A transdisciplinary research initiative on coastal protection and nature conservation in Sankt Peter Ording, North Sea: Is it a living lab?

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Summary

Under the pressure of global change coastal management increasingly requires interdisciplinary applied research combining the interests of coastal protection and nature conservation. In this, transdisciplinary collaboration is a key element of successful research. In the recent past the concept of transdisciplinary living labs has been put forward in applied research design and is nowadays embedded in many funding schemes and project initiatives. As the concept is both attractive and challenging, and as the wording has undergone various (mis-)interpretations, we discuss its applicability to typical coastal research initiatives.

Based on the transdisciplinary project Sand Coast Sankt Peter-Ording in the German Wadden Sea, this study explains the conceptual approach and communication pathways as well as exemplary research results. The project is compared to theoretical concepts of living labs, while discrepancies and challenges are discussed. We identify three main issues: Time restriction of limited funding periods, academic requirements of the science stakeholders, and the relevance of the project for the stakeholders from practice and their active collaboration.

It is concluded that typical transdisciplinary coastal research projects should contain main elements of living lab concepts. However, it must be understood that not all aspects of living labs can be met because of limited funds and project durations. Nevertheless, transdisciplinary projects can be successful if different stakeholders are actively involved and contributing, are satisfied by sustainable outcome, including the science stakeholders.

Keywords

Wadden Sea, Coastal protection, transdisciplinary, living lab, stakeholder, actors



Zusammenfassung

Unter dem Druck des globalen Wandels erfordert das Küstenmanagement zunehmend interdisziplinäre angewandte Forschung, die insbesondere Interessen des Küstenschutzes und des Naturschutzes miteinander verbindet. Dabei ist transdisziplinäre Zusammenarbeit ein Schlüsselelement für erfolgreiche Forschung. In jüngster Vergangenheit wurde das Konzept transdisziplinärer Reallabore entwickelt und ist heute in vielen Förderprogrammen und Projektinitiativen verankert. Da das Konzept sowohl attraktiv als auch herausfordernd ist und der Begriff verschiedenen (Fehl-)Interpretationen unterworfen war, diskutieren wir seine Anwendbarkeit auf typische Küstenforschungsinitiativen.

Anhand des transdisziplinären Projekts Sandküste Sankt Peter-Ording im deutschen Wattenmeer erläutert diese Studie den konzeptionellen Ansatz und Kommunikationswege sowie beispielhafte Forschungsergebnisse. Das Projekt wird mit theoretischen Konzepten von Living Labs verglichen, wobei Diskrepanzen und Herausforderungen diskutiert werden. Wir identifizieren drei Hauptprobleme: zeitliche Beschränkungen durch begrenzte Förderzeiträume, akademische Anforderungen der wissenschaftlichen Akteure und die Relevanz des Projekts für die Akteure aus der Praxis und deren aktive Mitarbeit.

Es wird der Schluss gezogen, dass typische transdisziplinäre Küstenforschungsprojekte wesentliche Elemente von Living-Lab-Konzepten enthalten sollten. Es muss jedoch berücksichtigt werden, dass aufgrund begrenzter Mittel und Projektlaufzeiten nicht alle Aspekte von Living Labs erfüllt werden können. Dennoch können transdisziplinäre Projekte erfolgreich sein, wenn verschiedene Akteure aktiv beteiligt sind und einen Beitrag leisten und mit den nachhaltigen Ergebnissen zufrieden sind, einschließlich der wissenschaftlichen Akteure.

Schlagwörter

Wattenmeer, Küstenschutz, transdisziplinär, Reallabor, Interessengruppen, Akteure

1 Introduction

The intertidal Wadden Sea in the South Eastern North Sea is a designated UNESCO World Heritage Site and subjected to multiple pressures: Pollution, sea level rise, increasing coastal protection needs and growing use by tourism, fisheries, and many others. Sustainable management must consider the multitude of landforms, valuable ecosystems, and uses, e.g. by integrated coastal protection (Winter 2018, Schoonees et al. 2019).

The beach and dune systems of Sankt Peter-Ording (SPO) in the German Wadden Sea are an example of an open coastline, featuring extensive strand plains, tidal channels, shore-parallel coastal dunes, salt marshes, lagoons and a dike line against flooding of the hinter-land (Figure 1). Where the dike is absent, a 1.2 km long natural dune system provides the ecosystem service of coastal protection. This is unique for the German mainland North-Sea coast, which otherwise is almost fully protected by artificial coastal defense dikes (Figure 2). SPO is a hotspot for biodiversity due to its various coastal habitats. The beach, dunes and salt marshes with their special flora and fauna are important habitats for migratory birds, amphibians, reptiles, and many endangered insect and invertebrate species. Increasing settlement and tourism have transformed the coast into an urban setting in the past century; however with attempts to keep a natural appearance along the coast. Since the building of the artificial dike line along the coast the natural quality of the dunes on the inland side has deteriorated, particularly due to the reduced influence of natural forces. This

is along the spread of non-native, invasive species, which are gradually displacing the native plants and animals (Weber et al. 2023).

Sea level rise and storm floods are the greatest threats to the beach and dune system of SPO (Santamaria-Aguilar et al. 2017). Currently the beach in the central area is eroding by around 8 meters per year (MELUR 2022), but this is expected to increase in the future due to climate change (Lee et al. 2023, Horton et al. 2020). The beach, foredunes, dunes, and the salt marshes behind them could shrink or disappear in the medium term. The loss of the barrier effect of these habitats would also further increase the need for coastal protection in the long term (Weber et al. 2023). This situation calls for holistic system understanding, comprising an interdisciplinary assessment of possible future developments, as well as research on adaptive mitigation pathways.

Sustainable solutions require transdisciplinary research approaches, i.e., the discourse of academic research groups with the society in the form of residents, decision-makers, authorities and other peer groups. In many contexts only the latter are called stakeholders, neglecting the fact that research itself also constitutes a stake, thus the scientific stakeholders having a fundamental interest in system understanding. It shall be noted that ignorance about this can cause conflicts in applied research projects.

The interaction of scientific actors with other stakeholders can happen on a large bandwidth: From total isolation of fundamental sciences (ivory tower), to information provider (knowledge transfer), to stakeholder orientation (transdisciplinary discourse), to stakeholder driven (contracted) research. In many contexts the transdisciplinary, stakeholder-oriented research is preferable. Since the early 2010s, such research interactions have more formally and methodologically been framed as "living labs" (Galbraith et al. 2008) or "real-world laboratories" (Schäpke et al. 2015). Despite a large body of literature on the subject and several examples from various disciplines, and despite the increasing calls for this approach in applied research funding (BMWi 2019), the realisation is often a matter of confusion or even abuse, probably because no consensus exists on procedures and definitions. This especially holds for coastal living labs, i.e., research projects that aim at system understanding and the integration of transdisciplinary approaches in complex and valuable ecosystems.

Early living labs had evolved around the need for a research infrastructure that allows observing the interaction of human beings with technological, logistical or organisational change. From small to large, we find examples of living labs that investigate distributed computing facilities in people's homes (Kidd et al. 1999), assess and evaluate the choice of household products and services (Liedtke et al. 2012), or the response of urban contexts with respect to sustainability (Bulkeley et al. 2019). Others have considered aspects of change in urban heating technology (Guo et al. 2020), the response of the marine ecology on human coastal interventions (Lai et al. 2016), and the governance of the ocean and blue economy (Kluger and Bartzke 2020, Franke et al. 2023)

In a study on sustainability science, Wanner et al. (2018) define living labs as a cyclical research method that "aims to contribute to local action for sustainable development and the empowerment of change agents". Key criteria to the definition of living labs are, inter alia, (1) transdisciplinarity, (2) participation, (3) co-creation, (4) active engagement on societal change or real-world experimentation, and (5) a normative standpoint towards sustainable development. The study presents the practical work in living labs in a cyclical manner,

in which co-design, co-production and co-evaluation cycles back and between science and practice.

Schäpke et al. (2018) compared about 14 projects that self-identify as real-world laboratories in that they (a) contribute to transformation, take (b) experiments as core research method as well as (c) see transdisciplinarity as the core research mode, (d) ask for long-term orientation, scalability and transferability of results; and, (e) make learning and reflexivity an important aim of their research method. Schäpke et al. (2018) outline semantical similarities and differences between real-world laboratories, (sustainable) living labs, (urban) transitional labs and transformation labs.

While the literature on living labs knows the notion of spatial structure, i.e., from household- to city-scale, less is known about different spatial scopes, shapes or contexts in which living labs might play out their specific strength in facilitating a holistic view on sustainability challenges. Living labs in coastal settings have addressed the sustainability challenge, driven by climate change (Clarke et al. 2022, Simpson et al. 2021), sea level rise (Calafat et al. 2022) and coastal squeeze (Lithgow et al. 2019). Kempa et al. (2023) report on a decentral living lab at the German North Sea coast. In that, multiple locations were established, with the aim to foster transferability of their results to respective coastal contexts, and to reduce the spatial inhomogeneity which often renders a sustainable transfer difficult.

In the context of managing coastal environments, changes in design and maintenance practices may show effects only over long periods. Adaptive approaches thus must consider short-term interventions and their immediate effects, but also their long-term effects. Typically research activities in coastal environments are embedded in temporary funding schemes, making long term adaptive and cyclic approaches difficult to realise.

This article presents a typical transdisciplinary coastal research project and discusses the question how much of a living lab concept is included in that approach. We aim to understand the specific challenges and differences of this stakeholder-driven initiative compared to literature's understanding of living labs in general. We reflect on communication pathways in the co-design and co-development stage as well as the corresponding, exemplary research results. It reflects both, the desire to answer practical questions posed at the grass root level in Sankt Peter-Ording, as well as the development of fundamental system understanding and analyses of critical success factors for this joint research project.

We describe three examples for applied research and transdisciplinary discourse. The first with a focus on scientific investigations of the morphodynamics of the coastal system (case 1), the second on engineering solutions (case 2), and the third case is an active intervention in the field in terms of dune restoration and forest conversion.

2 The project

The transdisciplinary project "Sand Coast Sankt Peter-Ording" (SCSPO) aims at the preservation of coastal habitats of SPO, a well-known but understudied beach and dune system in the German Wadden Sea (Hofstede 1997, 2003). The aims are to obtain fundamental system understanding of the morphodynamic characteristics of the beach-dune system, gain knowledge for adapting the coast to climate change and the accelerated sea level rise in the future, and to improve the environmental conditions of this natural area through extensive nature conservation and forest conversion measures. Between 2020 and 2026,

the project investigates the geomorphological development of the beach and develops nature-adapted coastal protection measures. The project actively restores dune ecosystems and supports the careful conversion of a coniferous beach forest into a sustainable "climate forest". The work is accompanied by a comprehensive range of participation and event offers for the general public and multiple stakeholders.

This transdisciplinary project was jointly implemented by the World Wide Fund for Nature (WWF) Germany, the Schutzstation Wattenmeer e.V., the local dike board (Deichund Hauptsielverband Eiderstedt), and working groups of Technische Universität Braunschweig and Kiel University. It is supported by stakeholders of the responsible state and district authorities, the municipality of Sankt Peter-Ording, and a network of citizens, volunteers, policy-makers and other partners. Participation takes place, for example, in handson nature conservation activities in the field, guided tours, multiple annual workshops and expert working group meetings.

An important element of the transdisciplinary set-up of the project are specialist groups. These small and active groups are the core exchange platform for presenting and discussing research concepts and results between the core team, authorities and the municipality.

3 Study area

The North Frisian Wadden Sea presents a dynamic coastal environment and is characterized by its unique geomorphology of tidal channels, tidal flats and barrier islands (Common Wadden Sea Secretariat 2024). The municipality SPO is located at the western end of the Eiderstedt peninsula on the west coast of Schleswig-Holstein, Germany (Figure 1). Even though the community includes only about 4,000 permanent residents, Sankt Peter-Ording is one of the most important tourist destinations in Germany with over 900,000 guests per year (as of 2021). The main reason for its high tourist value is the diverse natural coastal landscape, in particular the large sandy beach, which is unique in its shape and size on the mainland coast of the Wadden Sea.

The beach and dune system has formed by sediment deposits of the adjacent Wadden Sea only since the beginning of the 20th century (Figure 2). After merging of formerly two individual sandbanks, the beach currently has a total length of over 12 km and a width of up to two kilometers. Protected by the beach and a dune fringe, over 780 hectares of natural salt marshes have developed. A foredune chain with a height of up to 11 meters above mean sea level (MSL) has emerged since 1970. In its protection, several brackish beach lakes have formed (Mehrtens et al. 2023).

Further inland, around 70 hectares of older dune sites (mainly grey and brown dunes) as well as around 100 hectares of dune forest still exist in between the municipal areas of Sankt Peter-Ording. Similar to all other mainland German North Sea coasts these are separated from the foreshore by a dike except for a stretch of approx. 1.2 km. In this section, the dune system "Maleens Knoll" with a height up to 16 m MSL takes on the function of a dike and thus forms a rare natural protection for the hinterland from flooding. The dunes and dune forest areas on the inside of the dike are protected by Fauna Flora Habitats Directive (EU 1992) as "Dünen Sankt Peter", while the areas seawards of the dike belong to the "Schleswig-Holstein Wadden Sea" national park and the UNESCO World Natural Heritage site (Weber et al. 2023).

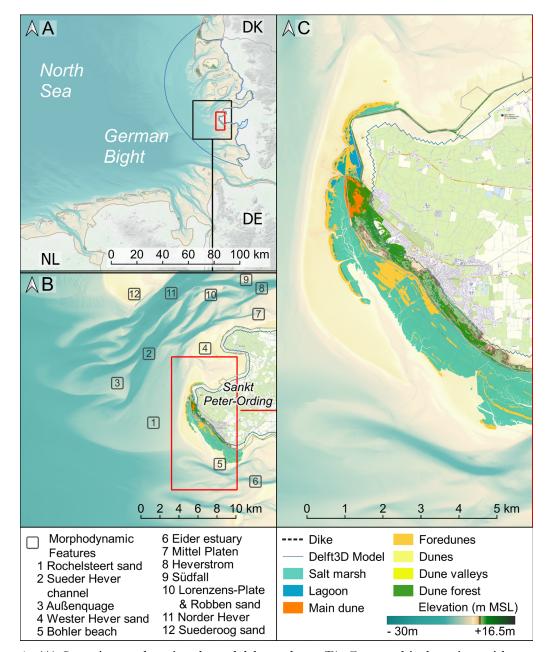


Figure 1: (A) Location and regional model boundary. (B) Geographical setting with associated features mentioned in the text. (C) Coastal area with different zone types. Background topographical data is based on public data provided by EMODnet (EMODnet Bathymetry Consortium) and the Federal Agency for Cartography and Geodesy of Germany (BGK 2024).



Figure 2: Cross shore schematic landscape of Sankt Peter-Ording - from left to right: North Sea and beach, outer dune chain, salt marshes with tidal creeks, dike, dunes inside the dike, forest and village. (© Rabe Landschaften).

Despite the outstanding value of the natural environment, the coastline of SPO is highly influenced by human development such as buildings, roads, dikes, tourism and recreation. The ecological quality of the inland dunes has deteriorated, particularly due to the reduced

influence of natural forces (sand drift, waves, flooding). In addition, there are other anthropogenic interventions in the coastal landscape such as reforestation, constructions, drainage, amongst others. This has favoured the spread of non-native conifers and other invasive species, which are gradually displacing the native plants and animals. As a consequence, we see a significantly changed ecology in the coastal habitats, especially the open dune habitats behind the dike due to the lack of natural dynamics like aeolian sand transport, and sporadic flooding.

4 Case studies

The transdisciplinary project is structured into different work packages. Here, three of these shall be presented in more detail. The group working on the first case is a science-oriented academic research group (CAU IfG). The scientific questions at the beginning of the project are depicted, and the project methods and most important results are presented in brief. Expectations of different stakeholders are listed. Communication pathways are explained, especially how the discrepancy between expectations and project content was communicated and agreed upon.

The second case is about a series of physical laboratory experiments performed to analyse sand dune stability against wave erosion, determining the dune systems' protection potential against storm surge impacts. The group conducting the research experiments has a coastal engineering background (LWI TU BS). Aims and tasks are described in brief, followed by a synopsis of the extensive research results. Physical experiment setups were discussed and co-developed with stakeholders. Results were co-analysed for deriving potential future adaptation strategies.

The third case covers direct measures on dune restoration and forest conversion implemented by the local dike board and NGOs. It is linked to the previous cases in as the state of nature is closely linked to the geomorphological situation and boundary conditions of the foreshore-beach-dune system (case 1), but also rely on nature-based coastal protection measures (case 2).

4.1 Case 1: Morphodynamics and transport pathways

The first subproject works on system understanding of the local barrier-sand beach morphodynamics, and its sedimentary connectivity within the North-Frisian Wadden Sea in order to evaluate its stability and future developments. The coastline is constantly being reshaped by the interaction of hydrological, geological and biological processes, especially under the influence of major storms. Processes like wave action, tides and winds produce complex sediment transport pathways when interacting with the different morphological units like channels, tidal flats, and barrier islands (Herrling and Winter 2018). While the Dutch and East Frisian tidal flats and channel systems have been very well studied, the sediment pathways in the North Frisian Wadden Sea so far have not received the same attention in scientific analyses.

4.1.1 Co-Design

At the beginning of the project, stakeholders and project partners had straightforward questions and expressed very clear expectations: The coastal defense authorities wanted to know what kind of natural protection potential was offered by the beach system and if the beach was and will be self-nourished naturally by near-shore sand bars in the future. Also, the municipality of Sankt Peter-Ording was concerned about the future ecosystem services of the beach, since it is a tourism hotspot. The nature conservationists focused on whether the beach could sustain its role in sheltering developing habitats and biodiversity. Amidst these stakeholder interests, there was a consensus on the need for predictions regarding future morphological changes of the beach.

While the imposed requests seem straightforward, the response however is complicated due to the non-linearity of natural systems and restrictions of numerical modelling (Vriend et al. 1993). It was explained that predictions of long-term coastal morphological development are not only limited due to shortcomings of numerical modelling systems and computational resources, but predominantly attributed to the uncertainty of future boundary conditions (Winter et al. 2006). While models certainly can simulate any hypothetical predictive set-up, the integrity of those results remains questionable.

An operational process-based numerical model can offer relevant insights into the processes of morphological development and quantify factors affecting it. Additionally, the model provides validated conditions (water levels, waves and winds) and sediment distribution maps for the nearshore area of Sankt Peter-Ording, which can then be utilized for the assessment of coastal protection, or for the open boundary forcing of physical flume models for testing dune stability. Some fundamental scientific topics of transdisciplinary relevance were agreed upon:

- Sediment transport pathways in the North Frisian Wadden Sea
- The effects of different forcing parameters on sediment transport
- A qualitative/quantitative understanding of the role of storms

4.1.2 Methods and Results

A process-based model simulating the effects of winds, waves and tides on coastal morphodynamics was set up using the Delft3D modelling system (Deltares 2024a, Lesser et al. 2004, Deltares 2024b). The model is driven by water levels, waves and winds prescribed at the open boundaries and extracted from the EasyGSH and COSMO (Bollmeyer et al. 2015, Hagen et al. 2020, 2021, Soares et al., 2024a). The selection of a representative period needs to take into consideration the variability of waves and wind forcing conditions for long time periods. The identified representative period (April 2003–March 2004) was found to show very good similarity to the total reference period (1975–2019) in terms of directional and speed class-based distribution.

For assessing the impact of storms on sediment transport pathways, three directionally distinctive high-energy events were selected for further simulations. These include Storm Tilo (November 8–10, 2007), representing a North Western event; Storm Anatol (December 3–5, 1999), indicative of a Western event; and a significant South Western event (February 4–6, 2011).

The project also included analyses of historical data (documents, nautical charts, and land surveys), and field surveys on the sediment distribution and morphology, which shall not be covered in this publication, but which formed a conceptual understanding of sediment transport pathways in the region, which was then discussed based on the numerical model results (Soares et al. 2024b).

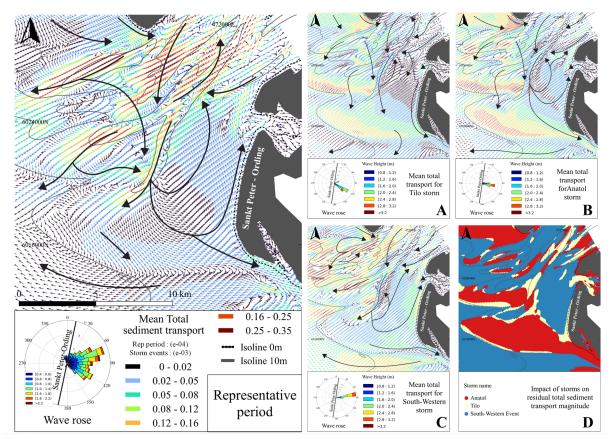


Figure 3 Left: Schematic residual sediment transport pathways under representative conditions in the nearshore region of Sankt Peter-Ording. Right (A, B, C): Transport pathways for directionally distinctive storms. D) Plot highlighting the dominant impact of different storms on the magnitude of sediment transport in different regions in the nearshore region of Sankt Peter-Ording.

An overview of sediment pathways in the North Frisian Wadden Sea computed for the representative period can be schematised as 1) A southward wave driven movement of sediments along the barrier island chain 2) Flood directed northward movement of sediment in the upper channels and inner basins, 4) The channel convergence pattern with prevalence in flood-oriented movement. 5) In the foreshore of every barrier island characteristic residual divergence patterns with associated zones of low transport magnitude were identified (Figure 3).

Simulations show that sediment transport towards the beach can arrive either from the southward longshore transport along the barrier islands or through the Heverstrom tidal channel. Through complex pathways and processes sediments from the two sources reach the Süderhever channel which then acts as a residual point source for sediments arriving to the beach over the Rochelsteert sand. A residual divergence pattern emerges over the Rochelsteert sand with one northward transport component and one southward, leaving a zone of low transport magnitude at the point of divergence.

Different storm conditions impact to different parts of the beach (Figure 3D), with a Western storm ("Anatol" 1999, Figure 3B) having a larger impact on the south end of the beach, a North-Western storm ("Tilo" 2007, Figure 3A) having a larger impact on the southern and central parts of the beach and the south-western storm having a greater impact on the northern Rochelsteert sand and the northern part of the beach.

4.1.3 Implications

In practice, numerical model simulations are often expected or perceived as to mirror reality, when in fact they are just realisations of the model's inherent parametrizations and assumptions to address data scarcity, gaps in system understanding, reduction of complexity, and computational limitations. In addition to the modelling approach and realisation, the goodness of a model is largely dependent on the accuracy of its forcing parameters and initial conditions, which are often spatially and temporally constrained. This is especially true for predictive simulations, as future forcing conditions obviously are unknown, necessitating alternative methods that may increase error likelihood.

Table 1: Expectations of non-scientific stakeholders versus project outcomes for case 1.

Expectations	Own aims	Delivered	Limitations
Future morphological	Representativity of	Fundamental system	Computational time
projection/predic-	boundary conditions	understanding	
tions			Model limitations
	Fundamental system	Communication on	
Quantitative assess-	understanding on	model feasibility	Scientific ethics
ments	sediment transport		
	pathways	Sediment distribution	
		maps	
	Extreme event im-		
	pact to coastal sys-	Sediment pathways	
	tems	maps	
		Extreme event	
		boundary conditions	
		to project partners	

In this project it was demonstrated how various forcing parameters like tides, winds, and waves, and different storm directions, affect sediment transport, and thus the system's morphodynamics (Table 1). Several identified gaps in knowledge could be filled by means of high-resolution process-based numerical models. However, despite being of scientific novelty and fundamental value, the results do not directly answer the above mentioned questions of stakeholders. We first needed to communicate research gaps in workshops, trying to raise awareness for numerical modelling limitations and assumptions. To mitigate between the understandable wish of some stakeholders for an application of the model for direct problem solving ('now that you have the model, then let it run for 100 years') and the principle of good scientific practice was more challenging. Especially the significant effect of single storm events, and their uncertainty in the future was explained. In this, the establishment of specialist groups helped. These consist of a subset of dedicated stakeholders to co-develop special subtopics, allowing flexible and frequent communication. In the

end, it was possible to convince that a bad model result is not necessarily better than no model result. It became clear how science is a stake too – the scientists participating with the aim of gaining fundamental knowledge and the opportunity to publish research articles, e.g., to satisfy the requirements for a successful PhD thesis.

4.2 Case 2: Stability and reinforcement of a natural dune system

In between the engineered mainland dikes of Sankt Peter Ording, the coastal dunes of Maleens Knoll provide a contribution to coastal protection by forming a rare natural barrier against storm surges and protecting the hinterland from flooding (Mehrtens et al. 2023). In order to maintain this coastal protection potential in the future, hybrid dune reinforcements are a widespread approach to increase natural dune resistance against erosion, while maintaining natural landform characteristics and ecosystem functions (Nordstrom 2019). To date only few experimental studies have addressed the performance and effectiveness of hybrid installation structures such as fixed walls (Feagin et al. 2015), rocks (Odériz et al. 2020) or geotextiles (Maximiliano-Cordova et al. 2023), calling for systematic analyses of different reinforcement options in hydraulic experiments.

4.2.1 Co-design

Knowing about the expertise and instrumental facilities of the research team of LWI, stakeholders of the coastal defence authorities expected an assessment of dune stability and the prediction of future developments for the beach and dune system at Maleens Knoll. Expectations were addressed rather unspecific. The scientists explained limitations of experimental facilities, such as 2D vs. 3D experimental conditions, the problem of scaling and other experimental assumptions, and limits in terms of resources for the very demanding physical laboratory experiments.

During the early phase of the project, workshops and specialist group meetings addressed the discrepancy between a general assessment and the feasibility of hydraulic modelling of natural dune systems. It was noted that while erosional tendencies in 2D laboratory settings are easily captured, it remains uncertain which contribution to the overall in-situ processes is provided by the three-dimensional nature of the sand transport, which scale effects exist from reduced scale models, and how the effects of vegetation can be incorporated into the experimental work. Eventually, it was understood that several simplifications are unavoidable during the physical modelling process; i.e., the scaling of boundary conditions, model geometry, and simplifications, as that consideration was given to vegetation (e.g., root systems and above-ground plants).

Also, model setup limitations had to be explained and communicated: A wave flume as used in this study generates waves at one end and directs them through the flume onto a model configuration of the sand dune. The generation, propagation, and angle of attack are essentially two-dimensional. Consequently, oblique wave attack and resulting currents, and thus also lateral sediment transport are limited by the flume's side walls, constricting sediment transport pathways compared to the real world. For the dune geometry, a length scale of 1:7 following Froudes similarity law was chosen. Finally, sediments were scaled using the DEAN parameter resulting in a D50 of 0,18 mm in order to maintain similarity regarding the settling velocity to properly model dynamic erosion processes (Dean 1991).

Experiments conducted within this work could only consider one representative dune cross-sectional profile. Ultimately, this approach does not allow for consideration of the entire dune system at Maleens Knoll. In reality, the coastal setting consists of several dune chains of varying extent, size and lateral habitat systems. The complex mosaic of salt marshes, lagoons, dune systems and coastal forest adds coastal protection benefits as they store flood volume and dissipate incoming wave energy. Interactions and feedback are highly non-linear and to date largely not quantified.

In the process, the direct and repeated contact within a specialist group allowed constructive co-design and co-development of the research. Applied research gaps on the local dune system at Maleens Knoll were formulated, resulting in three topics:

- Assessment of the protection potential against known storm surges
- Dune system performance under projected future conditions
- Options to reinforce the natural dune system

4.2.2 Methods and results

An attribution of protection potential was based upon a collection and analysis of historic coastal dune data. In this the flood protection potential of a natural sand dune was quantified. Historic coastal dune and beach profile data were provided by the state authority for coastal protection, national park and ocean protection of Schleswig-Holstein (LKN.SH) dating back to the year 1949. The data was fed into a sequential database of digital terrain maps of dune evolution until 2015. Assessment of both the grey dune Maleens Knoll reaching 16.5 m MSL as well as the younger up to 11 m MSL high white dune system regarding dimensions, volumes and morphodynamic evolution was conducted. An attribution of coastal protection potential against storm surge levels was achieved by applying a novel assessment tool for dune toe detection (Mehrtens et al. 2023).

In a specialist group, the physical experiments on fundamental sand dune stability as well as dune reinforcement options were co-designed. In a first step, a representative geometric cross-section model of the dune Maleens Knoll had been derived based on geospatial survey data and two joint field surveys in the study area in September 2021 and October 2022. Laboratory facilities at the TU Braunschweig include a wave flume with dimensions of 90 m length, 2 m width, and 1.5 m height (Figure 4). The dimensions constitute a presupposition for the experimental model setup including the dune geometry and hydrodynamic conditions. A uniform length scale of 1:7 based on Froude's similarity law was applied. Exchange with science partners from CAU Kiel regarding the sediment composition at the local beach-dune area supported the selection and scaling of the model sediment grain size. As part of the selection and definition of suitable hydrodynamic conditions, communication and data exchange were maintained with stakeholders from public authorities. A representative single test duration design was informed by local wave station recordings provided by state authorities (LKN.SH) and federal authorities. Finally, an actual storm surge event duration of approximately 5 h registered at the nearby Eider storm surge barrier led to a downscaled wave series test duration of 113 min. Wave conditions as well as characteristic local storm surge levels (with return periods of 50 yr and 200 yr) to be simulated were provided by the CAU project partner and discussed with state authorities (LKN.SH, Hirschhäuser und Bald 2022) and applied from nearby local dike sections directly adjacent to the dune Maleens Knoll (MELUR 2013). Furthermore, projected local sea level rise scenarios for the German Wadden Sea were applied from MELUR (2022) for Representative Concentration Pathways (RCP) RCP4.5 and RCP8.5 in 2050 and 2100 (Lee et al. 2023, van Vuuren et al. 2011, IPCC 2023).

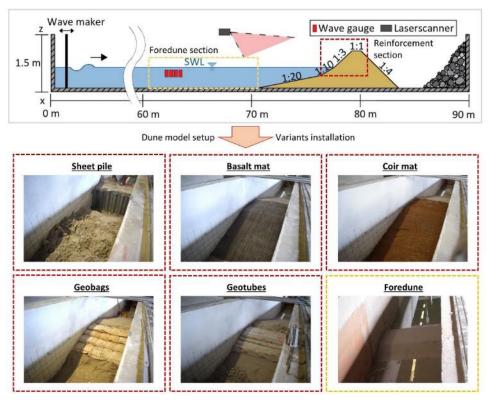


Figure 4: (Top) Cross section of the physical experiment setup in the wave flume with indicated sections for foredune placement and hybrid dune reinforcement structures. (Below) Tested reinforcement strategies.

Experimental series were carried out in the wave flume over two 4-month phases in spring 2022 and summer 2023. The first phase covered a total of 14 tests with a bare sand dune to investigate erosion and stability of a natural dune under various storm surge scenarios by combining local storm surge levels (with return periods of 50 yr and 200 yr) with projected sea level rises (under RCP4.5 and RCP8.5 in 2050 and 2100) to simulate current and future load cases. Results indicate that the modelled profile of the natural dune system (sand only), Maleens Knoll withstands at least two storm surge impacts of known or previously encountered magnitude under modelled lab conditions. With projected sea level rise scenarios, the modelled dune profile showed higher erosion volumes, suggesting a need for reinforcement strategies not for mid- (2050) but for long-term (2100) development. Various reinforcement strategies were implemented and tested within the designated 2D dune profile, exhibiting case-sensitive performance. Overall, reinforcement increased the erosion resistance of the system.

The third topic addressed reinforcement measures of different technical and biological engineering options. A selection of 8 options was mutually discussed and evaluated in the co-development process, again with stakeholders in the specialist groups. This process involved controversial exchange of arguments, partially containing perceived opinions on, e.g., durability of natural materials, opinionated views on legal frameworks, as well as expectations about protecting the natural environment from contaminants. A contrasting juxtaposition of strengths, weaknesses, opportunities and threats (SWOT) helped identify

suitable reinforcement (Figure 5). The measures range from hard engineering to nature-based options, with varying degrees of added protection.

	Dune reinforcement strategies			
	Sheet pile	Erosion protection mat	Geobags and -tubes	Foredune
Strengths	 High stability and durability Standardized construction procedure Minor disruption (largely invisible) and negative impact on flora and fauna 	 Made of natural materials (coir or basalt) to avoid plastic pollution Quick deployment and installation (terrain adaptable) Nature compatible (no barrier for flora and fauna) 	 Quick installation with available sediment resources Adaptable installation geometries (geotubes and geobags) High stability and durability (even when rinsed) 	 Dynamic system with natural growth potential No foreign material, only sand Natural system is preserved
Opportunities	 Remaining protection effect even after dune erosion Long-lasting solution (with enhanced safety feeling) Adaptable anchoring depth 	 Installation close to the surface with little earthworks Long durability of basalt fibers Temporary protection of coir fibers during vegetation growth 	 Long-term solution Flexible installation and usage at a short notice Invisible after proper installation 	 Increasing protective effect by reducing attacking wave energy Preservation of natural dune dynamics Formation of dynamically stable dune
Weaknesses	 Fixed barrier without continuity Very material-intensive installation Risk of injury at sharp edges if exposed after storm surge 	 Limited shelf life of coir fiber mats (approx. 3 years) Temporary limited erosion protection by coir mats Foreign material input in the nature reserve 	 Installation requires a large construction site and nature intervention Earthworks lead to soil movements Renewal required after storm surge damage 	 Large sand material transfer during storms Lower stability compared to established dune Limited lifetime
Threats	 Limited drainage Limited durability due to corrosion Potential undermining 	 Low acid, abrasion or water resistance Lack of protection if many fibers break Limited durability of natural materials 	 Pollution after storm surges Foreign material in case of damages Limited material durability 	 Dune erosion and long-term recovery progress Potentially insufficient protection level for multiple successive storm surge events Limited sand availability
		Coastal protect	tion approach	
	hard	sot	ft	nature-based

Figure 5: SWOT analysis results from the Specialist Group Climate Adaption outlining the ensuing test matrix for final experimental investigations. Reinforcement options are listed along the x-direction on the top, with the individual strengths, weaknesses, opportunities and threats identified on the left-hand side y-axis. Given underneath is a qualitative indication for the engineering design options.

These four measures were chosen out of a larger collection on the basis of their individual strengths and weaknesses identified in the SWOT analysis. The sheet pile wall was chosen, as it offers solid protection and an easy dimensioning approach, whilst requiring minimal invasive construction measures. Geobags and -tubes were chosen as another conventional approach, which has already been used at other sites but lacked environmentally friendly bag fabrics, which were available for testing during this project. The installation would require a large construction measure with maximal invasive character making this option a less favoured but possible one. The foredune option raised a lot of interest by the national park and WWF, as this would entail closing existing blowouts in the foredune chain and

reinforcing it if needed through nourishments to build a sand-only coastal defense layer. The erosion protection mats present an interim solution, as the mats themselves will not protect a dune from erosion entirely. The idea here entails an initial protection of a nourished or engineered dune with such mats until vegetation has developed and prevents the sand from too much erosion. Also, for potential interim protection of dune sections in between storm surges this option was discussed.

4.2.3 Implications

Research on dune erosion processes by storm waves and high-water levels has been codesigned with different involved stakeholder groups. At first, non-scientific stakeholders were informed about opportunities and limitations of hydraulic laboratory experimental research. In this, both stakeholder workshops and meetings of specialist groups were instrumental in conveying feasibility and expectancy. While not all expectations could be met, the mutual discussions during the co-design consultations remain a vital source of information for future testing, providing a much clearer view on necessities in the eyes of the local authorities and governing body representatives (Table 2). In the communication process, it remained difficult to gain a mutual understanding of the academic necessity to produce high-level, peer-reviewed journal publications as a vehicle to document scientific results, while it is nowadays a clear requirement for PhD students to write journal manuscripts in their pursuit to an academic degree.

Table 2: Expectations versus project activities for case 2.

Expectations	Own interests, aims	Delivered	Limitations
Attribution of the protection potential	Quantification of dune protection to	Protection level was assessed and conser-	Data coverage
of current dune system.	facilitate incorporation into standards.	vatively computed.	Data quality
COLL	Assessment of the system in question	Foredune system was also assessed on a spatiotemporal basis	
Erosion resistance	System understanding	Results of extensive	Model size 1:7
against known and projected storm surges	of the dune system Maleens Knoll	laboratory studies on dune erosion under varying boundary	Sediment cannot be scaled geometrically,
		conditions and con-	3D wave effects
		secutive storm surge impacts.	The influence of vegetation was neglected
Development and rel-	Method comparison	Comparisons of mul-	The reinforcement
ative investigation of dune reinforcement	Feasibility study	tiple reinforcement options within one	options had to be limited in number
options		dune profile	Resources in terms of
		guidelines for deci-	time, money and staff
		sion support, science	limited the number of
		and numerical model-	options to be investi-
		lers alike.	gated.

The limitations of the three major components of case 2 pertain to data coverage and quality, model assumptions and effects and the selection of tested variants from a larger set of possibilities. First of all, the data coverage and quality of the Sankt Peter-Ording dune and foredune systems is incomplete due to changing instruments from terrestrial line surveys towards airborne Lidar scans, survey approaches, coverage and intervals. Available data were processed and homogenized to form a coherent basis for ensuing analysis and physical experiments.

The limitations pertaining to the physical model originate from (1) the scaling of components, sediments and water kinematics, physics puts limits on the possibilities of accurately scaling all of these. Consequently, the results entail model effects, which would need to be addressed in large, unscaled experiments to increase validity. The approach of conducting erosion experiments in a 1D wave flume excludes any 3D effects present at the natural coast, where sediments would be transported longshore instead of being reworked in the dune toe area. Furthermore, the possible influence of vegetation coverage and root systems was neglected. Therefore, the conducted model experiments entail certain caveats, as most physical laboratory experiments do.

Lastly, the four investigated reinforcement options selected from a wider range were tested. A broader overview with other approaches would yield a more complete picture of possible mitigation options to adapt towards climate change-induced SLR. Nevertheless, the project runtime and available funding limit possible research, as money runs out, projects end and research facilities are not available to a single project for years on end. This necessitated the SWOT based selection process.

4.3 Case 3: Dune restoration and forest conversion

The third case covers on-site measures on dune restoration and forest conversion mainly behind the dike line, jointly implemented by the local dike board Deich und Hauptsielverband (DHSV) Eiderstedt, Schutzstation Wattenmeer and World Wide Fund for Nature (WWF). It is linked to the previous cases as the quality of nature depends on the geomorphological situation and boundary conditions of the foreshore-beach-dune system, but also relies on the nature-based coastal protection measures.

Only about 70 hectares of formerly open coastal dune habitats are preserved behind the dike. Because of the lack of natural dynamics and natural regeneration of the dune vegetation, an aging of the vegetation and a loss of the younger stages is observed. Coniferous trees from adjacent dune forest areas are nowadays spreading into the remaining open dune habitats. These trees stabilise the dune areas, leading to an additional reduction of dune dynamics (Figure 6). Added to this is the spread of garden refugees and invasive plant species, which have increased significantly in recent years. This development is a major ecosystem change, including the partial loss of habitats and loss of indigenous species. Among the invasive plants that occur are Japanese rose (Rosa rugosa), heath star moss (Campylopus introflexus), black cherry (Prunus serotina), American cranberry (Vaccinium macrocarpon), and Asian knotweed (Fallopia japonica) (Weber et al. 2023).

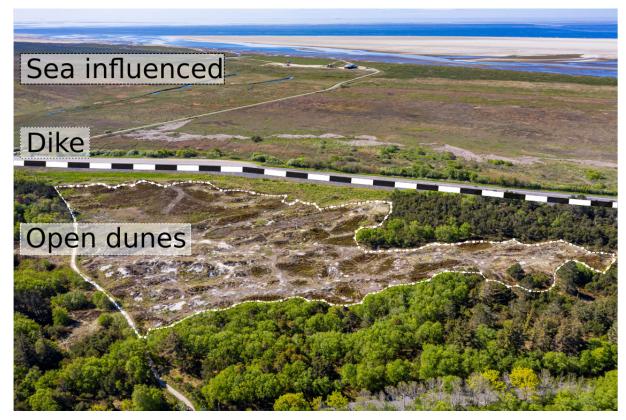


Figure 6: An example for an open dune area in Sankt Peter-Ording (white dashed area) experiencing extensive active nature conservation measures (removal of trees and invasive species), cut off from the natural sediment dynamics by the dike (black-white dashed line), with sea influenced habitats (black dashed line) on the other side. Picture: © Martin Stock.

In addition to the restoration of open dune areas, a conversion of the forest towards a higher proportion of deciduous trees is underway (in defined forest areas by the forest law). The forest of Sankt Peter-Ording was planted mainly with black pine (Pinus nigra) in the middle of the 19th century because the dune areas had been overused by people and major damage had been caused by storm surges (Hintze 1933, Fischer 1956). Nowadays, heat events are causing increasing damage to the relatively species-poor coniferous forests in Sankt Peter-Ording. Since the drought year of 2018, an increasing number of mountain and black pines have died completely or partially due to drought stress (Weber et al. 2023).

4.3.1 Co-Design

Nature conservation measures for the removal of pine trees in Sankt Peter-Ording have been in place since 2013 (i.e., before the SCSPO project). These activities are driven and supported by a local stakeholder alliance consisting of the landowner, local politicians, authorities and NGOs. They are legally supported by the requirements of the EU Habitats Directive (EU 1992), which obliges conservation measures in the protected areas specified in the local Fauna Flora Habitats management plan (MELUR 2016). These measures have been expanded through the SCSPO initiative as it became clear that further nature restoration measures and research were needed to preserve the habitats. Important impetus for the multi-year project development came, for example, from the expertise of a botanical and a zoological report (Gettner 2019, Winkler 2019). The central ecological objective for

today's often fragmented open dune habitats is to reconnect them, e.g., by creating corridors through forest areas. The local forester of the dike board became a key partner for the implementation of all measures. He not only supported the idea of ecological corridors, but also had developed an initial, basic concept for the conversion of the forest areas into mixed forest rich in species and structure, e.g., by spreading acorns with the help of the jay (see below).

Based on the restoration needs and the co-design of the project initiative, the following results and activities are shortly summarized below:

- Dune restoration measures
- Forest conversion measures
- Information, cooperation and participation

4.3.2 Methods and Results

In the open dune habitats, the initiative is active in the removal of conifers with forestry equipment and by hand; pushing back invasive species and garden refugees by digging up, mulching, mowing, cutting off, and manual removal; and creation of new open sand areas by sod plugging (Figure 7). Pushing back invasive species is a challenge. The manual or mechanical removal of species can rarely be complete and comprehensive once a species has spread widely. Permanent management usually then is necessary (Leung et al. 2005, Hess et al. 2019), which should utilise the forces of nature as much as possible.





Figure 7 Dune valley before (left) and after (right) removal of the cranberry (Picture: A. Weber).

A sustainable management option for the open dune areas behind the dike could be extensive grazing, e.g. by goats, donkeys or sheep, thus a model experiment to test grazing is planned in the Sand Coast initiative.

In order to maintain the dune forest's resilience to the consequences of climate change in the long term, it is to be converted from a monotonous coniferous forest into a mixed forest rich in species and structure. Therefore, the number of deciduous trees, especially oaks and beeches, is to be increased. Greater tree diversity minimises the risk of large-scale damage caused by drought or pests and promotes the climate resilience of the forest. For this purpose, additional regional seeds of deciduous trees are used, e.g. acorns and wildlings were implemented. The distribution of the acorns takes also place with the help of the jay, which hides the acorns as winter supplies. Young trees germinate the following year from acorns that are not recovered (Weber et al. 2023).

With the facilitation of the Sand Coast project, the nature conservation and forest conversion measures were accompanied by a comprehensive information, cooperation and participation program as part of the project design and implementation. Activities with local citizens are themselves part of implementation measures in the field. Different public relations work has been taking place, for example, through press and extensive website coverage, posts and short articles in social media, but also on-site discussions with stakeholders, presentations in municipal and regional committees (e.g., in the environmental committee of the municipality or in the national park board of trustees) or in field excursions. Continuous and recurring information over a longer period of time is considered appropriate here, so that interested parties can remain in permanent contact with the initiative.

Cooperation and participation require appropriate formats in which the stakeholders themselves can play an active and contributing role. A crucial part of the restoration measures is therefore a variety of hands-on activities (e.g. removal of invasive species by hand, planting of young oaks in the dune forest). There is keen interest in taking part in the activities, both from inhabitants from Sankt Peter-Ording and from tourists, travel groups and company outings. Between 2020 and 2023, for example, 39 hands-on activities with a total of 367 external participants, 14 guided tours with over 100 participants and a multi-year animal sighting campaign with almost 300 reports took place. Most stakeholders approach the Sand Coast initiative via the webpage and the contact form. In addition, people are made aware of the project by means of citizen science, in the form of animal sighting boards in the area. There is a barcode on the information boards that visitors can use to report their animal sightings online.

4.3.3 Implications

The activities with the stakeholders not only technically help to implement measures in the dunes and forest, but also contribute to the communication of the project objectives to the public and create opportunities for participation and co-design. People get to know the activities and larger aims, they communicate about it and can make contributions and provide feedback on the initiative themselves

The expectations of the nature conservation and forest conversion measures are to protect and restore the biodiversity of species and habitats. An initial assessment of the information, cooperation and participation activities in this case is summarized in Table 3. The joint activities have raised awareness for the topic and provided information about the purpose of the measures. People from the region and guests were able to take part, contribute to the project and learn something about it. It is understood that participation measures require long-term human and financial resources. The management of dunes and reforestation requires work after it, making the legacy of such project an important issue. While it must be understood, that not all nature conservation measures can be maintained, involvement of active groups and structures will allow to sustain activities also after completion of the project.

Expectations	Own interests, aims	Delivered	Limitations
Intensify and expand existing dune restoration	Best possible contin- uation of existing ac- tivities	Complement existing approaches and methods	New activities cannot always build on existing ones.
Sustainable, long- term effect of dune restoration measures	Conservation of bio- diversity and plants (dunes and forest ar- eas)	Dune restoration and forest conversion measures within the project duration	Measures need long- term continuation (and funding)
Combining protection against storm surges (coastal protection) and dune restoration (nature conservation)	Corresponding / like the expectations.	Dune restoration measures do not worsen the protection level.	Compromises have to be found in some cases
Awareness and acceptance of dune restoration and forest conversion.	Support for project activities	Support of hands-on activities, publicity, and policy briefings	Not every project measure is suitable for participation or easy to explain.

Table 3: Expectations versus project activities for case 3.

5 Discussion

The beach-dune system of Sankt Peter-Ording is a typical example of a coastal domain facing multiple pressures by natural (waves, storms), semi-natural (sea level rise, invasive species) and anthropogenic (hard structures, coastal protection, tourism) impacts (European Environment Agency 2006, Pontee 2013). Knowledge gaps and management tasks require dedicated research on local inter- and transdisciplinary aspects of fundamental and applied nature. Typically, such aspects are addressed by research initiatives which combine academic groups and other stakeholders (often defined as those actors who do not conduct research) based on third party funding.

The SCSPO initiative is a research and implementation project on both nature conservation and coastal protection for the SPO region. Multiple actors are involved and have formulated the need for actionable knowledge for nature-based coastal protection. Although not planned and performed as a living lab strictly in the definition of, e.g. Schneidewind et al. (2018), the project from the beginning was understood as a transdisciplinary approach with intense preparation and communication before and during the actual project duration by all project partners.

5.1 Transdisciplinarity

Schneidewind et al. (2018) describe different "modalities of structuration" that living labs may operate on. These are, i.e., interpretative schemes ("Do actors have a similar view on the research?"), allocative resources ("Is there sufficient funding to implement and monitor intervention actions and to sustain the living lab over a longer period of time?"), legitimatory rules ("Is there a common understanding about the degree to which science may

question current knowledge and regulations?"), and authoritative resources ("Is there organisational or political power to force a required change in policy or structure?"). Based on the SPO project, we focus on the discussion of the first and second aspects and add that scientists must be recognized as a stakeholder.

5.1.1 Interpretation aspect

Higgins and Klein (2011) identify scientific actors in living labs to play different roles; representatives of research institutions often function as brokers of information and as facilitators of certain anticipated structural frameworks that living labs offer. A more differentiated list of different roles in living labs is presented by Hilger et al. (2018) which comprises reflective scientists, facilitators, change agents, and (self-)reflexive scientists. A prerequisite of all project related content is the communication and a common understanding of the content and aims of the project and of every stakeholder. This development of a similar view on research requires mutual understanding, which can be achieved only in good relationships, trust, and interest. This may avoid disappointment in that abstract, high-level, simplified, and unfeasible expectations are mitigated and also that scientific results (output) can be used (outcome).

In the SCSPO project, mutual understanding was partly achieved by trust based on a history of long-term cooperation and personal relations, but mainly by continuous communication of expectations and feasibilities. It is noted that the development of similar views on research requires time and allocated funding. In this context the establishment of communication platforms other than stakeholder workshops and conferences were most effective: Bilateral communication and meetings of so-called specialist groups were effective means for achieving similar understanding on the research and implementations.

It is noted that this aspect requires further discourse and investigation based upon dedicated qualitative and quantitative social research, involving a suitable number of project realisations and actors of all involved fields.

5.1.2 Resources aspect

Whereas the aspect of "sufficient funding" is the main boundary condition of the design of any research initiative and should define a priori the project structure and feasibility, the time aspect is of fundamental importance during project performance. It not only governs the adaptive co-design, but also the implementation of research results into practice. Typical coastal research projects last 2-4 years (here 3 years for the engineering and natural science projects) up to which funding bodies agree to support specific academic activities. While this is logic from a governance- and politics-point of view, it cannot be in line with sustainable development and implementation long-term goals, in particular, where the adaptation of coastal protection systems against climate change drivers is concerned.

In addition to the necessary resources and time for funded scientific work, a transdisciplinary project requires sufficient capacity for applied and practical collaboration between the project partners, but also with actors outside the project. This includes, for example, time and resources for internal project meetings, but also for events like conferences, workshops and excursions, or the involvement of third parties in participative implementation measures, such as the hands-on activities. Obviously, the circular adaptation approach of living labs, i.e., the repeated iteration of project results and co-design stages cannot fit into a short-term research project. Contact and briefings in small expert groups and bilateral exchange instead of the whole group of stakeholders have solved the resources issue in the SPO example.

With respect to sustainable development goals, it is questionable whether short-term funding of research can pave the way to more sustainability. Only recently, new models have started to emerge, and amongst those are mid-duration projects, whose aim is to accomplish a broader mission goal, often termed "mission-based research". The Australian Government is among the early adopters of such a longer-term research funding agenda, with a concise mechanism for funding and evaluation of success (Diezmann 2018). While early traces of new funding formats have their roots in the "new public governance" movement which also is experimenting in German research contexts with "mission-based funding" (Orr et al. 2009). We mention here the first three funding calls in the context of the "German Marine Research Alliance", all of which were designed and implemented through a clear 9-year mission-orientation (Deutsche Allianz Meeresforschung 2019, European Commission et al. 2023). These 9-year mission-oriented research programs are split into three funding periods in which evaluation and assessment are inherently included, allowing to adjust and steer the alignment of the individual research missions. Since these mediumduration funding initiatives are still underway, constructive analysis will remain a topic of further research. An analysis of the output and outcomes of projects of different durations requires further discourse based upon dedicated qualitative and quantitative social research.

5.1.3 Scientist is a stakeholder aspect

Applied research projects are often driven by academic organisations that develop scientific questions, and inform or discuss options of interaction with partners. The latter may or may not take place in great detail during the project development phase (co-design). In the extreme case a "stakeholder" is only mentioned in a proposal, to secure funding for research in applied project calls (Table 4). On the other end, an institution may contract an academic institution for certain information, e.g. the mapping of a terrain or seafloor. This contract may or may not provide opportunities for scientific work.

Table 4: Different stereotypes of research projects and the respective roles of academic and non-academic actors. This holds for mono-, multi-, and interdisciplinary projects.

Project type	Role Academic Actor	Role Non-Academic Actor
Fundamental	Fundamental research, no application implied	No active role
Academic driven	Fundamental research with pos-	Receiver of information, possible
	sible application of output	implementation
Transdisciplinary	Co-design and co-development	Co-design and co-development of
	of fundamental and applied re-	research and outcome and imple-
	search and outcomes	mentation
Non-academic driven	Applied research for defined	Receiver of outcome, implementa-
	outcome	tion
Contracted	Provider of information, no re-	Receiver of information, direct im-
	search	plementation

In between those extreme cases, all partners will benefit, i.e., the academic partner uses the project results for scientific purposes and the non-academic partners for implementation. In the transdisciplinary case, all partners co-design their individual stakes towards joint aims. While this transdisciplinary give and gain approach thus seems ideal from a theoretical project management point of view, the stake of the actual researcher cannot be ignored; i.e. project-funded PhD students, who are expected to excel and publish fundamental scientific outcomes. The often-used separation of academic vs. stakeholder interest here hinders satisfactory solutions. Only if the stake of the active researcher is acknowledged a project can be successful. It is without saying that scientific progress also includes learning about new ideas and perspectives and inspiration from "yet infeasible" non-academic actors wishes. In the transdisciplinary SCSPO project, the co-development amongst academic and non-academic actors allowed the use of research outcomes for both, scientific system understanding and aspects of implementation.

5.2 Realisations

In practice, realisations of so-called living labs may be divergent from the exact definitions. In contributing to the actual discussion on the implementation of living lab approaches into many applied research calls, and based on the above reviewed literature as well as by providing a new view on contextualized living labs, we distil key elements that define promising projects in a coastal setting – without the need for adaptation of all aspects of a strict living lab:

Interdisciplinary collaboration: Modern research projects encourage collaboration among different disciplines, such as marine biology, ecology, hydrology, geology, engineering, social sciences, and economics and others. This interdisciplinary approach helps addressing the diverse aspects of coastal systems and fosters holistic understanding.

Transdisciplinary knowledge exchange and co-creation: Successful coastal projects promote action, knowledge exchange, and co-creation between researchers, stakeholders, and coastal communities. They facilitate workshops, forums, and collaborative platforms to share information, ideas, and experiences, fostering learning and mutual understanding. The SCSPO project has realised a variety of formats, e.g., the specialist groups, a conference, excursions and hands-on activities. This also includes education and outreach: Any larger coastal research project should incorporate education and outreach programs to raise awareness and build capacity among stakeholders and the wider public. This can involve workshops, training sessions, citizen science initiatives, and public events to promote understanding and the willingness to contribute, and be involved in coastal research and conservation.

Real-world coastal environment: Transdisciplinary projects shall be anchored with their research and practical activities within real coastal environments, whether it be a specific coastal region, estuary, or marine ecosystem. This setting allows to study the complexities, dynamics, and interactions of the physical, ecological, and socio-economic systems first-hand and in mutual cooperation. Whereas a living lab concept may suggest to include experimental infrastructure and perform real world experiments on site (Merino-Barbancho et al. 2023, Wang et al. 2022, Rădulescu et al. 2022) also in-depth understanding of systems may be a sufficient model result, or if communicated between – and acknowledged by all stakeholders. The SCSPO project combined both, provided system

understanding by numerical and physical modelling, and in-situ experiments in the field such as the removal of invasive plant species.

Co-design: Transdisciplinary projects actively involve and engage various actors as administration, environmental agencies and NGOs, municipalities and communities including their organisations, associations or boards, government agencies (Kindermann and Gormally 2013). It is understood that co-design can only start when the stakeholder mapping is finalised and a consortium has been formed. It is essential that also the researchers are seen as stakeholders, in the sense that they have an interest in the scientific outcomes as such. The participation of all actors from the earliest stage of the project design and their cooperation in the project work ensures that research outcomes are relevant, practical, and address the needs.

Sustainability / Legacy: Projects should ensure sustainable outcomes. This can be achieved by directly implementing project results into decision support, or transfer of project results into forthcoming activities. Projects should aim to develop sustainable and adaptive solutions for coastal management. Long-term goals and lasting positive impacts are in conflict with standardized project durations of 3 to 6 years and require longer time frames with integrative research and societal frameworks to achieve co-design driven and research supported change.

The integration of these elements into coastal research projects provides a unique opportunity to understanding, managing, and conserving coastal ecosystems while actively engaging and involving stakeholders and addressing real-world challenges.

6 Conclusions

The project Sand Coast Sankt Peter-Ording has generated system understanding on the beach morphodynamics and sediment transport: Numerical modelling of the SPO coastal system revealed the complex sediment transport pathways driven by wind, wave, and tidal forcing. Transport to the beach during average conditions occurs in a pathway across the Rochelsteert Sand, with a sediment divergence zone separating the northward and southward oriented transport. Simulations of distinct storm events demonstrated spatially variable impacts on sediment dynamics. While the models provided valuable system insights, predictive limitations and uncertainty in future forcing required careful communication with stakeholders.

Physical flume experiments showed how a dune profile based on the natural Maleens Knoll setting resists current storm conditions. Selected reinforcement options, e.g., geotextile structures and vegetation mats, increased erosion resistance. Co-design with stakeholders helped align scientific goals with practical needs, though experimental simplifications and scaling limitations were acknowledged.

On-site measures focused on restoring open dune habitats by removing conifers and invasive species and promoting natural dynamics. Forest conversion activities aimed to enhance climate resilience. The initiative included strong public engagement, with hands-on activities and citizen science. Sustained management and long-term commitment beyond the project duration were identified as critical for ecological success.

This transdisciplinary research project on coastal protection and nature conservation has been implemented by environmental non-governmental organisations (NGOs), a local dike board, public authorities, a local municipality, and includes two university working

groups. The project is compared to theoretical concepts of living labs, while discrepancies and challenges are discussed. We identify and concentrate on three main issues:

Resources: The development of similar views on research requires trust, time and funding. The application of circular adaptive concepts of adaptive co-development as a core component of living labs is infeasible in typical coastal projects with 2–6-year funding. In this context the establishment of communication platforms other than stakeholder workshops and conferences were most effective: Bilateral communication and meetings of so-called specialist groups were effective means for achieving similar understanding on the research and implementations.

Legacy: The implementation of the project into ongoing financed or volunteered activities of stakeholder groups, e.g. the reforestation measures, will allow the legacy of the project. Other aspects of legacy involve the use of project outcomes in other follow up projects. In our case preliminary results have led to a successful follow up project on dune dynamics. The models and results are published in open source journals. Models are being used in third party consultancy projects for other research targets.

Science is a stakeholder: While the idea of transdisciplinary research seems ideal from a project management point of view, the stake of the active researcher cannot be ignored: The often-used separation of academic vs. stakeholder interest here hinders satisfactory solutions.

Typical transdisciplinary coastal research projects should contain the main elements of living lab concepts. It must however be understood that not all aspects of living labs can be met, e.g., because of limited funds and project durations. Nevertheless, transdisciplinary projects can be successful if different stakeholders are involved and actively contributing and are satisfied by sustainable outcome, including the science stakeholders.

Designed as a collaborative project answering a rather typical funding scheme, the project followed a transdisciplinary approach. Despite not strictly following a living lab concept, the project cooperation, results, and sustainability satisfied all partners, thus can be called successful. Future research should implement social science methodology to evaluate measures to quantify the goodness of different transdisciplinary projects, being called living labs or not.

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8 Author contributions

The article was conceptualized by CW, funding acquisition and project administration was carried out by JF, AW, CW, and NG, investigations and formal analyses was performed by CW, JF, NG, OL, BM, CS, DS, AW. The writing of the original draft was carried out by CW, all authors contributed to the writing, review and editing of the current version.

9 References

BGK: Digitales Geländemodell Gitterweite 200 m (DGM200) - Digital Terrain Rastersize 200 m. Germany: Bundesamt für Kartographie. Last checked on 28/02/2024 https://gdz.bkg.bund.de/index.php/default/open-data/digitales-gelandemodell-gitterweite-200-m-dgm200.html, 2024.

BMWi: Freiräume für Innovationen: Das Handbuch für Reallabore: Space for innovation - The handbook for living labs. 1st ed. Berlin, Germany: BMWi. Last checked on 28/02/2024 https://www.bmwk.de/Redaktion/DE/Publikationen/Digitale-Welt/handbuch-fuer-reallabore.pdf?__blob=publicationFile&v=1, 2019.

Bollmeyer, C.; Keller, J. D.; Ohlwein, C. et al.: Towards a high-resolution regional reanalysis for the European CORDEX domain. In: Quarterly Journal of the Royal Meteorological Society, 141 (686), 1–15, https://doi.org/10.1002/qj.2486, 2015.

Bulkeley, H.; Marvin, S.; Palgan, Y. V. et al.: Urban living laboratories: Conducting the experimental city? In: European Urban and Regional Studies, 26 (4), 317–335, https://doi.org/

10.1177/0969776418787222, 2019.

Calafat, F. M.; Wahl, Th.; Tadesse, M. G. et al. (2022): Trends in Europe storm surge extremes match the rate of sea-level rise. In Nature 603 (7903), 841–845. https://doi.org/10.1038/s41586-022-04426-5, 2022.

Clarke, B.; Otto, F.; Stuart-Smith, R. et al.: Extreme weather impacts of climate change: an attribution perspective. In: Environmental Research: Climate, 1 (1), 12001, https://doi.org/

10.1088/2752-5295/ac6e7d, 2022.

Common Wadden Sea Secretariat: Report on the State of Conservation of the World Heritage property "The Wadden Sea (N1314)". With assistance of Common Wadden Sea Secretariat. 1st ed. 42 volumes. Wilhelmshaven, Germany (State of Conversation Report "The Wadden Sea (N1314)", 42). Last checked on 04/15/2024 https://www.waddensea-secretariat.org/sites/default/files/State%20of%20Conservation%20Report%20The%20Wadden%20Sea%20%28N1314%29.pdf, 2024.

Dean, G. R.: Equilirium BEach Profiles: Characteristics and Applications. In: Journal of Coastal Research, 7 (1), 53–84. Last checked on 02/28/2024 http://www.jstor.org/sta-ble/4297805, 1991.

Deltares Stichting: Delft3D: Simulation of multi-dimensional hydrodynamic flows and transport phenomena, including sediments. Delft, Netherlands: Deltares. Last checked on 02/28/2024 https://oss.deltares.nl/web/delft3d/get-started, 2024a.

Deltares Stichting: Delft3D-Flow. Simulation of multi-dimensional hydrodynamic flows and transport phenomena, including sediments. User Manual - Hydro-Morphodynamics. Delft, Netherlands. 2024b.

Deutsche Allianz Meeresforschung: Verwaltungsvereinbarung. DAM, revised 2019 1 (1), 1–9, Last checked on 04/15/2024 https://www.allianz-meeresforschung.de/app/uploads/2020/01/2019-DAM-Verwaltungsvereinbarung.pdf, 2019.

Diezmann, C. M.: Understanding research strategies to improve ERA performance in Australian universities: circumventing secrecy to achieve success. In: Journal of Higher Education Policy and Management, 40 (2), 154–174, https://doi.org/10.1080/1360080X.2018.1428411, 2018.

EMODnet Bathymetry Consortium: EMODnet Digital Bathymetry (DTM 2020): DTM Tiles E3-E5 covering the North Sea continental shelf sea: EMODnet Bathymetry Consortium.

EU: FFH Directive. Council Directive 92/43/EEC of 21 May 1992 on the conservation of natural habitats and of wild fauna and flora: EU 92/43/EEC (01992L0043-20130701). Last checked on 02/28/2024 https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A01992L0043-20130701, 1992.

European Commission; Directorate-General for Research; Innovation; Chimini, G.; Failler, P.; Galgani, L. et al.: Portfolio analysis, EU mission "Restore our Ocean and Waters by 2030" – Analysis of a portfolio of projects financed by sixteen EU programmes contributing to the objectives and enablers of the mission ocean and waters: Publications Office of the European Union, 2023.

European Environment Agency: The changing faces of Europe's coastal areas. Luxembourg, Copenhagen (EEA report, TH-AL-06-003-EN-C). http://publications.europa.eu/en/publication-detail/-/publication/91f2dece-3b60-4607-b0df-588013f2dd08, 2006.

Feagin, R. A.; Figlus, J.; Zinnert, J. C. et al.: Going with the flow or against the grain? The promise of vegetation for protecting beaches, dunes, and barrier islands from erosion. In: Frontiers in Ecology and the Environment, 13 (4), 203–210, https://doi.org/10.1890/140218, 2015.

Fischer, O.: Landgewinnung und Landerhaltung in Schleswig-Holstein. In: Das Wasserwesen an der Schleswig-Holsteinischen Nordseeküste, Eiderstedt, 3 (1), 294–298, 1956.

Franke, A.; Peters, K.; Hinkel, J. et al.: Making the UN Ocean Decade work? The potential for, and challenges of, transdisciplinary research and real-world laboratories for building towards ocean solutions. In: People and Nature, 5 (1), 21–33, https://doi.org/10.1002/pan3.10412, 2023.

Gaertner, M.; Larson, B. M. H.; Irlich, U. M. et al.: Managing invasive species in cities: A framework from Cape Town, South Africa. In: Landscape and Urban Planning, 151, 1–9, https://doi.org/10.1016/j.landurbplan.2016.03.010, 2016.

Galbraith, B.; Mulvenna, M.; Martin, S. et al.: Living Labs: Helping to Meet the Needs of Aeging People? In: Assistive Technology Research Series, 22, 105–118, Last checked on 2/28/2024: https://ebooks.iospress.nl/volumearticle/826, 2008.

Gettner, S.: Gutachterliche Stellungnahme zu Flora und Vegetation sowie möglichen Schutzmaßnahmen in ausgewählten Küstenlebensräumen von St. Peter-Ording: Im Auftrag des WWF: (internal status report) 1, 2019.

Guo, F.; Zhu, X.; Zhang, J. et al.: Large-scale living laboratory of seasonal borehole thermal energy storage system for urban district heating. In: Applied Energy, 264, 114763. https://doi.org/10.1016/j.apenergy.2020.114763, 2020.

Hagen, R.; Plüß, A.; Freund, J.; Ihde, R.; Kösters, F.; Schrage, N. et al.: EasyGSH-DB: Themengebiet – Hydrodynamik: Bundesanstalt für Wasserbau, 2020.

Hagen, R.; Plüß, A.; Schrage, N.; Dreier, N.: EasyGSH-DB: Themengebiet – synoptische Hydrodynamik: Bundesanstalt für Wasserbau, 2021.

Herrling, G.; Winter, C.: Tidal inlet sediment bypassing at mixed-energy barrier islands. In: Coastal Engineering, 140, 342–354, https://doi.org/10.1016/j.coastaleng.2018.08.008, 2018.

Hess, M. C. M.; Mesléard, F.; Buisson, E.: Priority effects: Emerging principles for invasive plant species management. In: Ecological Engineering, 127, 48–57, https://doi.org/10.1016/j.ecoleng.2018.11.011, 2019.

Higgins, A.; Klein, S. (2011): Introduction to the Living Lab Approach. In: Tan, Y.-H.; Björn-Andersen, N.; Klein, S.; Rukanova, B. (Eds.): Accelerating Global Supply Chains with IT-Innovation. Berlin, Heidelberg: Springer Berlin Heidelberg, 31–36, 2011.

Hilger, A.; Rose, M.; Wanner, M.: Changing Faces - Factors Influencing the Roles of Researchers in Real-World Laboratories. In: GAIA - Ecological Perspectives for Science and Society, 27 (1), 138–145, https://doi.org/10.14512/gaia.27.1.9, 2018.

Hintze, O.: Die Bepflanzung und Aufforstung des Dünengeländes von St. Peter und Ording 1 (1), 1–19, 1933.

Hirschhäuser, T.; Bald, M.: Information on representative extreme sea state for the Eiderstedt peninsula under various future sea level rise scenarios to be used in experimental setups. to Björn Mehrtens, Oliver Lojek, David Schürenkamp and Nils Goseberg. Braunschweig, Husum, 2022.

Hofstede, J. L. A.: Morphologie des St. Peter-Ording-Sandes. In: Die Küste, 59, 143–171, https://henry.baw.de/items/2c0d1f5c-295e-47c7-8070-62668ebda618, 1997.

Hofstede, J. L. A.: Integrated management of artificially created salt marshes in the Wadden Sea of Schleswig-Holstein, Germany. In: Wetlands Ecology and Management, 11 (3), 183–194, https://doi.org/10.1023/A:1024248127037, 2003.

Horton, B. P.; Khan, N. S.; Cahill, N. et al.: Estimating global mean sea-level rise and its uncertainties by 2100 and 2300 from an expert survey. In: Climate and Atmospheric Science, 3 (1), https://doi.org/10.1038/s41612-020-0121-5, 2020.

IPCC: Climate Change 2022 - Impacts, Adaptation and Vulnerability: Cambridge University Press, 2023.

Kempa, D.; Karrasch, L.; Schlurmann, T. et al.: Design and Insights Gained in a Real-World Laboratory for the Implementation of New Coastal Protection Strategies. In: Sustainability, 15 (5), 4623, https://doi.org/10.3390/su15054623, 2023.

Kidd, C. D.; Orr, R.; Abowd, G. D. et al.: The Aware Home: A Living Laboratory for Ubiquitous Computing Research. In: Goos, G.; Hartmanis, J.; van Leeuwen, J.; Streitz, N. A.; Siegel, J.; Hartkopf, V.; Konomi, S. (Eds.): Cooperative Buildings. Integrating Information, Organizations, and Architecture, vol. 1670. Berlin, Heidelberg: Springer Berlin Heidelberg (Lecture Notes in Computer Science), 191–198, 1999.

Kindermann, G.; Gormally, M. J.: Stakeholder perceptions of recreational and management impacts on protected coastal dune systems: A comparison of three European countries. In: Land Use Policy, 31, 472–485. https://doi.org/10.1016/j.landusepol.2012.08.011, 2013.

Kluger, M. O.; Bartzke, G.: A practical guideline how to tackle interdisciplinarity--A synthesis from a post-graduate group project. In: Humanities and Social Sciences Communications, 7 (1), https://doi.org/10.1057/s41599-020-00540-9, 2020.

Lai, R. W.S.; Perkins, M. J.; Ho, K. K.Y. et al.: Hong Kong's marine environments: History, challenges and opportunities. In: Regional Studies in Marine Science, 8, 259–273. https://doi.org/10.1016/j.rsma.2016.09.001, 2016.

Lee, H.; Calvin, K.; Dasgupta, D. et al.: IPCC, 2023: Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, H. Lee and J. Romero (eds.)]. IPCC, Geneva, Switzerland, 2023.

Lesser, G. R.; Roelvink, J. A.; van Kester, J.A.T.M. et al.: Development and validation of a three-dimensional morphological model. In: Coastal Engineering, 51 (8-9), 883–915. https://doi.org/10.1016/j.coastaleng.2004.07.014, 2004.

Leung, B.; Finnoff, D.; Shogren, J. F. et al.: Managing invasive species: Rules of thumb for rapid assessment. In: Ecological Economics, 55 (1), 24–36. https://doi.org/10.1016/j.ecolecon.2005.04.017, 2005.

Liedtke, C.; Welfens, M. J.; Rohn, H.; Nordmann, J.: LIVING LAB: user-driven innovation for sustainability. In: International Journal of Sustainability in Higher Education, 13 (2), 106–118, https://doi.org/10.1108/14676371211211809, 2012.

Lithgow, D.; Martínez, M. L.; Gallego-Fernández, J. B. et al.: Exploring the co-occurrence between coastal squeeze and coastal tourism in a changing climate and its consequences. In: Tourism Management, 74, 43–54, https://doi.org/10.1016/j.tourman.2019.02.005, 2019.

Maximiliano-Cordova, C.; Silva, R.; Mendoza, E. et al.: Morphological Performance of Vegetated and Non-Vegetated Coastal Dunes with Rocky and Geotextile Tube Cores under Storm Conditions. In: Journal of Marine Science and Engineering, 11 (2061), https://doi.org/

10.3390/jmse11112061, 2023.Mehrtens, B.; Lojek, O.; Kosmalla, V. et al.: Foredune growth and storm surge protection potential at the Eiderstedt Peninsula, Germany. In: Frontiers in Marine Science, 9, https://doi.org/10.3389/fmars.2022.1020351, 2023.

MELUR: Generalplan Küstenschutz des Landes Schleswig-Holstein (Coastal protection plan of the State of Schleswig-Holstein): Fortschreibung 2022 (continuation 2022). 1st ed. Kiel, Germany: MELUR (Generalplan Küstenschutz Schleswig-Holstein, 1). Last checked on 01/06/2023 https://www.schleswig-holstein.de/DE/fachin-halte/K/kuestenschutz/Downloads/Generalplan.pdf?__blob=publicationFile&v=5, 2022.

MELUR: Managementplan für das Fauna-Flora-Habitat-Gebiet DE-1617-301 "Dünen St. Peter". 1st ed. Kiel, Germany. Last checked on 2/28/2024 http://www.umwelt-daten.landsh.de/public/ natura/pdf/mplan_inet/1617-301/1617-301_MPlan_Text.pdf, 2013.

Merino-Barbancho, B.; Abril Jiménez, P.; Mallo, I. et al.: Innovation through the Quintuple Helix in living labs: lessons learned for a transformation from lab to ecosystem. In: Frontiers in public health, 11, 1176598, https://doi.org/10.3389/fpubh.2023.1176598, 2023.

Nordstrom, K. F.: Coastal dunes with resistant cores. In: Journal of Coastal Conservation 23 (1), 227–237, https://doi.org/10.1007/s11852-018-0653-6, 2019.

Odériz, I.; Knöchelmann, N.; Silva, R. et al.: Reinforcement of vegetated and unvegetated dunes by a rocky core: A viable alternative for dissipating waves and providing protection? In: Coastal Engineering, 158, 103675, https://doi.org/10.1016/j.coastaleng.2020.103675, 2020.

Orr, D.; Jaeger, M.; Schwarzenberger, A.: Performance-based Funding as an Instrument of Competition in German Higher Education. In: Tight, M. (Ed.): The Routledge international handbook of higher education, vol. 1. New York: Routledge (The Routledge international handbook series), 18. Last checked on 4/15/2024 https://www.taylorfrancis.com/chapters/edit/10.4324/9780203882221-22/performance-based-funding-instrument-competition-german-higher-education-dominic-orr-michael-jaeger-astrid-schwarzenberger, 2009.

Pontee, N.: Defining coastal squeeze: A discussion. In: Ocean & Coastal Management, 84, 204–207, https://doi.org/10.1016/j.ocecoaman.2013.07.010, 2013.

Rădulescu, M. A.; Leendertse, W.; Arts, J.: Living Labs: A Creative and Collaborative Planning Approach. In: Franklin, A. (Ed.): Co-Creativity and Engaged Scholarship. Cham: Springer International Publishing, 457–491, 2022.

Ramm, T. D.; Watson, C. S.; White, C. J.: Strategic adaptation pathway planning to manage sea-level rise and changing coastal flood risk. In: Environmental Science & Policy, 87, 92–101, https://doi.org/10.1016/j.envsci.2018.06.001, 2018.

Santamaria-Aguilar, S.; Arns, A.; Vafeidis, A. T.: Sea-level rise impacts on the temporal and spatial variability of extreme water levels: A case study for St. Peter-Ording, Germany. In: Journal of Geophysical Research: Oceans, 122 (4), 2742–2759. https://doi.org/10.1002/2016JC012579, 2017.

Schäpke, N.; Singer-Brodowski, M.; Stelzer, F. et al.: Creating Space for Change: Sustainability Transformations: The Case of Baden-Württemberg. In: GAIA - Ecological Perspectives for Science and Society, 24 (4), 281–283, https://doi.org/10.14512/gaia.24.4.17, 2015.

Schäpke, N.; Stelzer, F.; Caniglia, G. et al.: Jointly Experimenting for Transformation? Shaping Real-World Laboratories by Comparing Them. In: GAIA - Ecological Perspectives for Science and Society, 27 (1), 85–96, https://doi.org/10.14512/gaia.27.S1.16, 2018.

Schneidewind, U.; Augenstein, K.; Stelzer, F. et al.: Structure Matters: Real-World Laboratories as a New Type of Large-Scale Research Infrastructure: A Framework Inspired by

Giddens' Structuration Theory. In: GAIA - Ecological Perspectives for Science and Society, 27 (1), 12–17. https://doi.org/10.14512/gaia.27.S1.5, 2018.

Schoonees, T.; Gijón Mancheño, A.; Scheres, B. et al.: Hard Structures for Coastal Protection, Towards Greener Designs. In: Estuaries and Coasts, 42 (7), 1709–1729. https://doi.org/10.1007/s12237-019-00551-z, 2019.

Simpson, N. P.; Mach, K. J.; Constable, A. et al.: A framework for complex climate change risk assessment. In: One Earth, 4 (4), 489–501, https://doi.org/10.1016/j.oneear.2021.03.005, 2021.

Soares, C.; Knies, A.; Winter, C.: RepD3D: A tool for representative period identification and associated boundary condition extraction. MethodsX 14, 103109, https://doi.org/10.1016/j.mex.2024.103109, 2024a.

Soares, C.; Galiforni, F.; Winter, C.: Representative residual transport pathways in a mixed-energy open tidal system. Journal of Sea Research 201, https://doi.org/10.1016/j.seares.2024.102530, 2024b.

van Vuuren, D. P.; Edmonds, J. A.; Kainuma, M. et al.: A special issue on the RCPs. In: Climatic Change, 109 (1-2), 1–4, https://doi.org/10.1007/s10584-011-0157-y, 2011.

Vriend, H. J. de; Capobianco, M.; Chesher, T. et al.: Approaches to long-term modelling of coastal morphology: A review. In: Coastal Engineering, 21 (1-3), 225–269, https://doi.org/10.1016/0378-3839(93)90051-9, 1993.

Wang, A.; Chang, F. Y.; Yousefi, S. et al.: The Hitchiker's Guide to Successful Living Lab Operations. http://arxiv.org/pdf/2212.00008v1, 2022.

Wanner, M.; Hilger, A.; Westerkowski, J. et al.: Towards a Cyclical Concept of Real-World Laboratories. In: disP - The Planning Review, 54 (2), 94–114, https://doi.org/10.1080/02513625.2018.1487651, 2018.

Weber, A.; Fröhlich, J.; Gettner, S.; Scheffler, P.: Naturbericht St. Peter-Ording: Aktueller Zustand der Natur der Küstenlandschaft und Perspektiven zu ihrem Schutz: Nature Report Sankt Peter-Ording - Current status of the coastal landscape and protection perspectives. 1st ed. Sankt Peter-Ording, Germany (1) (1). Last checked on 2/28/2024 https://sand-kueste-spo.de/wp-content/uploads/Naturbericht-St.-Peter-Ording_Projekt-Sand-kueste_Sept2023.pdf, 2023.

Winkler, C.: Gutachterliche Stellungnahme zu dünentypischen Tierarten und ihren Lebensräumen sowie möglichen Schutzmaßnahmen in St. Peter-Ording: Im Auftrag des WWF Deutschland (internal report). In: Coastal Engineering Proceedings, 1 (1), 2019.

Winter, C.: Impact of coastal development on coastal ecosystems. With assistance of Cham Springer. In Till Markus, Markus Salomon (Eds.): Handbook on Marine Environment Protection: Science, Impacts and Sustainable Management, vol. 1. 1st ed. 2018. Cham: Springer International Publishing and Imprint: Springer, 139–148. Last checked on 4/15/2024 https://link.springer.com/chapter/10.1007/978-3-319-60156-4_7, 2018.

Winter, C.; Da Chiou, M.; Riethmüller, R. et al.: The concept of "representative tides" in morphodynamic numerical modelling. In: Geo-Mar Lett, 26 (3), 125–132. https://doi.org/10.1007/s00367-006-0031-5, 2006.

WWF Germany: Sandy Coast Sankt Peter-Ording. Project website. With assistance of WWF Germany, Christian Albrecht University Kiel, Technische Universität Braunschweig, Deich und Hauptsielverband Eiderstedt, Schutzstation Wattenmeer. Edited by Jannes Fröhlich. WWF Germany. Sankt Peter-Ording, Germany. Last checked on 4/15/2024 https://sandkueste-spo.de/, updated on 4/15/2024, 2024.