 m^3 of sand per meter of coastline sand was placed 4 meters seaward of the current intertidal waterline for each nourishment. In a beach nourishment strategy, 200 m^3/m sand was placed 2 meters landward from this waterline. For mega-nourishment, 2000 m^3/m sand was placed 7 meters landward from this waterline. 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 overlapped the initial coastline in a landward direction, a new nourishment with the same volume was placed. We assumed that 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. We applied a global mean sea level rise rate of previous decades (2 mm per year), the current rate (4 mm/yr), rates also likely expected in the coming decades (8, 16 mm/yr) and a potential but low likelihood rate (32 mm/yr) (IPCC, 2022c). 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 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).

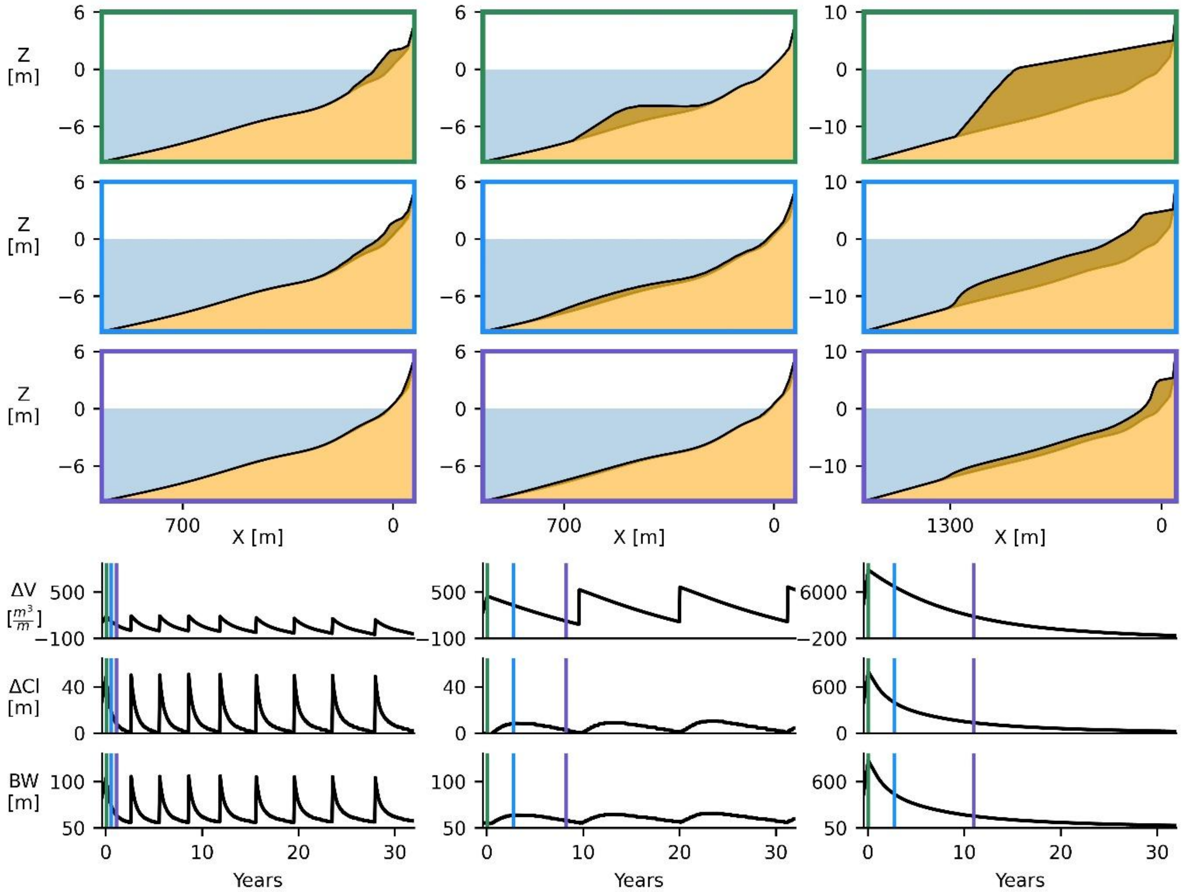


Fig. 1. Visualisation of simulating coastal profile development following beach, shoreface and mega-nourishment strategies at decadal timescales with the Crocodile model by Kettler et al. (2024). The model calculates the instantaneous bed level (Z) per horizontal coordinate (x) and timestep, and returns per timestep the change in coastal profile volume (ΔV) (in the vertically constrained section between -20m NAP and the dune top per meter coastline), the change of the coastline position (ΔCl) (as the average, intertidal coastline) and the beach width (BW) (as the horizontal distance between the coastline position and the dune foot at +3m 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 that reflects the concept's status, cause or outcome (Geukes et al., 2024; Hinkel, 2011). In this study, we define indicators based on model outcomes to estimate the physical supply of the coastal functions and their multifunctionality.

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 33 papers that followed, we screened their titles and abstracts, excluding 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 led to 24 indicators, of which we selected those that could credibly be simulated at decadal timescales with Crocodile. See Appendix A for the step-by-step referenced literature review results.

We combined indicators that presented overlapping information into indicators that reflect unique information. Following these steps, we identified seven indicators for the physical potential to supply three functions: recreation, ecology and flood safety (Table 2). Additionally, 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, as this is central to the safety sand nourishment strategies can provide coastal climate adaptation (UNEP, 2022). These indicators can be determined from five model outcomes of which we calculated the status per timestep with Crocodile (Fig. 2).

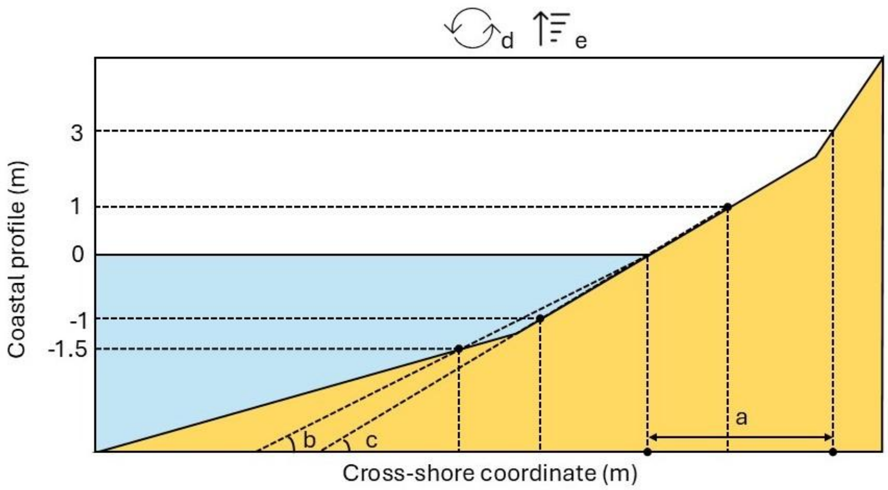


Fig. 2. Visualization of the model outcomes used for indicating coastal function supply: a) beach width, b) beach face angle, c) intertidal area angle, d) nourishment frequency, and e) total volume nourished per meter coastline.

The status of an indicator can relate to the supply of a coastal function in different ways (Hinkel, 2011; Manning et al., 2018). We applied 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 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; (3) a 'threshold-plus', where before or after a certain threshold the benefit increases linearly. 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. For each identified indicator, we studied additional literature to identify the most appropriate relationship and, if applicable, the threshold value or values. 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 1

Relationship types between an indicator status and coastal function supply. The first three types were defined by Manning et al. (2018).

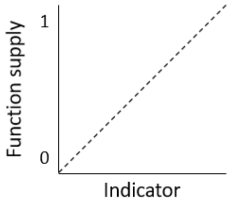
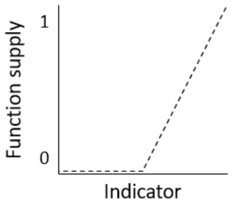
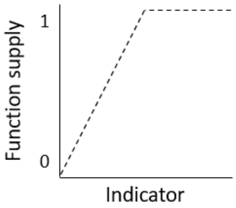
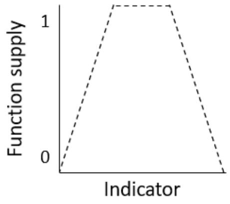
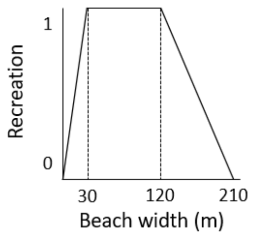
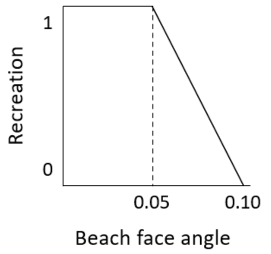
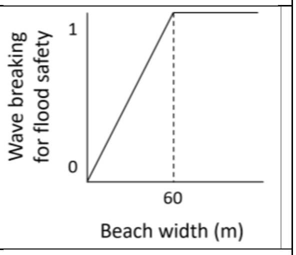
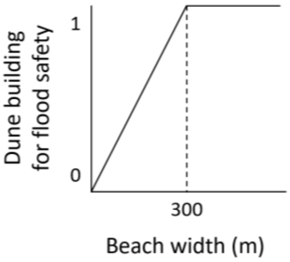
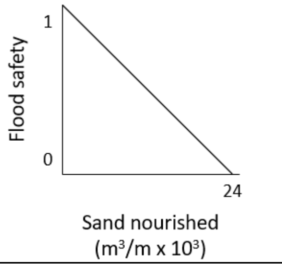
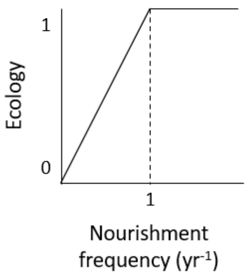
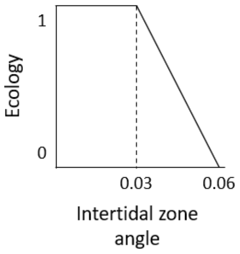
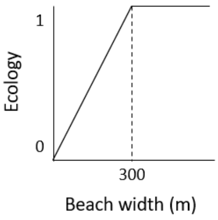
Linear	Threshold	Threshold-plus	Combined threshold-plus
			

Table 2

Description and relationship of functions of sandy shores and their indicators that can be calculated per timestep based on model outcomes of Crocodile, as identified in our structured literature review. See Appendix A for their step-by-step referenced identification.

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 (+3m 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 beyond which the recreationists are at a too-large distance from the seashore. The ideal width is highly locality-dependent and often depends on the initial beach width.	
	Beach face angle. Slope of high waterline to 1.5m depth	0-5%	The beach face's slope indicates the beach's safety for sunbathing and swimming. Below the threshold, the safety is optimal, after which it decreases linearly.	
Flood safety	Beach width for wave breaking. The width between the average waterline and the dune foot	> Initial beach width	By reducing wave energy, at least maintaining the current beach width delivers substantial flood protection benefits. The optimal range of this indicator depends on local conditions.	
	Beach width for dune building. The width between the average waterline and the dune foot	> 300 meters	The beach can offer aeolian sand transport to allow for dune building, which protects against high water levels and storm surges. Beach width and dune volume generally positively correlate up to 300 meters, after which sufficient sand is available for aeolian transport.	
	Total volume sand nourished	< 24 * 10^3 m^3/m sand	The volume nourished demonstrates the feasibility and efficiency of sand use, which are central to the flood safety of the coast. 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.	

Ecology	Nourishment frequency	0-1 nourishment per year	The intertidal macroinvertebrates are killed by sand nourishment. Recolonization can start immediately after nourishment and is generally back to initial abundance levels after one year.	
	Intertidal zone angle. The angle of the high waterline (+1m) to the low waterline (-1m)	0-3%	The intertidal zone slope indicates the suitability of the local intertidal habitat for intertidal macrofauna. The intertidal macrofauna indicates the biodiversity benefits of the beach as it is key in the cycling of nutrients and organic content from the sea to the rest of the coastal ecosystem. Dissipative slopes are generally considered optimal, after which the favourability of the intertidal area decreases.	
	Beach width for dune building. The width between the average waterline and the dune foot (NAP +3)	> 300 meters	The beach width allows for aeolian transport, for marram grass growth. This can bind sand, which creates dune volume, habitat and further dune biodiversity benefits. 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.	

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 for cross-shore profiles corresponding to the different nourishment strategies, sea level rise and erosion per timestep. 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 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 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 coastal multifunctionality was supplied, which we refer to as the multifunctionality scores. Here, we assumed 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.

We analysed the indicators temporally but assessed the functions and multifunctionality scores as averages over time. As the time between the status of an indicator and its benefit to a function varies per indicator, an analysis of these scores per timestep would not credibly show what benefits they could bring, limiting 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*

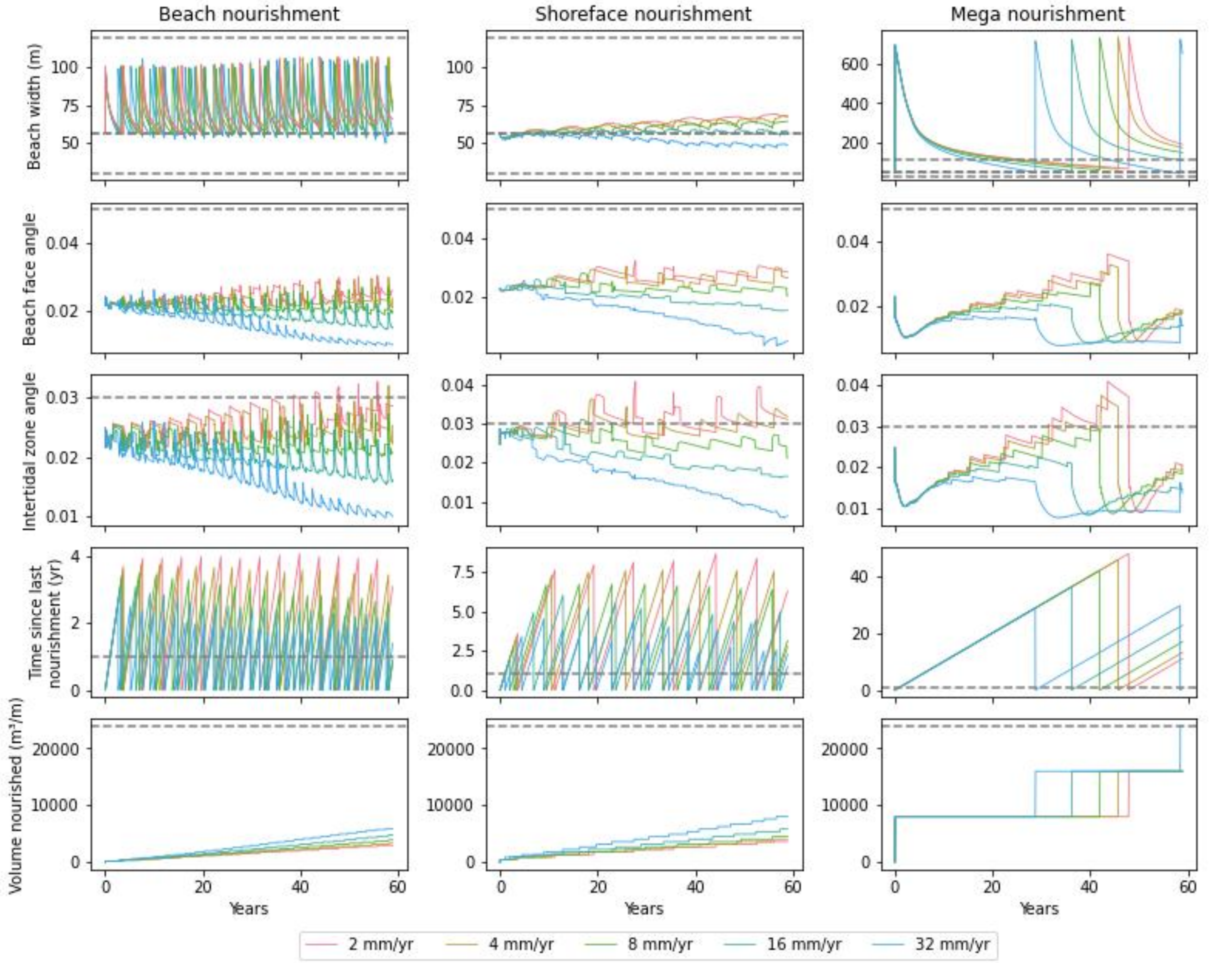


Fig. 3. Indicator values of coastal functions over time per nourishment strategy and rate of sea level rise with an erosion rate of 40 m^3/m/yr. Horizontally, the subplot columns show the three nourishment strategies. Vertically, each row shows an indicator's development. Colours indicate simulation 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.

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, 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 meters is never reached.

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 nourishments 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 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 depending 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

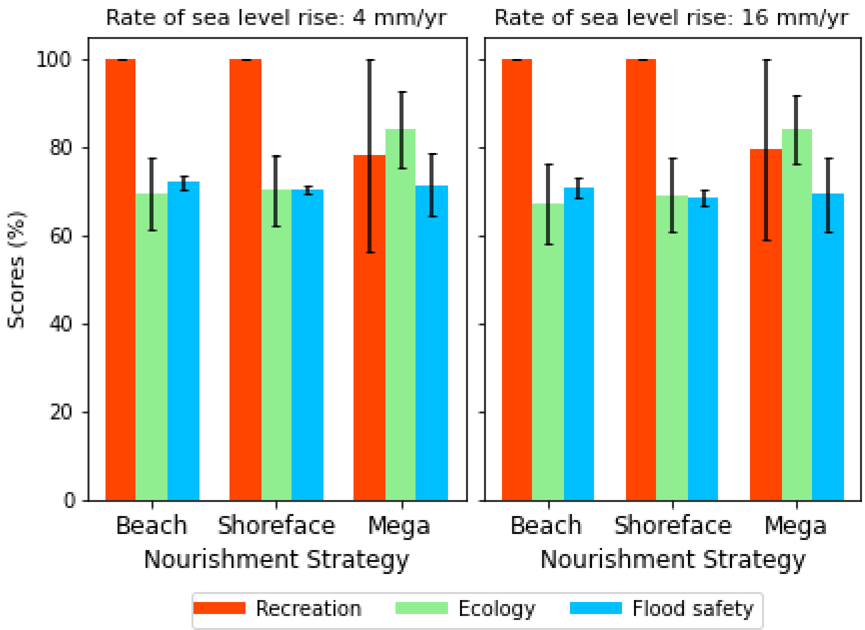


Fig. 4. The extent of function supply per nourishment strategy for two sea-level rise scenarios, as scores in percentages. Each column shows the outcomes per sea level rise scenario. The bar groups show the outcomes per nourishment strategy. Bar colours show the outcomes per function. These scores were calculated for an 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 equally supply coastal functions, providing optimal recreational supply, whereas mega-nourishments better supply ecological functions (Fig. 4, Appendix C). Beach and shoreface nourishments optimally provide the physical requirements for recreational use. Mega-nourishments score lower and more volatile supplying recreational coastal functions. However, compared to beach and shoreface nourishments, mega-nourishments score relatively high on providing the potential for ecological benefits. All three strategies supply flood safety almost equally well.

Beach and shoreface nourishment strategies score almost equal 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. Recreational scores remain similar under all sea level rise scenarios. Generally, ecology scores decrease as sea level rise increases. However, at higher erosion rates, shoreface and mega-nourishment's scores on ecology generally rise slightly with increased sea level rise scenarios, due to flattening the profile and increasing beach width by increased nourishment. Flood safety scores generally decrease slightly as sea level rise increases. 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*

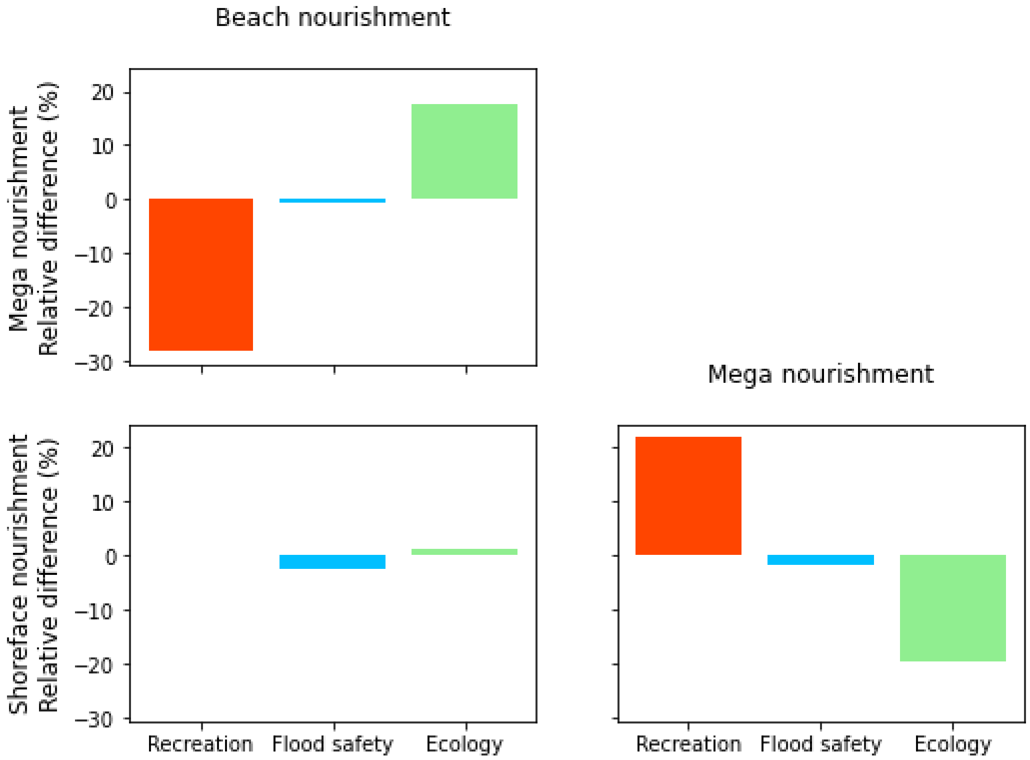


Fig. 5. Relative difference in the potential to supply coastal functions between nourishment strategies. The figure shows the comparison between the contributions of an individual function to the multifunctionality scores. The scores are calculated for a sea level rise rate of 4 mm/yr and averaged over 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 more-or-less equal, the functions they benefit differ.

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 28.0% lower recreation scores, 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% increased recreation scores, roughly equal flood safety scores (-1.70%), but 19.6% lower ecology scores. So, even though multifunctionality scores are similar, the potential benefits to the functions that drive these scores differ considerably.

4. Discussion

4.1. The extent to which sand nourishment strategies can supply coastal multifunctionality is high and robust for diverse sea level rise and erosion scenarios. Sand nourishment strategies may be viable multifunctional coastal climate adaptation in the coming decades.

Sand nourishments can physically supply coastal multifunctionality to a high extent. This potential is generally robust over sea level rise scenarios and erosion rates (Appendix B and C), to adjusting the relationship between indicators and functions supplied (Appendix D for this sensitivity analysis), and adjusting the starting conditions towards more dissipative profiles. They do, however, decrease when we set the initial conditions to be much steeper (Appendix E), which is in line with the general trend that more dissipative beaches allow for more coastal functions.

The three strategies' high supply of coastal multifunctionality implies that sand nourishments may be a viable and multifunctional approach towards coastal climate adaptation of sandy shores. The robustness furthermore implies that the results of this model, which was calibrated to a Dutch coast but displays a general dissipative beach and for which we utilised generally applicable indicators, may be generalizable to other dissipative sandy shores. However, the outcomes were relatively sensitive to adjusting the optimal range for beach width for recreation, for which we found diverse locality-specific values (Appendix D). Thus, in assessing sand nourishments at other localities, optimal indicator ranges for beach width may be adjusted accordingly.

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 governance and management structures required. 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 criterium 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 potential 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.

4.2. Even though the multifunctionality scores are similar and high, the desirability of distinct nourishment strategies differ as the drivers of this multifunctionality differ. Conflicting outcomes on different interests and functions between nourishment strategies must therefore still be addressed.

Despite the similar multifunctionality outcomes for diverse strategies, sea level rise scenarios and erosion rates, the underlying functions are strongly divergent. Over all simulated sea level rise scenarios and erosion rates, beach and shoreface nourishments generally allowed for more recreational potential, while mega-nourishments lead 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 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. These different perspectives can be integrated into a multicriteria decision-making framework (Ruangpan et al., 2021). 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). Such research 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. 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 promoted 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 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 physical requirements to deliver multiple benefits simultaneously at decadal timescales by combining indicators with a cross-shore sand distribution process model. 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; Kindeberg et al., 2023; Stronkhorst et al., 2018).

Our approach of applying a physical process-based model with indicators of coastal functions can be considered for further assessment of sand nourishment effects on coastal multifunctionality. This 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.

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. 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, as Ferreira et al. (2024) call for. In such sections, indicator ranges can be adjusted to local contexts, and longshore morphological, social and ecological factors can be included, such as sediment transport, macrofauna recolonisation and visitor movement. Here, locality-specific demands can be taken into account. For instance, at a landscape scale, higher weights can be given to recreational functions for areas with high population densities nearby, weights can be affected 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.

Conclusion

We assessed sand nourishment strategies for multifunctional climate adaptation at decadal scales by evaluating the impacts of changes in the coastal profile on overall multifunctionality, individual coastal functions and specific indicators. Our study shows that all three main nourishment strategies can to a high extent supply coastal multifunctionality at decadal timescales and are thus viable approaches for coastal climate adaptation. However, the coastal functions supplied and their drivers differ depending on the strategy. Our outcomes suggest that we can regard sand nourishments 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 potential to fulfil the environmental and societal functions we desire, even in the face of increased climate change impacts.

Acknowledgements

This research is an output of the Dutch Research Council (NWO) research project ‘C-SCAPE: Sandy strategies for sustainable coastal climate change adaptation’ (grant number 17595).

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