A modeling application of integrated nature based solutions (NBS) for coastal erosion and flooding mitigation in the Emilia-Romagna coastline (Northeast Italy)

Silvia Unguendoli [a,*], Luis Germano Biolchi [a], Margherita Aguzzi [a], Umesh Pranavam Ayyappan Pillai [b,1], Jacopo Alessandri [a,b], Andrea Valentini [a]

[a] Hydro-Meteo-Climate Structure of the Agency for Prevention, Environment and Energy of Emilia-Romagna, Arpae-SIMC, Bologna 40122, Italy
[b] Department of Physics and Astronomy, University of Bologna, Bologna 40127, Italy

HIGHLIGHTS

- Nature based solutions (NBS) can be an innovative and tangible approach to deal with coastal protection.
- Potential of integrated eco-sustainable NBS (artificial dune and seagrass) is assessed with numerical simulations.
- Dune acts as a barrier against marine ingression, and seagrass reduces wave impact along the coast.
- The integrated NBS approach improves highly the capability in mitigating coastal inundation during extreme scenarios.

GRAPHICAL ABSTRACT
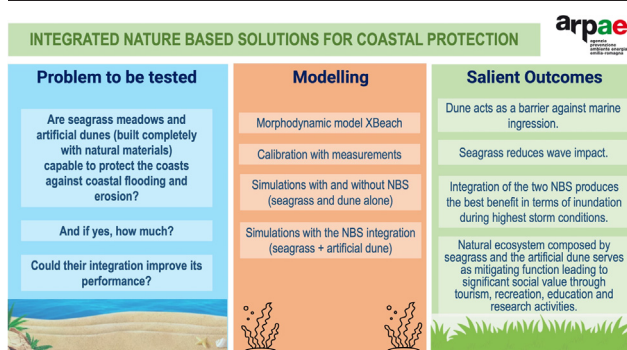
ABSTRACT

Worldwide, climate change adaptation in coastal areas is a growing challenge. The most common solutions such as seawalls and breakwaters are expensive and often lead to unexpected disastrous effects on the neighboring unprotected areas. In recent years, this awareness has guided coastal managers to adopt alternative solutions with lower environmental impact to protect coastal areas, defined as Nature-Based Solutions (NBSs). NBS are quite popular around the world but are often analyzed and implemented individually at pilot sites. This contribution analyzes the effectiveness of two NBS to mitigate coastal impacts (coastal flooding and erosion) under three historical storms along the Emilia-Romagna coasts and the induced improvements due to their potential integration. Through numerical simulations with XBeach, this study demonstrated that the presence of seagrass meadows of _Zostera marina_ produces an average attenuation of 32 % of the storm peak with a maximum attenuation of 89 % in incoming wave height. Seagrass also mitigates flooded areas and maximum inundation depths by 37 % and 58 % respectively. The artificial dune leads to higher mitigation in terms of inundation of the lagoon (up to 75 %), also avoiding any morphological variations behind it. Seagrass has also been shown to be able to reduce beach erosion volumes up to 55 %. The synergic effect of the two NBS improves the capacity to mitigate both inundation (with a benefit of up to 77 % for flooded area attenuation with respect to cases without any defenses) and coastal erosion. Results of the study suggest that the two NBS will work together to produce co-benefits in terms of preservation of their efficiency, development of habitats for organisms and vegetation species, and thereby offering an important social value in terms of possible tourism, recreation and research.

* Corresponding author at: Viale Silvani 6, 40122 Bologna, Italy.
 E-mail address: sunguendoli@arpae.it (S. Unguendoli).
1 _Umesh Pranavam Ayyappan Pillai_ presently @ Institute of Coastal Systems-Analysis and Modeling, Helmholtz-Zentrum Hereon, Geesthacht 21502, Germany.

1. Introduction

Climate change impacts in coastal regions play a crucial role in society due to the fact that one-third of the global population lives within 100 km of a coastal zone, about two-thirds of global megacities are situated on the coast (Martínez et al., 2007), and one-tenth (McGranahan et al., 2007; Plomaritis et al., 2018) are located in coastal zones <10 m above sea level. In the face of a changing climate and its effects on coastal environments, their protection is crucial for the populations (Church et al., 2013; Vitousek et al., 2017; Ferreira et al., 2019) occupying these regions and has become increasingly topical, and politically sensitive in a worldwide context. Coastlines which are important boundaries for the mainland are highly prone to erosion owing to urban expansion and extreme storms increase due to climate change (Creel, 2003). In this context the sandy coasts comprising beach-dune systems will be vastly exposed (Ranasinghe, 2016; Vousdoukas et al., 2018b) to associated changes in waves, storm surges, and mean sea level (Lee et al., 2021), thereby intensifying the reported global trends in coastal erosion (Mentaschi et al., 2018). In the coming decades the majority of the coastal regions will experience impacts from extreme weather events and rising sea level (Oppenheimer et al., 2019) such that 190–630 million people are estimated (Kulp and Strauss, 2019) to be inundated by 2100.The intensification of storm intensities, land subsidence and increased sea level rises can lead to increased risk of coastal floods (Lionello et al., 2007; Syvitski et al., 2009; Lin et al., 2012; Conte and Lionello, 2013; Reguero et al., 2015) . Various examples in the past reveal the adverse effects of low-frequency high-impact events on developed nations such as: St. Agatha storm (2015) over the Adriatic (Perini et al., 2015b), Xynthia (2010) storm in France (Bertin et al., 2012), Hercules (2014) storm in UK (Masselink et al., 2016), and Katrina (2005) and Sandy (2012) hurricanes in the USA (Clay et al., 2016; Kantha, 2013). The occurrence of these events built immense awareness pointing to the fact that developed nations and their coasts may be severely exposed to coastal hazards and must deal with their relative aftereffects.

Around half of the population (Statistical Office of the European Communities and European Commission, 2011) in Europe lives in regions that are <50 km from the sea sand hence most coastal regions face the threats of coastal and climatic hazards (Ciavola et al., 2011; Masselink et al., 2016; Ganguli and Merz, 2019; Schweiger and Schuettrumpf, 2021). Across Europe, impacts from coastal flooding are expected to significantly increase with rising sea levels (Vousdoukas et al., 2018a; Maul and Duedall, 2019). Hence in the context of sustainable coastal protection there is a great interest in adapting nature-based solutions (NBSs) to analyze the advantages of ecosystem services and thereby impart more economic/social benefits (Sutton-Grier et al., 2015; Schoonees et al., 2019; Moraes et al., 2022) . All over the world, NBS have been thoroughly studied in an attempt to mitigate coastal risks, and associated social and territorial effects although its implementation and development process is still in the early stages. Thus, NBS are seen as a potential means to address social challenges using principles of nature that are cost-effective and provide societal, economic and environmental benefits while also creating resistance to natural disasters (Faivre et al., 2017). More specifically, NBS aim to use nature to provide the maintenance, development, and restoration of biodiversity and ecosystems as a means to address multiple concerns simultaneously (Nesshöver et al., 2017; Keesstra et al., 2018). Pauleit et al. (2017) reported that the scope of the NBS concept is broader than ecosystem-based adaptation, more abstract (in terms of application to urban planning) than green infrastructure, and based on ecosystem service approaches to the benefits of nature for human well-being. Hence, NBS could be used as an umbrella term for other concepts that are receiving increased attention at political and academic levels (Nesshöver et al., 2017; Pauleit et al., 2017). Therefore, NBS are alternatives to manage risks arising from hydro-meteorological events. NBS can be deployed to protect, manage and restore natural/modified ecosystems (Cohen-Shacham et al., 2016) thereby imparting crucial ecosystem services for biodiversity and human well-being.

NBS can be used as a complementary and/or alternative approach to engineering structures. Coastal protection approaches in a traditional sense depends on "hard" engineering solutions which are not enough to hold the pressure increase from intense hydrometeorological hazards induced by climate change (Kumar et al., 2020). Such structures pose maintenance costs that are impractical and therefore there is a demand for low-cost, resilient and sustainable solutions (Morris et al., 2018). Various forms of ecosystems in coastal environments (Kirwan and Megonigal, 2013; Rodriguez et al., 2014) such as seagrass meadows, salt marshes, dunes, biogenic reefs, etc. have a high capacity to protect the coasts against flooding and eroding via hydrodynamic energy dissipation, owing to the characteristics of the submerged vegetation and its associated structural complexities (Temmerman et al., 2013; Hanley et al., 2014; Ondiviela et al., 2014; Boudouresque et al., 2021; Da Ros et al., 2021). Contrary to the "hard" engineering structures, nearshore vegetated ecosystems can amplify the soil elevation and soil vertical acceleration on account of biomass accumulation from below the ground and particle trapping via the water column (Duarte et al., 2013; Potouroglou et al., 2017). Today, many studies support the application of NBS to overcome the limitations associated with purely rigid engineering structures, also named gray solutions (Nesshöver et al., 2017). Ondiviela et al. (2014) examined the contribution of seagrass to coastal protection through a review of the most relevant existing knowledge. While the main conclusion achieved is that seagrass meadows cannot protect shorelines in every location/scenario, it concludes that the role of seagrass in coastal protection should be actively included, and not be overlooked in coastal planning. Narayan et al. (2016) compared the importance of seagrass/kelp beds, mangroves, coral reefs, and salt marshes with submerged breakwaters in reducing flood wave height, and coastal erosion using 69 case-studies. They stressed that the costs of measures based on salt marshes and mangroves could be two to five times cheaper compared with engineering structures for flood waves ~ up to 50 cm. A recent study by van Zelst et al. (2021) reports that in maintaining coastlines across the world the integration of coastal vegetation with infrastructure designs could yield cost savings with sustainable management of coastal ecosystems.

Over the past few decades, numerous field and laboratory studies have been performed to determine the effects of vegetation on wave attenuation (Maza et al., 2013; Ondiviela et al., 2014; James et al., 2021). A 40 % reduction in wave heights during storm events, revealing the capacity of a dense seagrass meadow was reported by Ondiviela et al. (2014). Along with *Posidonia oceanica*, three other native sea-grass species (de los Santos et al., 2019) occur along European coasts: *Zostera marina, Zostera noltei,* and *Cymodocea nodosa*. As reported in Procaccini et al. (2003), *Zostera marina* is present along central Adriatic coasts, and it could really exist along the coast if the mean wave heights are <0.4 m. In the North Adriatic Sea Danovaro et al. (2020) had reported a study for a 40-year period using aerial photographs/satellite images which revealed that the seagrass meadows grow in patches and not as continuous meadows along the coastal regions. Hence in this study across the Emilia-Romagna (ER) coastal belt the seagrass landscaping was chosen to reproduce the natural distribution of seagrass as evident from satellite images, from 2 m depth to 10 m, to avoid a position too close to the shoreline and to allow sunlight to penetrate the rather turbid coastal waters (Umesh et al., 2022).

Coastal dunes are frequent morphological features along coastlines (Berard et al., 2017; Schweiger et al., 2020) and are exclusive regions of biodiversity that protect the land against waves and storm surges by being at the forefront of protection against coastal flooding (Harley and Ciavola, 2013a). They are naturally dynamic coastal features that are highly prone to degradation and must therefore be protected. Storm-induced erosion is widely investigated with the XBeach numerical model (Roelvink et al., 2009). In the past this coastal erosion model has proven its applicability in accurately predicting storm-induced dune erosion (Splinter and Palmsten, 2012; Muller et al., 2017; van Ormondt et al., 2020). Several studies in the past have reported on the effects of vegetation on nearshore hydrodynamics and morphodynamics (Arnold Van Rooijen, 2019; Bendoni et al., 2019; Harter and Figlus, 2017; Nederhoff, 2014; Passeri et al., 2018; van der Lugt et al., 2019). Dune restoration projects that integrate vegetation efforts with natural, sustainable, and soft solutions have become increasingly popular, as reported in a study by D'Alessandro et al. (2020). The study

conducted by Montblanc et al. (2020) on a rapidly eroding coastline in Bellocchio (Northern Adriatic Sea, Italy) under the current and future sea level scenarios concluded that a complete rehabilitation of the existing dune-system, including its reconstruction and revegetation, can be considered as a disaster reduction solution for coastal protection under current and future scenarios. The application of combining seagrass meadow restoration with sand nourishment termed as "green nourishment" has a high potential as NBS to mitigate coastal erosion/flooding (Chen et al., 2022).

The integrated management of coastal zones adopted by the ER Region (northern Italy) requires strategic, coordinated and concerted actions at local and regional levels, directed and supported by a specific reference framework at a national level. Due to a high littoral vulnerability to coastal erosion and the risk of marine ingression, the Regional Action Plan (Danjon, 1960) identifies coastal stability as a crucial environmental problem. A high concentration of anthropogenic interests, and activities related to a multiplicity of sectors are of immense importance for the regional economy, thereby emphasizing the importance of an adequate local coastal management (Armaroli et al., 2012; Harley et al., 2012; Coelho et al., 2020). For many years the management and protection plans of the coastal areas in the ER region have been based on infrastructural interventions and rigid works to protect the coast, included breakwaters and seawalls. However, these solutions have highlighted numerous disadvantages and problems related to their construction (excessive costs), maintenance, and unwanted effects caused in neighboring areas (Nunn et al., 2021). Therefore, different solutions involving sustainable and ecological efficiency should be investigated so their benefits and drawbacks can be appropriately analyzed. As an example, ecosystem-based coastal defense strategies have been recommended to replace hard infrastructures (Gracia et al., 2018). In recent years a significant growth and demand has been observed in scientific and engineering interest to investigate how natural coastal defenses can actually improve coastal protection.

This study was executed within the OPERANDUM (OPEn-airlaboRAtories for Nature-baseD solUtions to Manage hydro-meteo risks) project (https://www.operandum-project.eu/) and its main goal is to provide science-based evidence for the usability of NBS ranging from local to landscape scales, and to foster the market opportunities, upscaling and replication of NBS in Europe and other non-European territories. OPERANDUM consists of several Open Air Laboratories (OAL) in Europe (Gallotti et al., 2021). In OAL Italy, two types of NBS for coastal risk mitigation have been investigated, namely: an artificial dune entirely composed of natural materials, and a seagrass meadow.

While numerous studies on the reconstruction of dunes have been reported in the past (Lemauviel et al., 2003; D'Alessandro et al., 2020; Montblanc et al., 2020), this paper proposes an innovative approach through the construction of an artificial dune, an alternative to already existing dunes, and entirely built with natural materials. The dune is made of sand, coconut fibers, and wooden poles assembled in a modular structure that can therefore be adapted to any type of beach and shoreline length.

The artificial dune is a passive erosion control system, intended as an artificial embankment that must be put in place in a specific coastal area affected by wave erosion especially during storms. The dune aims to protect the areas behind it against wind, waves and tidal actions. In contrast with traditional embankment or reinforced earth systems, realized using only natural materials and technologies, this approach aims to minimize environmental impacts (i.e. pollution due to bulldozers or working vehicles, soil contamination, or natural environment destruction) even during the construction phase, and to mimic the natural behavior of previously existing, and effective natural sand dunes.

Unlike the more common applications in which NBS are used in a complementary way to gray solutions or alone, this study is unique in it aims to investigate the potential of integrating two eco-sustainable NBS intended to significantly reduce environmental impacts. Thus, the goal of the study is to understand the interaction of wave impacts with the combination of an artificial dune built with natural materials and a seagrass meadow. The integration of the two NBS is investigated in terms of potential flood reduction and the mitigation of negative impacts on beach morphology.

The paper is divided as follows: Section 2 describes the study area, the investigated NBS and the modeling approach adopted for the simulations. Section 3 reports on and discusses the simulations' results. In Section 4 a brief discussion on the study is performed and in Section 5 the main conclusions of the study are outlined.

2. Materials and methods

2.1. Study area

Bellocchio Beach is a natural reserve located in Lido di Spina (Italy) in the northern Adriatic Sea (Fig. 1a). The beach is one of the remaining natural coast of the ER region and is located between the Reno River (to the south), and the city of Lido di Spina (to the north). It consists of a three-kilometer low, sandy beach with a lagoon behind it. There are no natural or artificial defenses except for a temporary sand deposit and a little cross-shore wooden groyne located on the northern beach (Fig. 1b). Indeed, littorals to the north and south are protected by hard structures. The Dolce Vita Beach Club on the northern part of the beach is built on a rock armor acting as a barrier against sediment transport (Aguzzi et al., 2020).

Bellocchio Beach is a transitional ecosystem (dune and lagoon) characterized by inland human activities and infrastructure, both exposed to marine flooding. The main risks identified are therefore related to the loss of ecosystem functionality, the damage to infrastructure, and the loss of potential tourism.

Most incoming hydro-meteorological hazards are induced by storms that produce marine flooding and coastal erosion. The most intense storm waves are generated from east to northeast and are associated with Bora weather conditions. These events are generally characterized by large, steep waves. Surge events mainly occur during *Scirocco winds* that blow from south to east, creating smaller waves with a long wave period (Harley et al., 2012).

With regard to sediment supply, the Reno River provides the largest amount, which has been strongly limited as a result of human intervention and the presence of rigid structures. The main long shore transport is south-north oriented as indicated in Fig. 1b. Emerging from the negative sediment balance, Bellocchio beach retreat rates are around 8 m/year. Furthermore, local subsidence is a concern, with current rates about 2 mm/year (Aguzzi et al., 2020).

Both the beach and the lagoon are threatened by marine flooding. Despite the limited surface, the area is one of the sites with greater biodiversity. There are 19 habitats protected by the EU Habitat Directive (European Commission, 1992) including i.e. *Spartina* meadows, *Salicornia* annual pioneer vegetation and other muddy and sandy areas, embryonic mobile dunes. In addition, there are over 40 species of birds (The European Union, 2010), some of which nidificate more or less regularly in the area. It is one of the most important sites at a regional level for the protection of nidification: *Charadrius alexandrinus* ("Fratino" in italian) and *Haematopus ostralegus* ("Beccaccia di mare" in italian) (The European Union, 2010).

A residual natural dune system is located on the Natural Reserve of Bellocchio and extends for about 1.4 km along the beach (Fig. 2). The dune system suffered great damage over the years due to extreme events, which led to a strong variability in dune crest heights (from 1.2 m up to >2 m) and widths ranging from 40 m to 70 m (Montblanc et al., 2020). Washover lobes caused by marine ingression, especially during intense storm events, can be observed in the area behind Bellocchio Beach.

The tidal regime is semi-diurnal and micro-tidal, with a neap tidal range of 0.3–0.4 m, and a spring tidal range between 0.8 and 0.9 m. Wind waves arrive mostly from NE and SE, with a significant wave height (Hs) of 0.4 m representing average conditions, while during storm events, wave heights can reach up to 4.5–5.6 m (Ciavola et al., 2007; Armaroli et al., 2012).

2.2. NBS description

In this paper two NBS are investigated: a seagrass meadow of *Zostera marina* and an artificial dune built completely with natural materials.
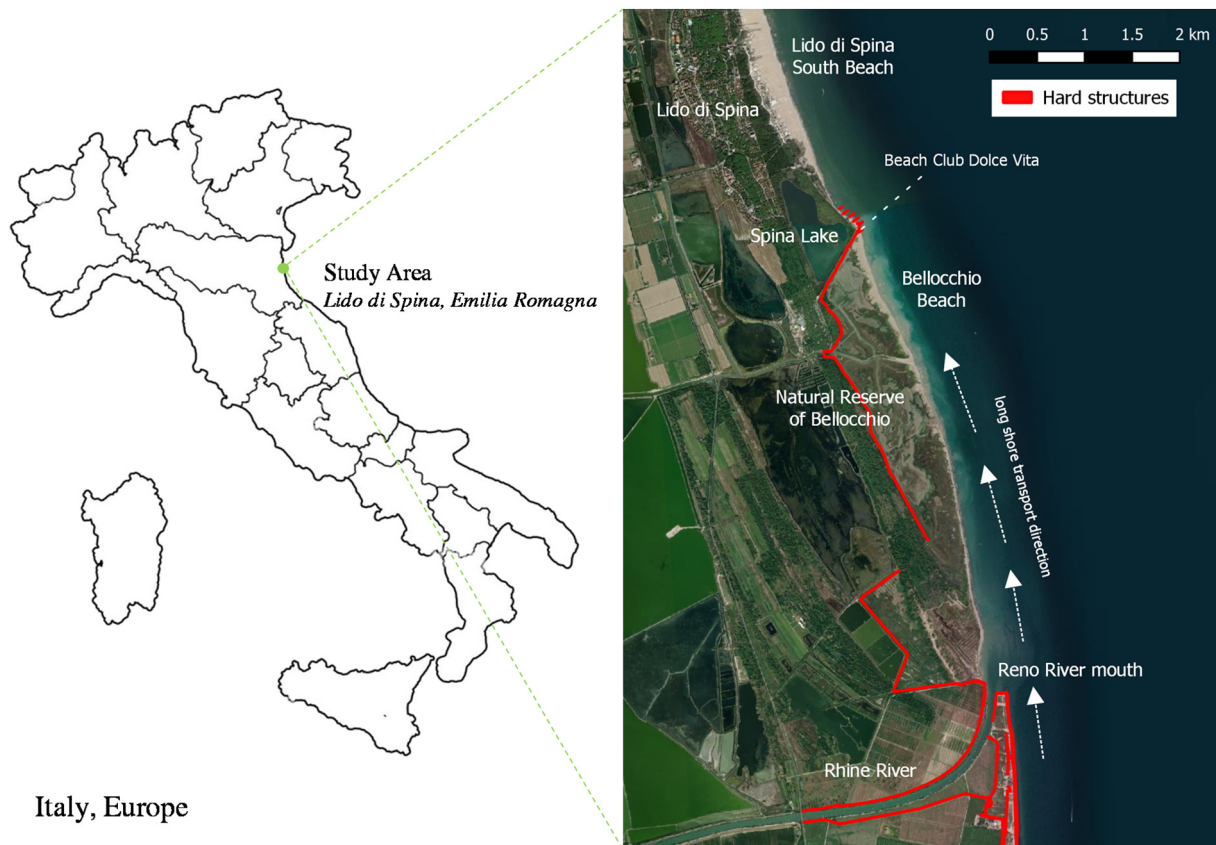
Fig. 1. (a) Location of the Bellocchio Beach in the Emilia Romagna coastal region and (b) the main longshore sediment transport orientation, and the hard structures location (indicated in solid red lines).

2.2.1. Seagrass meadow

The first NBS investigated consists of coastal vegetation placed on the sea bottom with the aim of providing protection by attenuating and/or dissipating waves.

Seven species of seagrasses occur in the Mediterranean Sea (Boudouresque et al., 2009; Ruíz et al., 2009; de los Santos et al., 2019). *Cymodocea nodosa*, *Zostera marina* and *Zostera noltei*, native to the Mediterranean, have a broader temperate distribution. *Posidonia oceanica* is the only one that is endemic to the Mediterranean (Ruíz et al., 2009).

More specifically, among the few species that survive in northern Adriatic Sea, *Zostera marina* is able to live in a marine environment influenced by freshwaters and it is present along central Adriatic coasts as reported in Procaccini et al. (2003). As stated by Boudouresque et al. (2021) in the northern part of the Mediterranean Sea (i.e. Adriatic sea), the decline of *Zostera marina* meadows has been related to human activities: pollution, turbidity, freshwater inputs, anoxy. On the contrary, extensive meadows are still thriving in many localities i.e., Venice Lagoon, the Gulf of Fos (France), Els Alfacs Bay (Spanish Catalonia), Thau Lagoon (Pergent et al., 2012).

Zostera marina is principally constrained by two physical thresholds, namely, wave height or exposure and light (Hirst et al., 2017). Especially, it can exist along the coasts if the mean wave height is <0.4 m and a mean percentage irradiance of >33 % (Hirst et al., 2017). For these reasons, this species was selected to investigate the effect of submerged seagrass meadows on wave heights via numerical simulations. Future deployment of the seagrass has not been foreseen within the project's duration.

2.2.2. The artificial dune built completely using natural materials

An artificial dune is an engineered structure that mimics the function of natural dunes. Artificial dunes aim to reduce both coastal erosion and flooding in adjacent coastal lowlands. They consist of a barrier in between the sea and land, similar to a seawall. Unlike the latter, the NBS are"dynamic", i.e. the dune/beach system interacts a great deal and is constantly undergoing small adjustments in response to changes in wind and wave climate, or sea level. Its construction involves the placement of sediment from dredged sources on the beach which is then reinforced with a structure composed of biodegradable material. In the project the NBS is designed to be 100 m long, 3.5 m a.s.l. (above sea level) high with a slope of 1:2 (Fig. 3c). The design is the responsibility of RINA-Consulting (https://www.rina.org/it/), partner of the OPERANDUM Project. Different types of experimental solutions are foreseen. A more complete description of the modeling techniques and the monitoring system that guided the design of the dune can be found in Aguzzi et al. (2021).

The first section of the dune is realized using a reinforced bio-soil system, while the second section has an innovative modular tubular system (Fig. 3a,b). For both types flexible, semi-permeable natural materials are used, such as coir geotextile and wood (Fig. 3d). The bio-soil reinforced type (Fig. 3a) comprises overlapping layers of sand and coir geotextile, displayed in (Fig. 3d, source: Naturalea, https://naturalea.eu/en/) up to the required height and slope. The body of the dune is supported by two lines of wooden poles.

The tubular structures (Fig. 3b) are generated from geotextile or geomembrane fabrics by joining the opposite edges with zips. One single tubular element is joined to another tube simply by zipping them together, avoiding the need for sewing or welding on-site, and long tubes are obtained by connecting several tubes together until the desired length is achieved. This structural solution is made with three tubular modules arranged longitudinally between four lines of wooden poles, giving the dune the desired slope and layout.

The body of the dune is covered by sand with an average thickness of 20–30 cm. Two different cover solutions are adopted along the dune length.
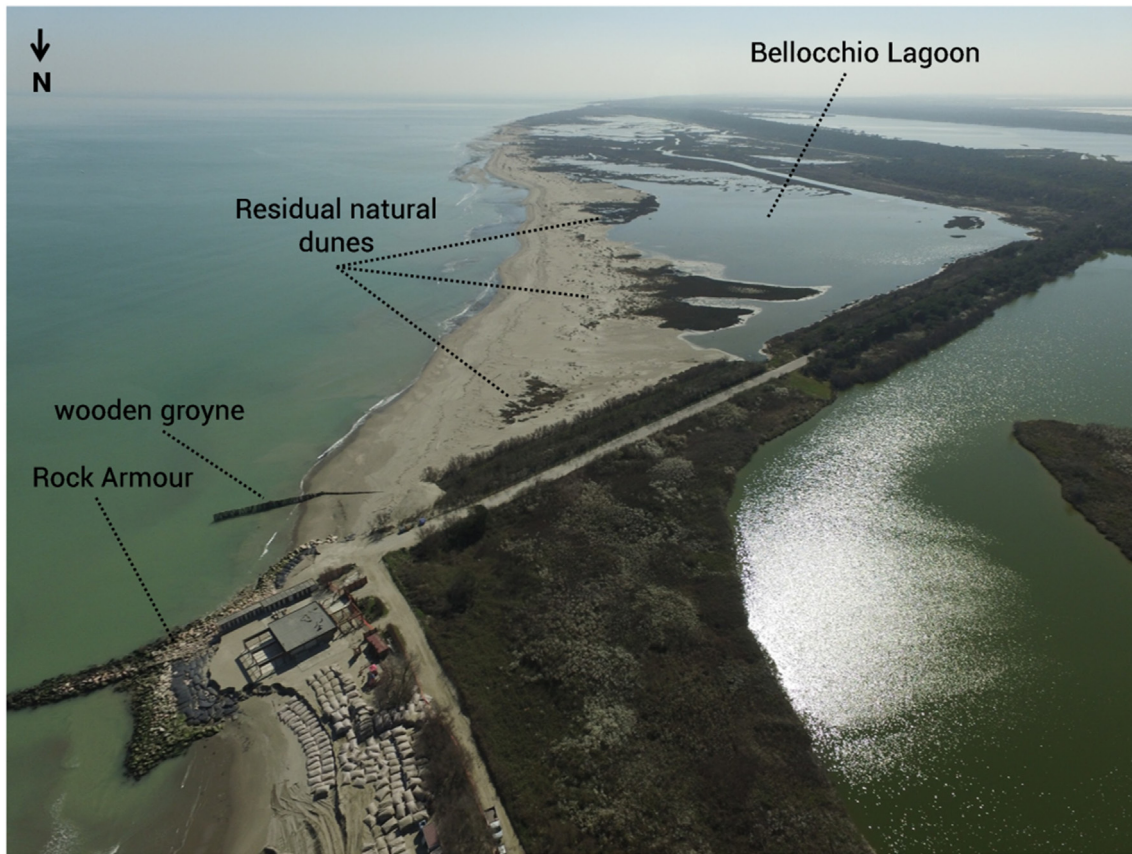
Fig. 2. Aerial view of the northern part of Bellocchio beach, indicating the location of the residual natural dunes, the wooden groyne, and the rock armor.

Autochthonous plant species are planted in part on the coir net and in part directly in the sand (Fig. 3a,b).

On the seaward side and on the terminal ends of the dune another wood protection is installed. It consists of a double wood palisade filled with wooden stacks and heather fascines from plant materials available on site. In the front of the dune fascines are disposed horizontally, while on the ends fascines are placed vertically. These structures protect the foot of the dune and inland area by absorbing energy and trapping sand brought by storm waves.

The proposed artificial dune will actually be built on the beach, however due to an unfortunate intense storm in the winter of 2020 the beach was heavily damaged and a different site was chosen for the actual construction. However, due to its environmental peculiarities and coastal issues, numerical modeling was performed using the original site.

2.3. Methodology

2.3.1. Modeling approach

The performance of actions to mitigate coastal flooding and reduce impacts on beach's morphological evolution via NBS (described above) was assessed through numerical simulations using the XBeach hydro-morphological model. Current beach conditions without any natural defenses (denoted as "REF") were modeled and compared with three different NBS scenarios, as summarized in Table 1, encompassing the seagrass effect only (denoted as "VEG"), the presence of the artificial dune (denoted as "DUNE") and their combined effect (denoted as "INT").

The use of the two NBS was tested with respect to the unprotected scenarios during significant storm conditions that took place on the beach from 2010 to 2020. Three historical storms (hereafter named S1, S2 and S3) that caused heavy damage to the natural environment of the study area were selected with the goal of evaluating if and how NBSs could improve coastal protection against flooding and erosion under storm conditions. Table 1 lists the simulations performed and their names.

The effect of seagrass meadows on waves was explored. Significant wave height with and without vegetation were compared at two local stations of the model domain. The percentage wave attenuation (att_w) was evaluated with Eq. (1):

$$att_w = \frac{H_{s,REF} - H_{s,VEG}}{H_{s,REF}} \cdot 100 \qquad (1)$$

where $H_{s,\ REF}$ and $H_{s,\ VEG}$ are the significant wave height without and with vegetation respectively.

The efficiency of both the seagrass and the dune in reducing flooding impacts was evaluated by calculating the maximum inundation depth ($IDmax$), defined as the non-simultaneous maximum water depth on the beach domain and derived from the runup values modeled with XBeach. The maximum inundated area was also estimated for each run, defined as the area involved by the inundation based on the maximum flood depth maps. Therefore, it represents the non-simultaneous maximum inundated area. The assessment of the flooded area was performed within the lagoon area. The percentage rate of flooding attenuation (att_{flood}) was defined as in Eq. (2):

$$att_{flood} = \frac{Aflood_{REF} - Aflood_{SIM}}{Aflood_{REF}} \cdot 100 \qquad (2)$$

where $Aflood_{SIM}$ is the maximum inundated area with an NBS design and $Aflood_{REF}$ the maximum inundated area without NBS estimated from the reference simulation, both calculated for the same historical storm. Likewise, the attenuation of the $IDmax$ was also calculated referred to the highest value reached by the lagoon, named att_{IDmax}.
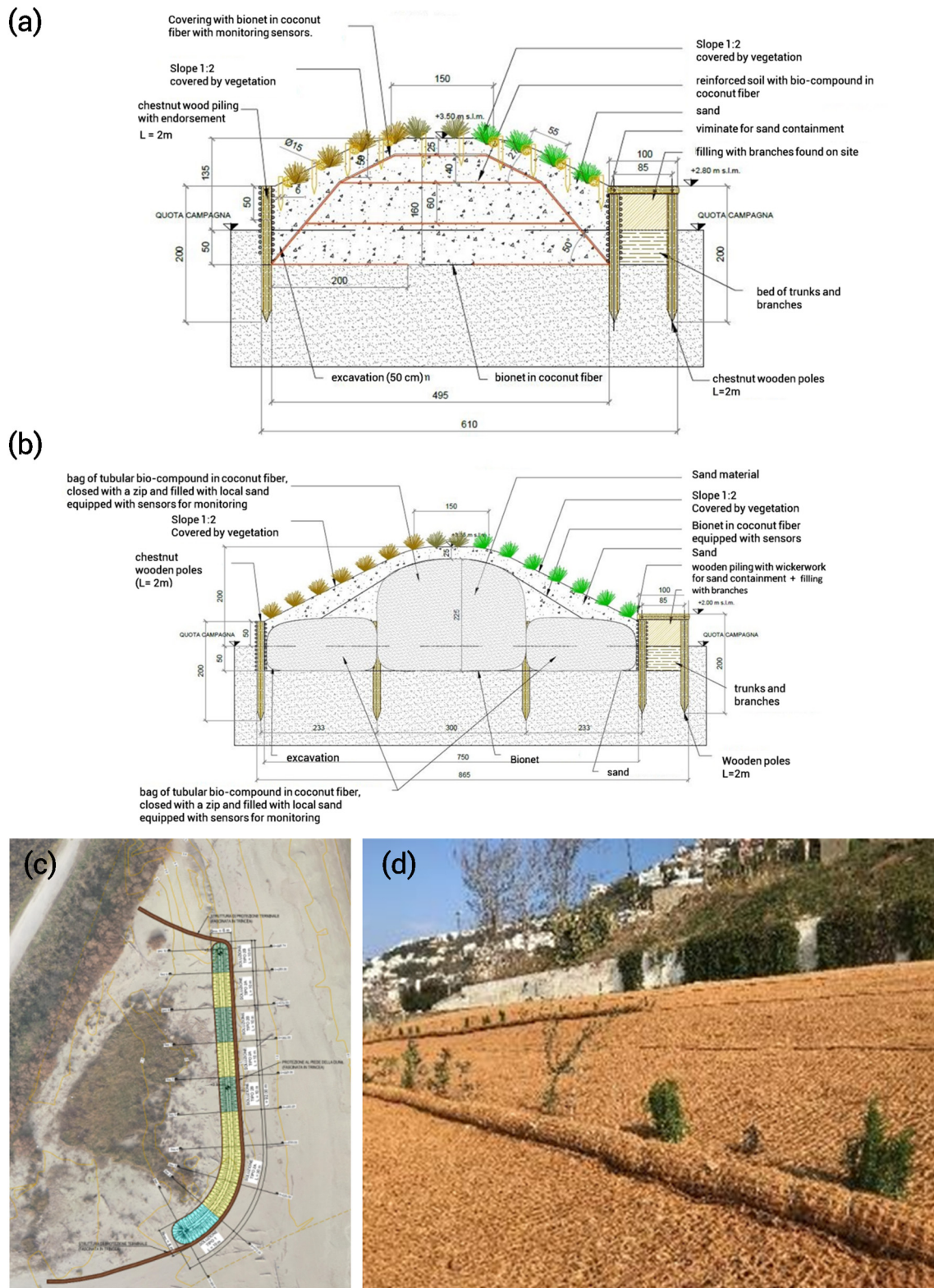
Fig. 3. Dune layout and details. (a) Detail of reinforced bio-soil system (layout 1), source: RINA-C (b) Detail of modular tubular system (layout 2), source: RINA-C, (c) Dune layout map where: yellow zones indicate bio-soil reinforced with coir net, light blue identifies tubular modules in coir net with hinge system patent and green parts are covered with runoff control system in coir net, source: RINA-C and (d) Coir blanket with runoff system control, source: Naturalea.

A cross-shore section that is located in a coastal stretch subjected to strong erosion was chosen for morphological analyses of the landward movement of the shoreline and the eroded volumes of the subaerial beach. Percentage rates of shoreline retreat and eroded volumes were defined in the same manner as the previous indicators (att_{shore}, att_{ero}).

Bathymetry changes were also calculated by subtracting the original topography from the topography at the end of each simulation, identifying

Table 1
Summary of numerical simulations performed with XBeach.

Description	Identifier	Storm	Simulation name
Current beach conditions without any NBS	REF case	S1	REF1
		S2	REF2
		S3	REF3
Scenario with the seagrass effect	VEG case	S1	VEG1
		S2	VEG2
		S3	VEG3
Scenario with the artificial dune protecting the entire Bellocchio beach strip (about 1.5 Km long)	DUNE case	S1	DUNE1
		S2	DUNE2
		S3	DUNE3
Scenario with both the seagrass and the artificial dune	INT case	S1	INT1
		S2	INT2
		S3	INT3

positive values as accretion, and negative values as erosion (Montblanc et al., 2020).

2.3.2. XBeach model

XBeach (Roelvink et al., 2009) is a state-of-the-art open-source model designed to simulate nearshore hydrodynamics and morphodynamics. XBeach, which is the acronym for "eXtreme Beach behavior model", seeks to assess the natural coastal response during time-varying storm and hurricane conditions. It is a two-dimensional depth-averaged (2DH) model that solves coupled cross-shore and alongshore equations for wave propagation, flow, sediment transport and bed level changes. The model includes the hydrodynamic processes of short-wave transformation (refraction, shoaling and breaking), long-wave (infragravity wave) transformation (generation, propagation and dissipation), wave-induced setup and unsteady currents, as well as overwash and inundation. The morphodynamic processes include bed load and suspended sediment transport, dune face avalanching, bed update, and breaching. It is able to predict dune erosion, overwash and breaching of dunes and barrier islands (Lindemer et al., 2010; Ferreira et al., 2018; Schambach et al., 2018; Schweiger et al., 2020). In several studies the model has been validated with a series of analytical, laboratory and field test cases using a standard set of parameter settings (Roelvink et al., 2009; McCall et al., 2010; Vousdoukas et al., 2011). Moreover, XBeach is capable of simulating flow, waves, sediment transport and coastal morphological changes (Roelvink et al., 2009) in scenarios that include NBS, such as mangroves, sea grass, coral reefs, etc. As demonstrated by Van Rooijen et al. (2016) XBeach allows incorporating the effect of vegetation on wave evolution based on isolated rigid cylinder theory. As stated by Kumar et al. (2021), XBeach has great potential for evaluating NBS detailed performance at the local scale. A detailed presentation of the governing equations and the boundary conditions is available in Roelvink et al. (2009).

2.3.3. Model setup

A two-dimensional version of XBeach (Roelvink et al., 2009) was applied to morphodynamics during representative storm events along the ER coast. The XBeach simulations were realized by applying the surfbeat mode commonly used during storm conditions (Bart, 2017). Version 1.23.5526 of XBeachX was adopted for this study.

The 2D computational domain consists of a 3.2 km × 2.6 km section of Bellocchio Beach at Lido di Spina, ER in Italy (Fig. 4). The structured grid
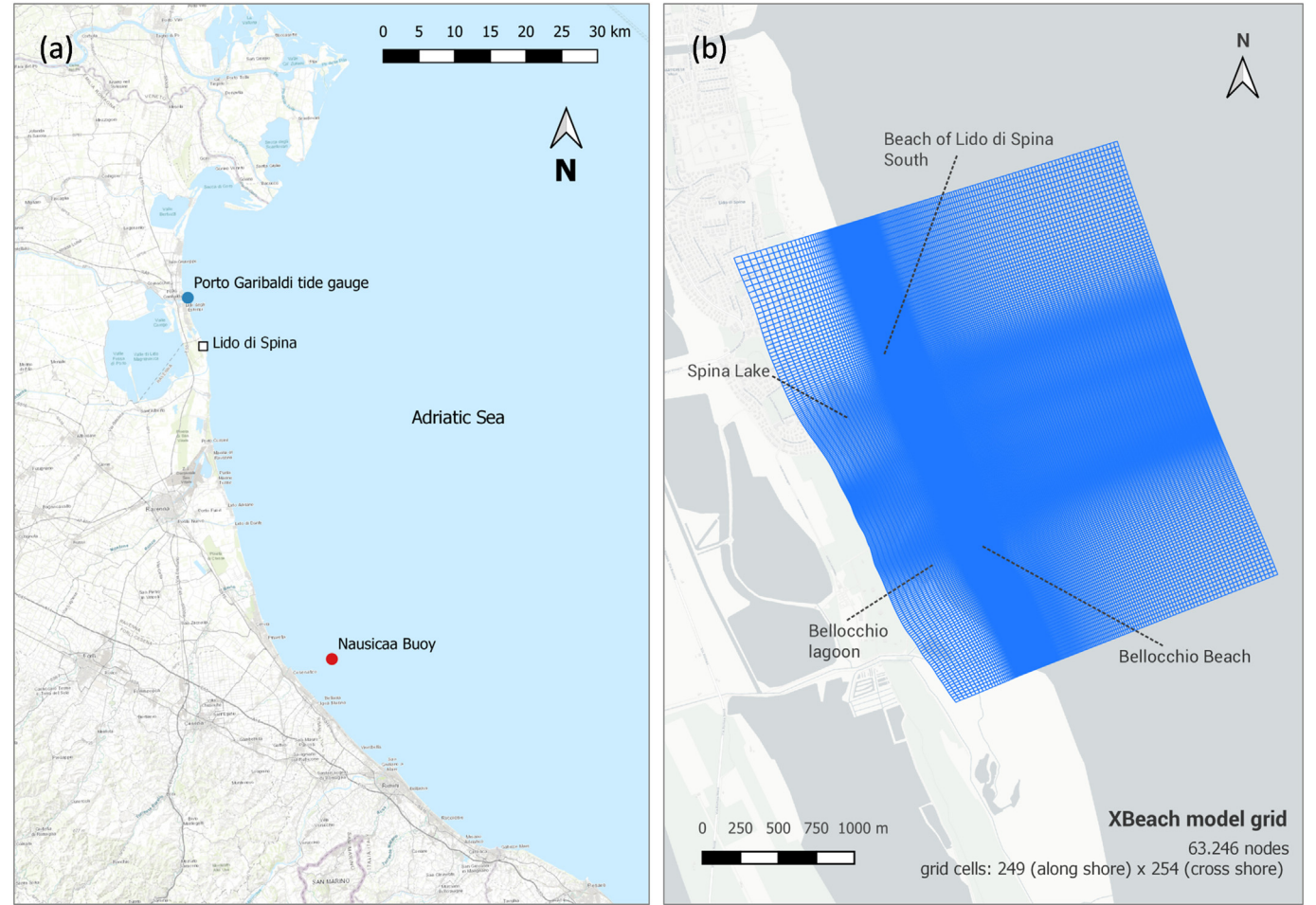

Fig. 4. (a) location of the Nausicaa Buoy and the Porto Garibaldi tide gauge along the Emilia-Romagna coast (Italy), and (b) the model grid of Bellocchio Beach at Lido di Spina, Emilia-Romagna (Italy).

consists of 249 grid cells in y-direction (alongshore) and 254 grid cells in x-direction (cross-shore), and a total of 63,246 nodes. A variable resolution of grid size was applied with a model resolution in the range 1–20 m cross-shore and in the range 5–30 m alongshore (increasing resolutions were applied appropriately). The morphological and hydrodynamic grid extends landward to cover the entire lagoon area, often affected by flooding conditions, and seaward to about 10 m depth. Different topo-bathymetric measurements were interpolated on the morphological grid and used as input for the simulations. The available data consist of:

- Topo-bathymetric survey conducted in 2020 for the OPERANDUM Project, focused on the beach area where the dune will be built.
- Topo-bathymetric survey conducted in 2019 as part of the Regional Topo-bathymetric Network systematically monitored by Arpae, consisting of about 250 beach cross-sections covering the entire regional littoral.
- LIDAR data collected at Lido di Spina in February 2019 on behalf of the ER Regional Service (Autorità di Bacino Distrettuale Fiume Po).

The bed composition was defined with D50 and D90 grain diameters of 0.2 and 0.3 mm respectively and was considered constant across the whole domain (Aguzzi et al., 2020). Sediment transport was simulated using a depth-averaged advection-diffusion equation where the van Thiel-van Rijn formulation is adopted for the calculation of sediment flux (van Rijn, 2007; Thiel de Vries, 2009). Bed friction was modeled through Manning's roughness coefficient (*bedfriction*) and set to 0.02 for sandy sediments. In order to accelerate the morphological variations with respect to the hydrodynamic processes, an acceleration factor of 5 (*morfac* = 5) was adopted (Roelvink et al., 2009).

Variable water levels and wave forcing during three storm events were imposed at the sea open boundary of the model, while zero-gradient alongshore water level conditions (Roelvink et al., 2009) were invoked on the lateral boundaries. Offshore wave conditions were specified using the JONSWAP spectrum (Joint North Sea Wave Project). Waves (height, direction and period) and sea level time series used to force the model were extracted respectively from the Nausicaa Buoy located offshore of the Cesenatico municipality at about 10 m depth (44.2155 lat, 12.4766 lon) and the Porto Garibaldi tide gauge in Ferrara (44.6779 lat, 12.2494 lon). The time-series observed at the chosen stations (showed in Fig. 4) are consistent and constantly validated.

The effects of vegetation on wave propagation were included in XBeach through formulations that take into account vegetation-induced sea-swell wave attenuation, mean flow reduction, mean water level effects and infragravity wave attenuation (Van Rooijen et al., 2016). In XBeach vegetation is schematized as rigid cylinders that exert a force on the fluid, with parameters including vegetation stem height (ah), diameter (bv), and density (Nv). Multiple layers of vegetation could be introduced to define, for instance, mangroves, which have dense roots and sparse stems. In this study one vertically uniform vegetation layer was used to simulate seagrass.

The model was calibrated against available topographic data by varying a few parameters that have a significant impact on morphodynamic evolution (Vousdoukas et al., 2011; Vousdoukas et al., 2012; Roelvink et al., 2018). A detailed description of the calibration can be found in the results section.

2.3.4. NBS modeling schematization

The effect of vegetation is implemented in XBeach through formulations that take into account the wave energy dissipation occurring when waves propagate through a vegetation field. To take into account the damping effect of vegetation on the incident waves, the expression derived by Mendez and Losada (2004) was added to the short wave action balance in Eq. (3):

$$\frac{\partial A}{\partial t} + \frac{\partial c_g A}{\partial x} = -\frac{D_{break} + D_{veg}}{\sigma} \tag{3}$$

where $A = E_w/\sigma$, E_w is the wave energy, D_{break} is the wave dissipation due to breaking and D_{veg} is the wave energy dissipation due to the presence of

vegetation. Following Suzuki et al. (2012) the expression was slightly adjusted to take into account vertical layering of the vegetation (Eq. (4)):

$$D_{veg} = \sum_{i=1}^{n_v} D_{veg,i} \tag{4}$$

where D_{veg} is the total short wave energy dissipation due to vegetation, nv is the number of vertical vegetation segments and $D_{veg,\ i}$ is the short wave energy dissipation due to the vegetation layer i (Eq. (5)):

$$D_{veg,i}$$
$$= \frac{1}{2\sqrt{\pi}} \rho \tilde{C}_D b_v N \left(\frac{kg}{2\sigma}\right)^3 \frac{\left(\sinh^3 k\alpha_i h - \sinh^3 k\alpha_{i-1} h\right) + 3\left(\sinh k\alpha_i h - \sinh k\alpha_{i-1} h\right)}{3k \cosh^3 kh} H_{rms}^3 \tag{5}$$

Using this expression, both vertically uniform vegetation (e.g. sea grass) and vegetation with a (strong) variation in characteristics over the vertical axis can be modeled (e.g. mangroves).

The damping effect of vegetation not only affects the dissipation of wave energy, but also infragravity waves and mean flow, and is modeled as a drag force directly included in the depth-averaged Generalized Lagrangian Mean (GLM) formulations (Andrews and Mcintyre, 1978). The vegetation-induced drag force (Eq. (6)) is calculated as the sum of the vegetation-induced drag force per vegetation layer (Eq. (7)):

$$F_{veg}(t) = \sum_{i=1}^{n_v} F_{veg,i}(t) \tag{6}$$

$$F_{veg,i}(t) = \int_{\alpha_{i-1}}^{\alpha_i} \frac{1}{2} \rho \tilde{C}_{D,i} b_{v,j} N_i u^L(t) |u^L(t)| dz \tag{7}$$

The bulk drag coefficient (C_D) is an expression for the dissipation of wave energy and force exerted by the fluid on the entire seagrass meadow. For this simple exploration, a drag coefficient of 1 was used (Beudin et al., 2017), although the drag force exerted on the vegetation can vary considerably, between values close to 0 to 3 (Nepf and Vivoni, 2000; Tanino and Nepf, 2008). Seagrass physical characteristics necessary for the parameterization were taken from Mazzella et al. (1998) in terms of number per shoot / m² (277.8 n°/m²), mean leaf length (21.3 cm), and mean leaf width (0.38 cm).

The seagrass landscaping, shown in Fig. 5 was derived from Umesh et al. (2022) which presents a seagrass assessment via validated numerical simulation of marine seagrass meadow in the ER (Italy) coastal strip in the offshore area of Bellocchio Beach.

Umesh et al. (2022) demonstrated that *Zostera marina* meadows applied to the ER coastal belt by means of WW3 simulations (Alves and Ardhuin, 2016) were found to be efficient in the reduction of wave energy (> 50 %). It was shown that the amount of significant wave height (Hs) reduction depends on seagrass landscaping, and a combination of broken vegetation stripes and clusters were seen to be effective in reducing wave energy at the coast compared to other landscape designs. The most effective seagrass landscape presented by Umesh et al. (2022) was investigated in this paper through XBeach simulations (Fig. 5).

The geometry of the artificial dune was included in the initial bathymetry of XBeach runs by raising the topography point by point. Although several artificial dune cases were studied by other authors (Gesing, 2019; Harley and Ciavola, 2013b; Schweiger et al., 2020) no well-documented modeling case studies with XBeach or others numerical models of artificial dunes similar to the one presented in our study have been found by the authors. Therefore, given the NBS complexity (due to different building materials) and in order to achieve as real a representation as possible, some assumptions were made.

First, the construction of the artificial dune provides a unique opportunity to study its responses on a prototype scale with the potential for improvements in design criteria. However, it consists of a limited "experiment" of a coastal defense that needs to be considered on a wider scale in order to produce real improvements in coastal risk mitigation. For this reason, while the actual deployment extends for about 100 m, in

Fig. 5. Seagrass meadow belt and dune position along Bellocchio Beach in Lido di Spina. The seagrass location is displayed with green polygons while the dune layout is represented by a solid red line.

order to mimic the function of a barrier against marine ingression, the simulations were carried out considering an artificial dune that protects the entire coastal environment subject to frequent flooding. The modeled dune is presented in Fig. 5 and extends for about 1,5 km alongshore. Due to the varying amplitude of the beach, a constant distance from the shoreline could not be maintained. However, the structure was placed on the subaerial beach ensuring the protection of residual dunes that have been disappearing over the years due to intense storm impacts (Montblanc et al., 2020).

Given that variations in bed friction have potential influence in morphological changes during storm events, similar to other studies (Passeri et al., 2018; Schambach et al., 2018; Schweiger et al., 2020), a constant Manning's bottom friction of 0.2 was applied to the entire domain with the exception of the dune structure, where an increased value of 0.6 was set. The reason is to consider the roughness of the coir blanket and its function in restraining sand.

Given its innovative modular tubular system, layout 2 (described in Section 2.2.2) was chosen for the modeling experiment presented in this study. The artificial dune is considered a semi-fixed dune (Lemauviel et al., 2003; Yizhaq et al., 2009) due to its modular tubular structure,

which is supposed to be more resistant than melted sand. In XBeach it was defined as a non-erodible layer with an additional sand cover of 0.5 m.

2.4. Storm selection

Storms are considered the main factor controlling changes in beach morphology (Armaroli et al., 2013; Plomaritis et al., 2018). In this study the effectiveness of NBS was assessed by calculating the coastal impacts of historical storm events using the process-based XBeach model (Roelvink et al., 2009). In order to evaluate the degree of protection against severe storms experienced along the ER coast offered to the coastal lagoon by the two natural solutions, the storms were selected by analyzing the storms observed from January 2007 to December 2020. This analysis was applied to the wave time series measured by the Nausicaa Buoy. Sea level time-series were derived from the Porto Garibaldi tide gauge observations. The stations location is indicated in Fig. 4a.

In this study a storm is defined as an event with significant wave height >1.5 m. Two storms are considered separate if the wave height decays below the threshold for 12 or more consecutive hours. In order to classify the events, the methodology specific to the Western Mediterranean by (Mendoza and Jiménez, 2005) was adapted to the Northern Adriatic by (Armaroli et al., 2007) and followed in this study. The total energy of each storm (E) is defined as the time integral of the squared significant wave height computed between the beginning and the end of the event following the methodology in Mendoza and Jiménez, 2005 (Eq. (8)):

$$E = \int_{t_1}^{t_2} H_s^2 dt \qquad (8)$$

Where t_1 and t_2 indicates the total duration of the event and H_s is the significant wave height. Each storm is then characterized (i.e. weak/moderate/significant/severe/extreme) based on the energy classes indicated in Perini et al. (2011).

The three storms selected, summarized in Table 2 in terms of duration, starting and ending date, maximum wave height, maximum sea level and storm energy, share the fact that they produced destruction and damage in the study area. Hereafter the storms will be referred to in the text as S1, S2 and S3 from least to most recent, as indicated in Table 2.

As reported by the ER Region Authorities that manage the geodatabase of sea storm impacts, during S1 intense winds blowing from the North-East (Bora winds) caused strong localized erosion in the emerged beach at Lido di Spina for a total extension of about 1.5 km producing an estimated loss of about 50,000 cubic meters of sediment. Damage to the wooden groynes was also observed.

S2 was characterized by strong winds initially coming from the N and then from NE (Bora), exceeding velocities of 70 km/h and with gusts up to 100 km/h. Wave height reached values up to 3.7 m offshore and 2 m near-shore while a water level peak of 0.85 m was measured by the Porto Garibaldi tide gauge. On the beach of Lido di Spina the broad flood area led to damage to tourist facilities, street inundation and driftwood and natural debris on the beach. A great deal of damage was suffered by the so-called winter dune, temporary sand mounds built to protect the beach during the winter. Moreover, >80 % of the piles of the wooden groynes located in front of Bellocchio Beach were destroyed or severely damaged.

S3 was an extreme storm widely studied at the local regional level (Perini et al., 2015a) due to its complexity and its exceptional character. The maximum wave height of 4.66 m coming from North-East (characteristic of the local "Bora Winds") and the maximum sea level rise of 1.31 m

Table 2
List of observed damage events selected for the modeling simulations using XBeach.

Storm	Start date	End date	Duration (hours)	Hs$_{max}$ (m)	SL$_{max}$ (m)	Dominant Wave Direction	Energy (m²·h)	Class
S1	2010-03-07 12:00 h	2010-03-10 00:30 h	80	3.91	0.86	North-East	382.27	3
S2	2013-11-10 23:30 h	2013-11-11 17:30 h	37	3.79	0.85	North/North-East	322.01	3
S3	2015-02-05 04:30 h	2015-02-06 09:00 h	50.5	4.66	1.31	North-East	414.85	4

reached during the storm are the highest values measured by the Nausicaa Buoy and the Porto Garibaldi station since 2007. The storm is one of the most catastrophic events for the ER littoral due to the concurrence of the highest wave and level values ever recorded. Damage in terms of erosion, marine ingression, infrastructural and coastal defense damage extended throughout the region's coast. Based on the energy classification, all the events analyzed were classified as "significant" except for S3, which is considered a "severe storm".

3. Results and discussion

3.1. Model calibration

Any model requires careful calibration to existing data sets before it can be used with any confidence (Splinter and Palmsten, 2011). A good modeling of sediment transport processes requires as many topography and bathymetry measurements as possible. XBeach experts commonly use beach profiles measured before and after storm events or small-scale laboratory experiments (Schweiger and Schuettrumpf, 2021) for model calibration. In this study, the amount of useful data close to storm events is rather limited. However, along the ER littoral a Regional Topo-Bathymetric Network (RT-BN) consisting of about 250 cross-shore sections is systematically surveyed to monitor morphological changes. The time interval between subsequent field measurements is around six years. Moreover, a topographic survey limited to the subaerial beach around the footprint of the artificial dune was performed in 2019 and 2020.

Calibration of the model was performed by adopting a dual approach: (i) by comparing the model outputs with morphological variations between 2019 and 2020 through the Brier Skill Score (BSS) index calculation (van Rijn et al., 2003; Sutherland et al., 2004; Roelvink et al., 2009); (ii) by assessing the annual trend of shoreline retreat along the surveyed cross-shore transects during the RT-BN and comparing the model outputs. Since the BSS assessment can only be performed for the emerged profile (where topographic data exist), a quantitative assessment of shoreline retreat was needed.

The BSS is given in Eq. (9) for comparing measured and simulated profiles.

$$BSS = 1 - \left[\frac{\langle |x_p - x_m|^2 \rangle}{\langle |x_b - x_m|^2 \rangle} \right] \tag{9}$$

where x_p is the predicted profile from XBeach; x_m is the measured profile (post-storm) and x_b is the initial (pre-storm) profile. The BSS classification given by van Rijn et al. (2003) states that BSS < 0, bad; 0–0.3, poor; 0.3–0.6, reasonable/fair; 0.6–0.8, good; and 0.8–1.0, excellent.

The domain used for the calibration is described in Section 2.3.3 and plotted in Fig. 4. The observed average annual trend in shoreline retreat is about 8 m/year along the study area (Aguzzi et al., 2020). XBeach simulations were performed for the period January 2019–December 2019. Observed data retrieved by the Nausicaa buoy, located at Cesenatico, and the Porto Garibaldi tide gauge were used as inputs (Fig. 4).

A shortlist of sensitive parameters relevant to the morphodynamic processes to verify model performance was chosen based on the best available literature review (Vousdoukas et al., 2011; Bugajny et al., 2013; Simmons et al., 2019; Schweiger et al., 2020).

The first step was to increase the parameterized wave asymmetry sediment transport component (*facua*), which will result in less net offshore sediment transport. The parameter was varied in the range 0–1 with an interval of 0.1, and a BSS of 0.82 was achieved with a value of *facua* = 0.2 (excellent according to van Rijn et al., 2003). A shoreline retreat of about 8 m was calculated, in accordance with the observed trend.

Furthermore, the breaker index in the wave dissipation model (*gamma*) was varied between 0.4 and 0.9 (Simmons et al., 2015). The best BSS of 0.63 was achieved with the default value of 0.55, therefore the *gamma* parameter was set to its default in the model simulations.

The last step was to increase the bed friction factor *fw*, which influences wave dissipation near the surf zone. Here again, the best BSS (0.75) with sensitivity tests was reached with the default value, while no relevant accordance with annual shoreline trends was achieved by increasing the parameter.

In conclusion, the best fit with the observed morphological variations was found with a *facua* value of 0.2, which influenced the erosion/deposition process reproducing the correct morphological trend of the beach for the period 2019–2020. Past studies have revealed the fact that erosion overestimation in XBeach can be partially overcome by increasing the facua parameter based on a site-specific calibration (Bugajny et al., 2013; Nederhoff, 2014; Shahrizal et al., 2018; Simmons et al., 2019; Vousdoukas et al., 2011).

3.2. Seagrass's effect on waves

In order to evaluate the effect of submerged seagrass on wave propagation the variation of significant wave height within the meadow was investigated. The effect of vegetation was studied under three selected storm conditions (S1, S2 and S3, see Section 2.4) by comparing modeled wave height with (VEG cases) and without (REF cases) the seagrass meadow at eight stations (Fig. 6, on the left). Table 3 summarizes the attenuation on waves induced by the seagrass for each stations plotted on the map in Fig. 6 (on the left) together with the wave height variations at Station 2, Station 3 and Station 6 during S1, S2 and S3 (Fig. 6 a-i).

Overall, the seagrass meadows produce a maximum attenuation in wave height variation in the range 49–89 %. The highest value was observed during S3 at Station 1 (89 %) while the lowest reduction (49 %) occurred at Station 5 during S1 (Table 3). Incident waves are clearly decreased by the seagrass, producing an important attenuation in coastal risks. As indicated in Table 3, considering all the stations the mean attenuation in wave intensity ranges from 19 % to 34 %.

The wave height through the seagrass meadow tends to be attenuated over the entire storm duration with a greater impact on higher waves (Fig. 6). A similar result is also confirmed in the study of Umesh et al. (2022). In the same area, Montblanc et al. (2020) performed a study that investigated the use of vegetation to protect the coastal area by means of re-vegetation of the natural dune system. By investigating the vegetation effect on the wave peak at each station a maximum attenuation of 46 % was observed at station 2 during S1. In this case, the vegetation was able to reduce the wave peak from 2.64 m to 1.42 m. The wave peak percentage attenuation varies between 14 % (S1, Station 7) and 46 % (S1, Station 1). Overall, the vegetation is able to effectively produce an average attenuation of 32 % at the storm's peak.

3.3. Mitigation of coastal flooding due to seagrass

Having already established that seagrass can help mitigate incoming wave intensity, the effect of vegetation on coastal inundation was also investigated. Here we present a quantitative analysis of the maximum inundation areas and depths derived from the results of XBeach runs with (VEG) and without vegetation (REF). The purpose is to demonstrate the feasibility of this NBS to contrast inundation of the lagoon during the selected historical events.

Fig. 7 shows the inundation maps for S1, S2 and S3 with and without the seagrass effect (VEG and REF cases). Overall, the presence of seagrass tends to reduce the inundated area within the lagoon system, with the exception of S3. During this storm (Hmax = 4.66 m, SL = 1.31 m) seagrass is not efficient in reducing the extension of the maximum inundation. The percentage attenuation in the flooded area produced by the vegetation (VEG) in contrast with the REF cases is 32 % during S1and 37 % for S2. During S3 there is no attenuation induced by seagrass (0 %) versus the REF case.

Even though simulations found that seagrass induced an average attenuation of 25 % in wave height during S3, the failure to reduce the flooded area depends on water levels. In fact, Umesh et al. (2022) demonstrated
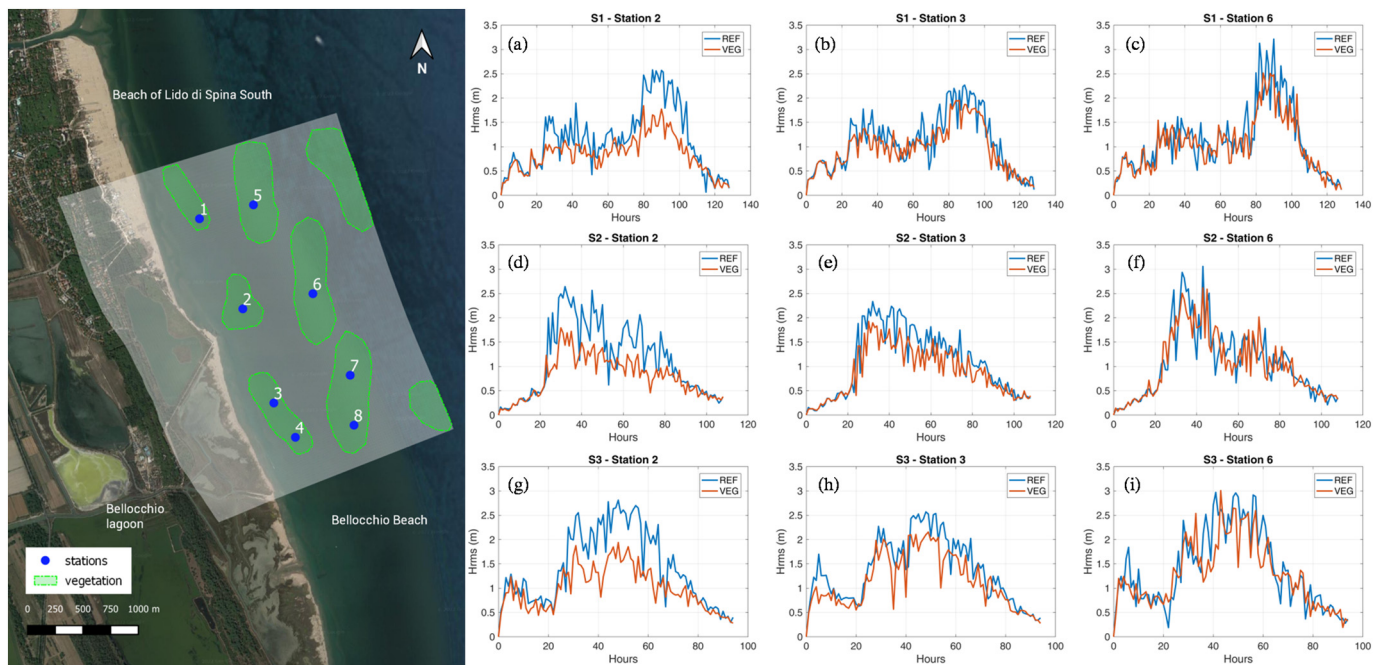
Fig. 6. Comparison of modeled significant wave height at three locations of the model domain within the seagrass meadows (Station 2, Station 3, Station 6), with (VEG) and without vegetation (REF) during the three storms investigated in the study (S1, S2 and S3). The map (image on the left) shows the vegetation pattern together with the locations. In the panel (right) showing the wave height (a-i) at the three locations, the blue line indicates the run without vegetation while the orange line represents the run with the seagrass.

that sea level is not affected by vegetation. The peak water level of 1.31 m observed during S3 produced a considerable inundation of the lagoon even in presence of seagrass, although an attenuation of 14 % in inundation depth is observed (Fig. 8). As mentioned above, ER coasts are particularly vulnerable to high water levels due to their morphological conformation characterized by low-lying sandy beaches and low-lying hinterlands often situated either close to or even below mean sea level (Harley et al., 2012). The risk of coastal flooding is higher the greater the rise in sea level (Armaroli et al., 2012; Oppenheimer et al., 2019).

The ER coastline is typically a low environment with semidiurnal and micro tidal regime (spring tidal range = 0.9 m), although storm surge anomalies of up to 0.6 m can occur, especially in winter months (Harley et al., 2012). The significant rise in sea level during S3 is an exceptional value for the regional coasts (Harley et al., 2011; Armaroli and Duo, 2018).

However, it is important to note that reduced values of maximum inundation depth are observed within the lagoon and showed in Fig. 8. The higher attenuation in water depths occurred during S1 (58 %). Maximum inundation depths within the lagoon without and with vegetation were

respectively 1.42 m and 0.59 m. Significant attenuations were also modeled during S2 (40 %) and S3 (14 %), Fig. 8.

While seagrass has proven effective in reducing the flooded area and maximum inundation depths, the results show that the lagoon is inundated during all storm events.

3.4. Sedimentation and erosion: can seagrass help?

It has been demonstrated by numerous researchers in the past that vegetation impacts not only the wave intensity, but also the concentration of suspended sediments and their sedimentation (Boudouresque et al., 2021; Chen et al., 2022). The morphological response of the seabed to S1, S2 and S3 was examined through the comparison of the final bed elevations observed for the scenario with (VEG) and without vegetation (REF cases) and presented in Fig. 9 (a,b,c). In the REF cases of S1, S2 and S3, due to the marine ingression in the lagoon, flow channels developed on Bellocchio Beach between the residual natural dunes, acting as artificial breaches for hinterland flow propagation. Thanks to wave and flooding attenuation, already demonstrated in this study, in the VEG runs the flow channels are not generated (see maps (a) and (c) of Fig. 9 where the channel locations are marked with black dashed circles and named "Channel n"). Moreover, the washover lobes formed within the lagoon area in the REF cases are heavily attenuated in VEG simulations, in particular under S1 and S2 (Fig. 9a,b). Instead, Fig. 9c indicates that there are no relevant changes in beach washover lobes during S3. For seagrass meadows (VEG cases), erosion of the shore at the beach of Lido di Spina South (northern part of the domain) is reduced compared to all REF cases. Indeed, a general tendency of accumulation in the region immediately shoreward is observed.

Finally, in contrast with REF cases, where seagrass meadows are present there is an increase in sediment deposition on the bottom (Fig. 9). The sedimentation is induced by the local presence of vegetation, which tends to trap sand. The seagrass in the meadows is buried after the storm events; in fact, accumulation (blue areas) is visible in Fig. 9 after the storms (S1, S2, S3). A similar behavior is also confirmed by Chen et al. (2022) that investigated the impact of seagrass planting on sediment erosion and transport in a green nourishment case. The comparison of the final beach

Table 3
Percentage of wave height attenuation (att_w) at eight locations in the seagrass meadows. Attenuation is calculated on VEG runs with respect to the REF run outputs. The following data are provided for each station: maximum attenuation, mean attenuation and the attenuation occurring at the wave height peak of the REF simulations. Results are also indicated for each storm (S1, S2, S3).

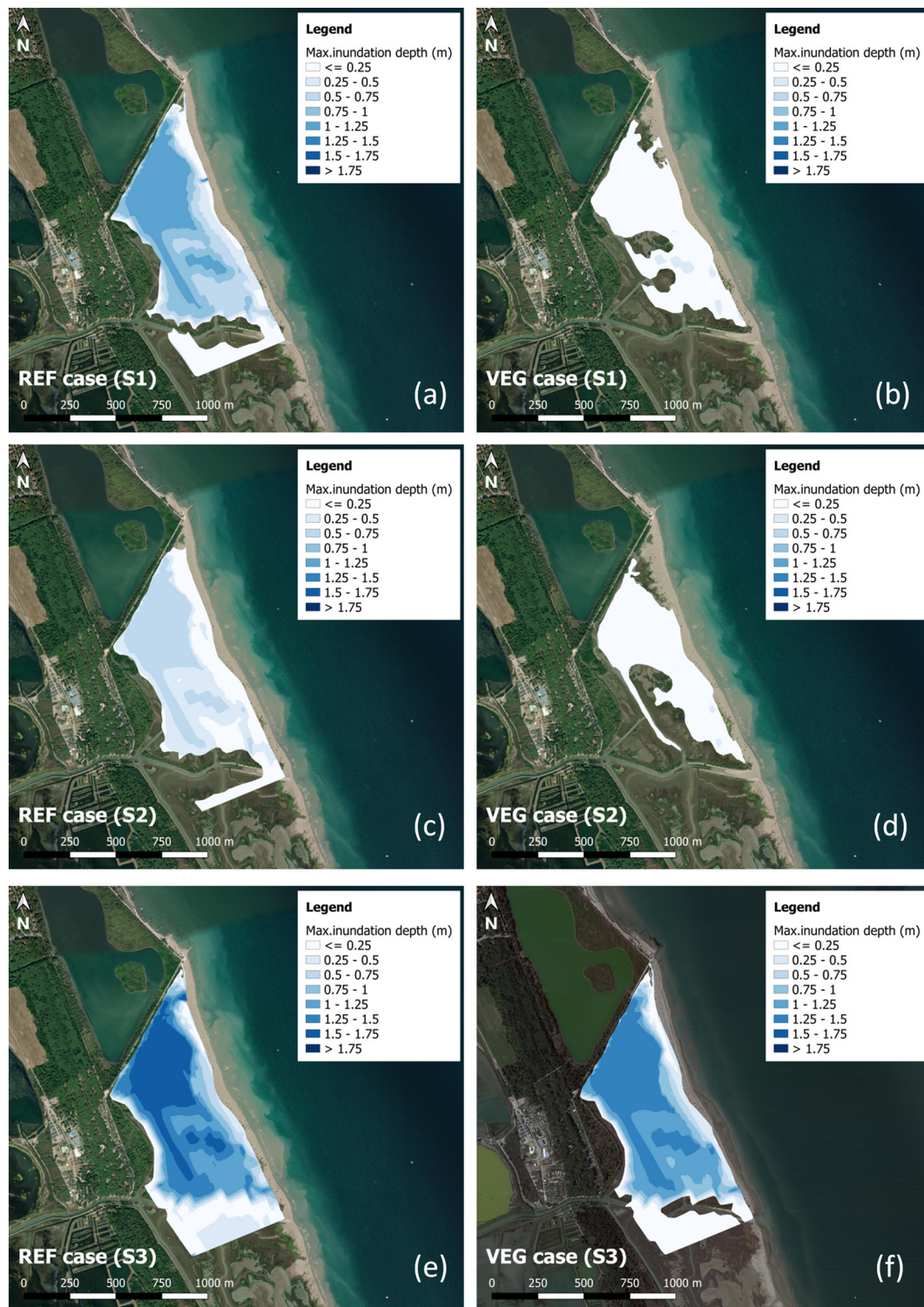| | att_w max.(%) | | | att_w mean (%) | | | att_w of H_{max} (%) | | |
	S1	S2	S3	S1	S2	S3	S1	S2	S3
Station 1	85 %	84 %	89 %	30 %	33 %	34 %	38 %	44 %	38 %
Station 2	66 %	57 %	65 %	28 %	27 %	27 %	46 %	36 %	31 %
Station 3	69 %	50 %	65 %	22 %	19 %	20 %	19 %	17 %	18 %
Station 4	62 %	58 %	65 %	30 %	26 %	29 %	35 %	43 %	37 %
Station 5	49 %	54 %	52 %	22 %	20 %	22 %	33 %	54 %	28 %
Station 6	56 %	66 %	61 %	19 %	21 %	21 %	14 %	23 %	36 %
Station 7	75 %	78 %	54 %	22 %	21 %	26 %	28 %	28 %	39 %
Station 8	54 %	65 %	58 %	20 %	20 %	19 %	24 %	30 %	25 %

Fig. 7. Inundation maps (a,b,c,d,e,f) during the three selected storms, with (VEG) and without seagrass effect (REF). The maps on the left (a,c,e) present the maximum inundation depths occurring without any defenses (REF) while the images on the right show the maximum inundation depths observed with the seagrass effect (VEG).

profile (continuous purple line) with (VEG) and without (continuous green line) vegetation (REF) together with the initial profile (dashed green line) along a cross-shore section is plotted in Fig. 10. Overall, the NBS reduces the beach erosion in between −1.5 and 1.5 m elevation (Fig. 10a,b,c). The attenuation in shoreline retreat (Table 4) induced by the seagrass (VEG) with respect to the REF runs varies from 29 % (S2) to 55 % (S3).

The highest reduction is observed during S3 (H_{max} = 4.66 m, SL = 1.31 m), although a similar attenuation occurred also during S1 (H_{max} =

3.91 m, SL = 0.86 m, E = 382.27 m^2h) which was less energetic than S3 (E = 414.85 m^2h).

In S1, the shoreline movements was limited from x = 663 m (REF) to x = 681 m (VEG), preventing approximately a 18 m wide section of beach from eroding (Fig. 10a). The total volume of beach erosion was also reduced from 55 m^3/m (REF) to 32 m^3/m (VEG) with an attenuation of 43 % (Table 4).

During S2 and S3, the seagrass respectively prevents about a 9 m and 23 m wide section of the beach from eroding (Fig. 10b,c) producing a
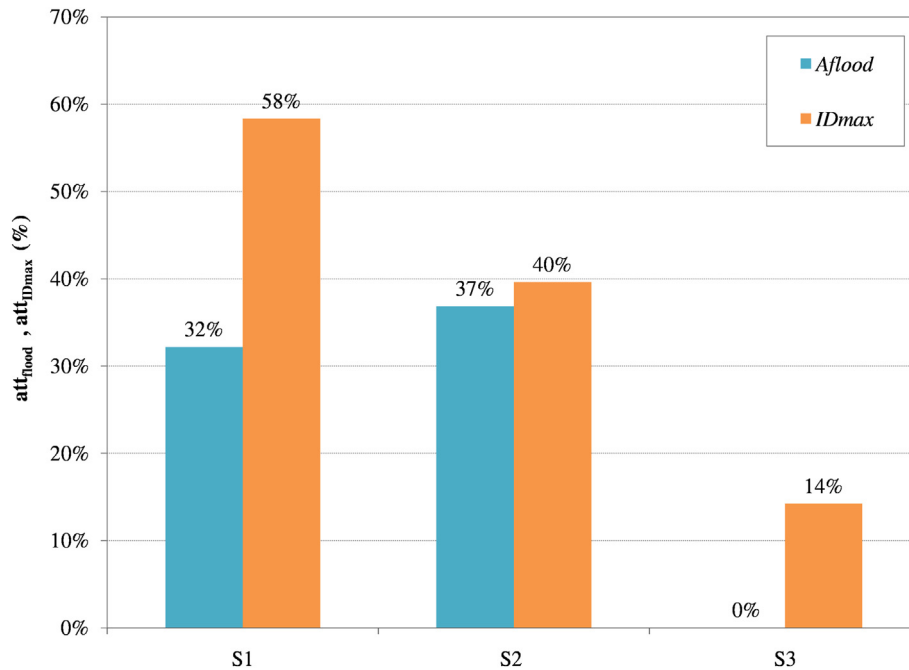
Fig. 8. Percentage attenuation in terms of inundated area (att_{flood}) and maximum inundation depth (att_{IDmax}) induced by the seagrass in the lagoon with respect to the REF case without any defenses. Attenuation in the inundated areas is indicated in teal while orange represents maximum inundation depth.

mitigation that prevents the erosion of the beach section of 29 % (S2) and 55 % (S3). The use of seagrass meadows also improves the mitigation of eroded volumes, leading to a considerable attenuation ranging between 43 % and 50 % during S1 and S3, respectively (Table 4).

The results suggest that under S3 conditions, the seagrass produces the highest benefits in coastal erosion mitigation in terms of shoreline retreat (55 %) and eroded volumes from the subaerial beach (50 %) indicating that the attenuation is greater the greater the intensity of the event.

A different use of vegetation as a real solution for Disaster Reduction was investigated in the study by Montblanc et al. (2020) conducted in the same coastlines of Bellocchio (Italy, Northern Adriatic Sea) by means a dune system revegetation. The result in this study highlighted that vegetation impacted wave energy dissipation is a prime factor that can highly mitigate coastal flooding and erosion under current and for future sea level rise. It is interesting to note that, irrespective of its implementing location (on the dune top or on the sea bottom) the role of vegetation is highly relevant for this coastal area.

3.5. The artificial dune to contrast marine ingression

The artificial dune is an alternative solution to vegetation deployed to mitigate coastal risks such as flooding and erosion. In contrast with the seagrass meadows, the dune is located on the subaerial beach with the main goal of increasing the beach's elevation to contrast marine ingression. Several studies have demonstrated the importance of high beach elevation in dealing with extreme storm conditions and expected future increased sea level (Vousdoukas et al., 2018b). The artificial dune's performance in avoiding coastal inundation of the lagoon environment is summarized in Table 5 in terms of percentage attenuation of the flooding area and the lagoon's maximum inundation depth. As term of comparison, results related to VEG simulations are also included in Table 5.

The dune's role in contrasting marine ingression into the lagoon is well confirmed by the percentage attenuation in the areas affected by flooding which varies in the range 51 % - 75 %. The least attenuation is observed under the most extreme conditions (S3) induced by a combination of waves and sea level, respectively of H = 4.66 m and SL = 1.31 m, compared to S1 and S2 which experienced lower wave heights and water levels. As shown in Table 5, the results highlight that the dune was more

effective in reducing lagoon inundation (51 %–75 %) than the seagrass (0 %–32 %).

As expected, this attenuation results in lower inundation depths within the lagoon. Fig. 11 presents the maximum inundation depths modeled during the storms (S1,S2,S3) in the DUNE cases.

The best attenuation of 99 % is achieved in the DUNE case during S2 (Fig. 11b). Overall the attenuation ranges from 75 % (during S3) to 99 % (during S2). Here again, the lowest mitigation occurs during S3.

Comparing the attenuation of maximum inundation depth produced by the DUNE cases (75–99 %) with the VEG cases (14–58 %), it is clear that the dune is more effective in protecting the lagoon against flooding.

This novel NBS approach (the artificial dune) seems to guarantee high mitigation of the overwash impacts due to its capability in providing a substantial raising of beach elevation, with respect of the more traditional measures (i.e. beach nourishment). As demonstrated by Plomaritis et al. (2018), even if there is a significant reduction of the overwash discharge with an associated impact reduction, coastal flooding remains an important hazard during extreme conditions, even after the implementation of a nourishment plan.

3.6. Artificial dune: effects on morphological variations

The results of XBeach simulations with the artificial dune (DUNE cases) were also investigated in terms of morphological variations modeled during the three historical storms (S1,S2,S3) presented in Fig. 12 and quantified in Table 6 together with the percentage attenuation induced by the addition of the dune.

Along the cross-shore section indicated with a green line on the map of Fig. 12 (on the right), the behavior of the beach profile under S1 and S2 conditions is similar with (DUNE) and without (REF) the dune. No attenuation in erosion of the beach's width occurred (0 %) with the dune. During both storm cases (S1 and S2) the storm produces a considerable erosion of the beach's foreshore, which results from the strong offshore sediment flux induced by undertow as waves wash over the beach.

However, focusing on the eroded volumes, especially for S1 and S3, there is an evident respective attenuation of 9 % and 35 % due to the dune. In fact, the dune is effective in containing the landward limit of the beach erosion to the dune's foot, avoiding any morphological variation behind.
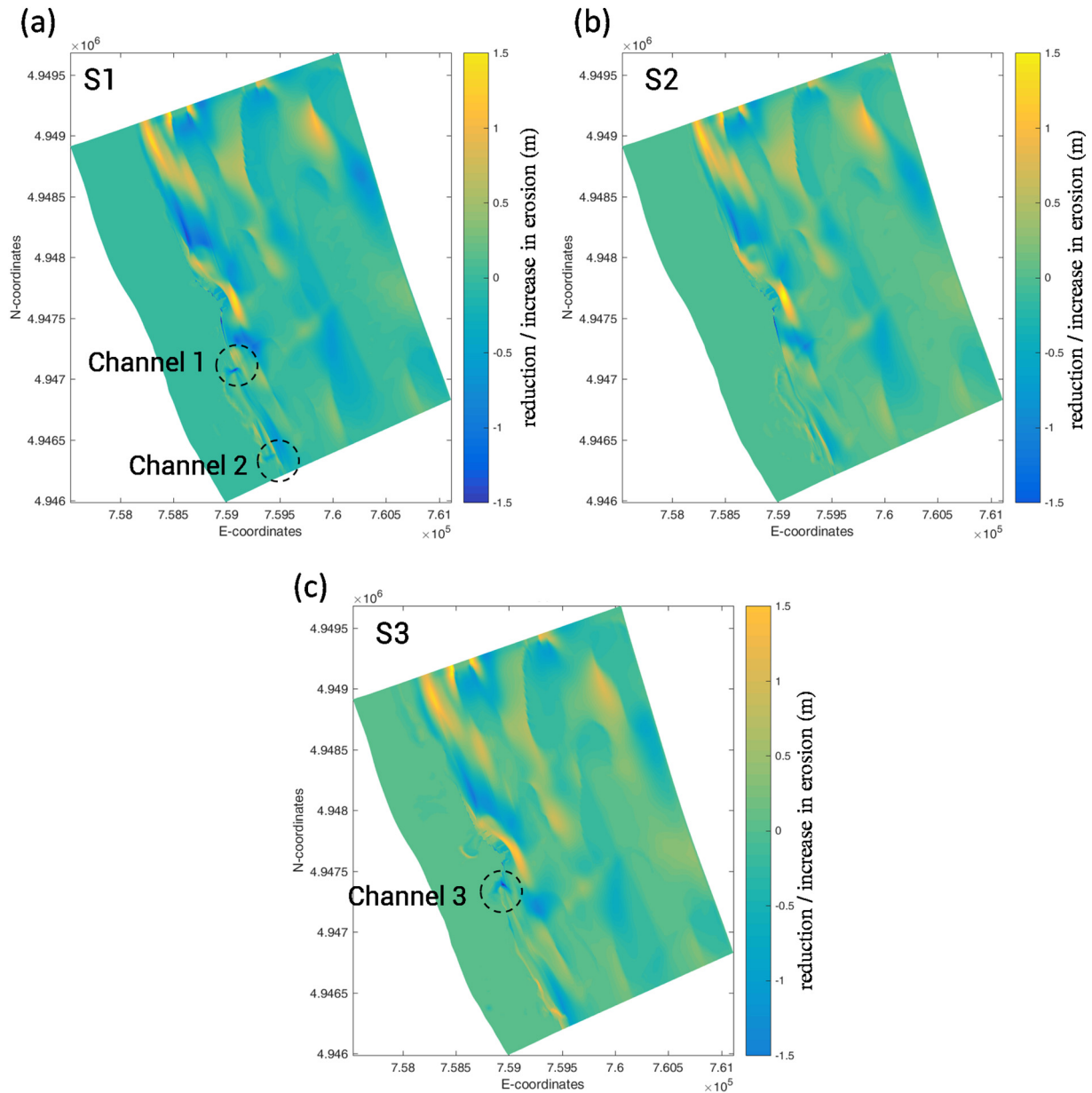
Fig. 9. Comparison between cumulative sedimentation-erosion for the XBeach runs with (VEG) and without (REF) seagrass, for each simulated storm (S1, S2, S3). Negative values mean that seagrass produce an attenuation of beach erosion with respect to the REF case. Conversely, where values are positive an increase in erosion occurs.

The maximum mitigation in beach erosion is observed during S3 (Table 7), where the landward limit of erosion in the DUNE case is limited to the dune's foot, approximately x = 640 m, instead of x = 620 m in the REF case (Fig. 12c). At the dune's foot there is also visible local erosion caused by the imposition of the dune as a hard structure. However, a kind of sediment accumulation can be seen immediately in front of such erosion, at the seaside. This frontal accumulation is one of the expected behaviors of the dune that will tend to accumulate sand on the seaside, leading to a tendency for the structure to grow and further stabilize following its natural accretion (De Vries et al., 2015).

Overall, results suggest that the dune acts as an obstacle against storm impacts and moves the landward limit of beach erosion to the dune's foot, totally avoiding any morphological variation behind.

3.7. Co-benefits of the NBSs

The previous sections showed encouraging results with respect to mitigating waves, coastal flooding areas and the erosion occurring in the beach and inland trough the use of the artificial dune and seagrass meadows. Here we want discuss on the possible integration of the two NBS with the purpose of creating a synergy in coastal risk mitigation through eco-sustainable solutions with a low impact on nature. With the goal of investigating the improvements derived from their integration compared to their separate use, XBeach runs with both the NBS were performed for the three selected historical storms (S1,S2, S3).

Results of INT runs (Table 7) indicate that the attenuation in the maximum flooded area compared to the REF cases ranges from 65 % to 77 %, with the highest reduction observed under S1 conditions (Hmax = 3.91 m, SLmax = 0.86 m). Therefore, a significant decrease in values of maximum inundation depth is also visible for all the storms (79 % - 99 %). For S2, the attenuation of 99 % suggests that the inundation depth values with the NBS integration are almost zero.

It is interesting to note that by integrating the two NBS a benefit in reducing the inundation breadth is achieved compared to their use on their own. Table 7 displays the percentage benefit in reducing the extent of the lagoon inundation and the induced water depths in INT cases with respect
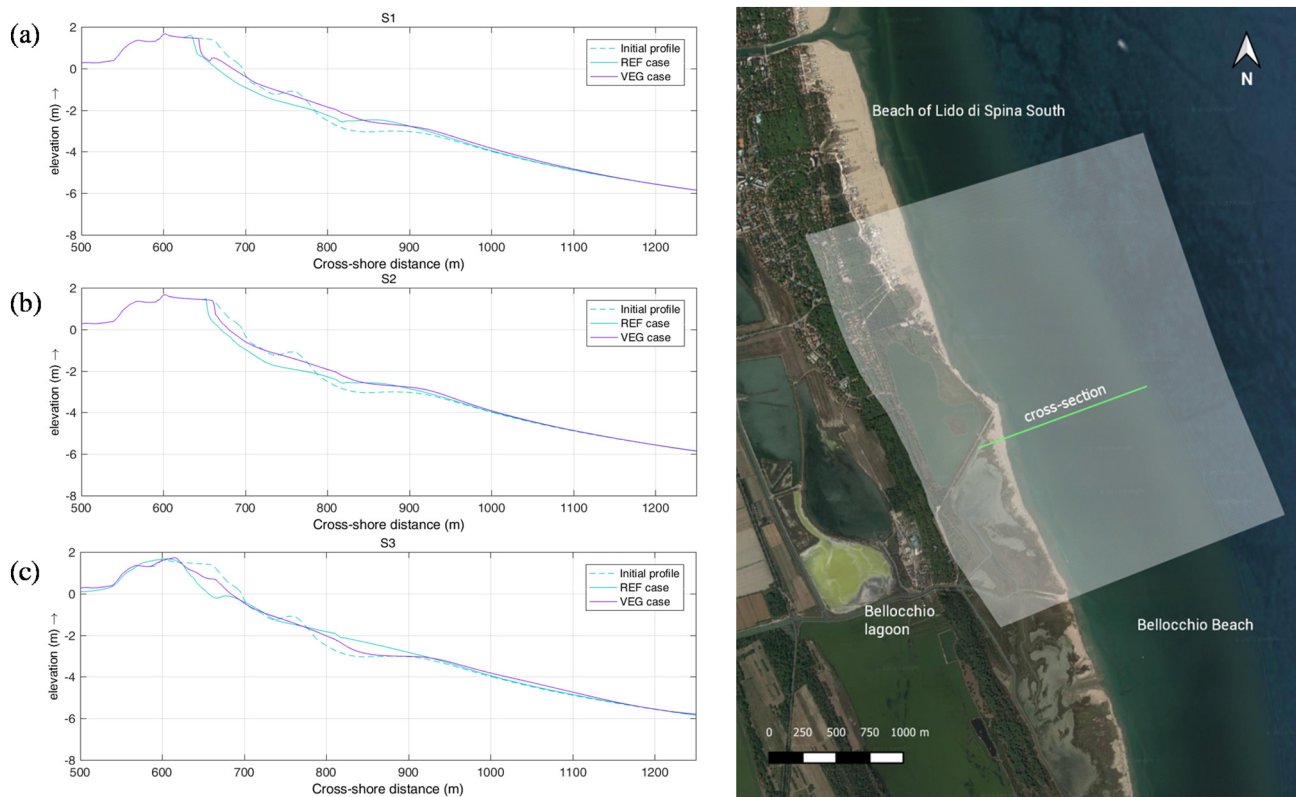
Fig. 10. Morphological variations along the cross-shore transect indicated on the map (on the right) at the end of the three selected storms S1(a), S2(b), S3(c) with (VEG case) and without (REF case) the seagrass. REF cases are presented with dashed (initial profile) and continuous (final profile) light blue lines, respectively. The final profile with the seagrass is plotted with a purple continuous line.

to DUNE and VEG cases (positive values indicate an improvement in mitigation). The highest gain in all INT cases is achieved versus VEG cases, varying between 39 % and 65 % for the inundation area and 38 % - 65 % for inundation depths. Adding the seagrass effect to the dune seems to be less beneficial in contrasting inundation breadth (1 %–14 %) and depths (0 %–5 %) than the DUNE-only cases. Since the risk of inundation strongly depends on the beach slopes (Harley and Ciavola, 2013b), seagrass has been demonstrated to be efficient in decreasing incoming wave intensity, while the artificial dune works better than seagrass in dealing with the inland marine ingression, due to its ability to increase the beach's elevation. Overall, the greater benefits produced by the INT cases compared to the DUNE and VEG cases are seen during S3 conditions (Hmax = 4.66 m, SL = 1.31 m).

Having already established that the dune provides the best protection of the lagoon against marine ingression, the impacts on morphological variations were also investigated. Percentage attenuations in shoreline retreat and beach erosion (in terms of volumes) of all three modeled cases (VEG, DUNE and INT) are compared in Fig. 13.

The efficiency in reducing landward shoreline movement modeled in the INT cases for all the storm events seems to be more due to the presence of the seagrass (VEG) than the dune (DUNE). In fact, attenuations of the integrated simulations (INT) are comparable with those achieved with the seagrass alone (Fig. 13a). Analyzing the results in terms of beach erosion (Fig. 13b), there is no significant improvement achieved by integrating the two NBS (INT, 19 % - 35 %) compared to the use of seagrass alone (43 % - 51 % attenuation). As already demonstrated in this study, the dune surely limits the landward erosion of the beach at the dune's foot but from the foreshore a larger amount of sediment is moved seaward due to the undertow currents generated. This means a larger amount of sediment is lost from the beach. However, the addition of the seagrass in front of the beach where the dune is implemented led to significant improvements, increasing the percentage attenuation by an average of 16 % (Fig. 13b).

The combined implementation of the two NBS was more effective in mitigating marine ingression compared to their separate use. Numerical simulations allowed for a quantification of the benefits in reducing coastal

Table 4
Shoreline retreat (m) and eroded volumes (m) at the cross-shore indicated in Fig. 10 for the REF runs (without costal defenses) and the VEG runs (with the seagrass) for each storm modeled (S1,S2,S3). The percentage attenuation of both shoreline retreat and eroded volumes is also presented for each VEG simulation with respect to the REF run.

	Shoreline retreat (m)		att_{shore} (%)	Eroded volume (mq/m)		att_{ero} (%)
	REF	DUNE		REF	DUNE	
S1	35	17	52 %	55	32	43 %
S2	29	21	29 %	38	18	51 %
S3	42	19	55 %	60	30	50 %

Table 5
Percentage of attenuation in inundation area and maximum inundation depth in the lagoon with the dune (DUNE cases) compared to the reference simulations without coastal defenses (REF cases) for the three storm conditions analyzed (S1,S2,S3). The attenuation in the VEG cases is also reported in the table for comparison. All values refer to the lagoon area.

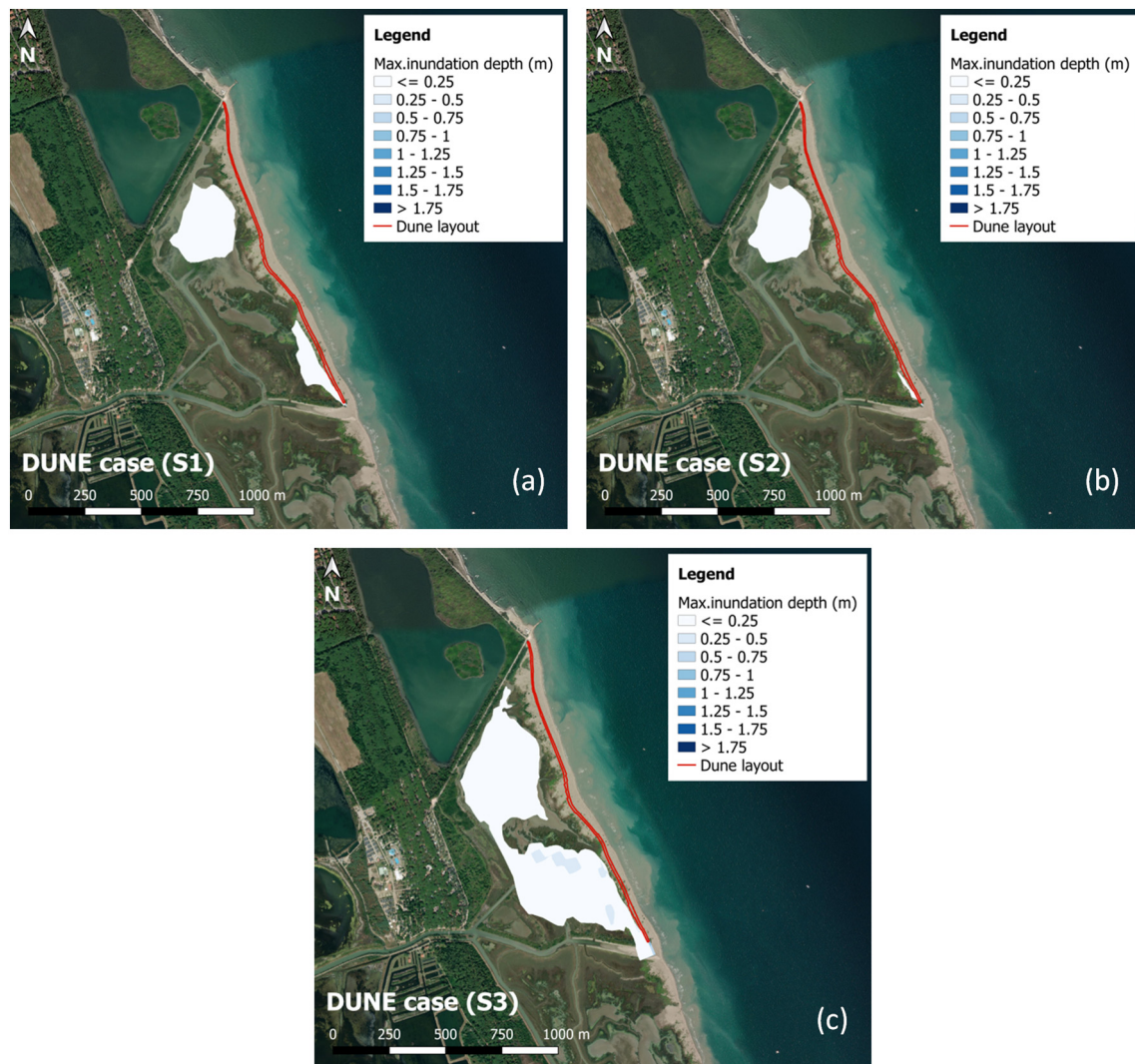| Storm	H_{max} (m)	SL_{max} (m)	DUNE vs REF		VEG vs REF	
			att_{flood} (%)	att_{IDmax} (%)	att_{flood} (%)	att_{IDmax} (%)
S1	3.91	0.86	74 %	95 %	32 %	58 %
S2	3.79	0.85	75 %	99 %	37 %	40 %
S3	4.66	1.31	51 %	75 %	0 %	14 %

Fig. 11. Maximum inundation maps obtained from XBeach simulation with the artificial dune (DUNE cases) under the three storms analyzed (S1,S2,S3). The maximum inundation depths are represented on the map using colors ranging from white (lower values) to blue (higher values).

inundation and erosion, but several relevant physics and socio-economic implications are also worthy of note.

The wave attenuation modeled in XBeach due to seagrass suggests that over the time the dune will be subjected to inferior seaward forcing which will preserve the dune's stability and functionality for a longer period of time. In this sense, the seagrass acts as a protection not only for the beach but also for the dune itself, helping it to maintain its effectiveness over time. Moreover, dunes are highly dynamic structures that will tend to grow and stabilize over time due to several natural factors (such as wind and spontaneous vegetation growth) which are endangered by extreme storm conditions acting on the beach. The attenuation of waves due to the seagrass will permit a more rapid and intensive development of the dune.

As stated by Gambi et al. (1990) a large variety of organisms - especially juvenile stages - find shelter in seagrass meadows (for this reason defined as "nurseries") from physical factors and predators, and also find food. Thereafter, in addition to these supporting functions (i.e., habitat for organisms, flora and coastal species) and mitigating functions (i.e., attenuation of coastal flooding and erosion), significant social value can be provided by this integrated ecosystem through tourism, recreation, education and research.

4. Limitations of the study

Simulations carried out with the XBeach model had the purpose of comparing the performance of the two different NBS in mitigating coastal inundation and erosion. Model results are strongly dependent on the schematization and the parameters used to describe these NBS within the model.

Although the effect of vegetation is already included in XBeach (Van Rooijen et al., 2016) and partially corrected by drag coefficient, the modeling of the effects of storms and high wave energy conditions on seagrass meadows (and vice versa) could be improved (van Rooijen et al., 2015). The correct value of C_D would need accurate calibrations based on in-situ experiments and also its magnitude can be impacted by the incident wave and current forcing during the incident conditions (Houser et al., 2014). The seagrass flexibility could be added to account for the bending of the seagrass' leaves due to the currents, hence reducing the efficiency of the seagrass in waves energy reduction (Beudin et al., 2017). Furthermore, a failure scheme could be introduced for seagrass destroyed either by strong current or sediment burial in severe storms which was not considered in this study.

Several studies modeled natural or artificial dunes with XBeach (Roelvink et al., 2009; Danish and Authority, 2012; Splinter and Palmsten, 2012; Bugajny et al., 2013; Harley and Ciavola, 2013b; Miani et al., 2015; Karunarathna et al., 2018), however the complexity in materials encompassing in the proposed artificial dune is not yet implemented and/or studied with XBeach. The model was developed to simulate the behavior of sand dunes and is therefore unable to accurately represent the wood material and its implications. The schematization applied in this
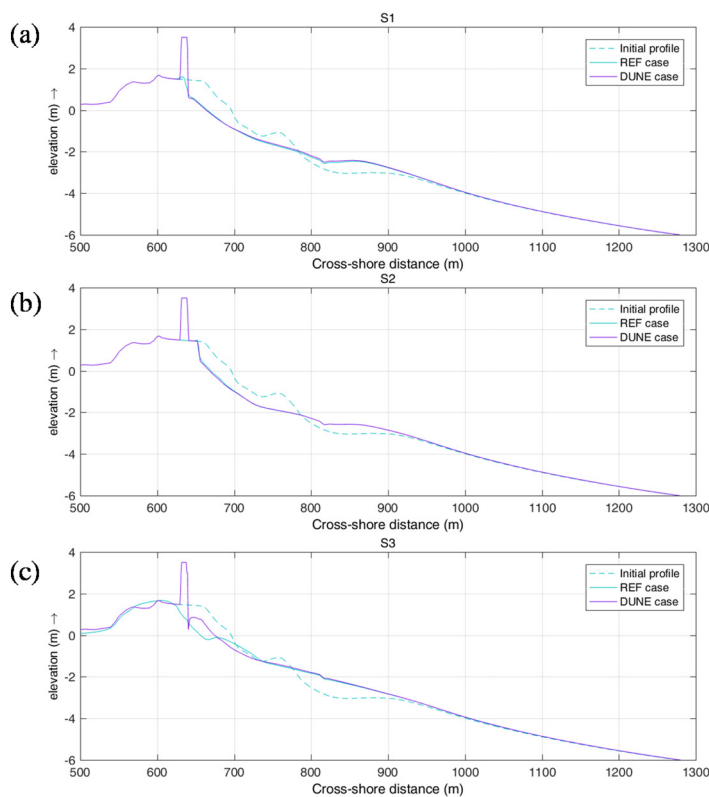
Fig. 12. Morphological variations along the cross-shore transect indicated with a green line on the map (on the right) at the end of the three selected storms S1(a), S2(b), S3 (c) with (DUNE case) and without (REF case) the artificial dune. REF case profiles are presented with dashed (initial profile) and continuous (final profile) light blue lines. The final profile with the dune is plotted with a purple continuous line.

study is a first attempt to represent the artificial dune but further experiments and investigations can be relevant in improving its model reproduction.

Moreover, the limited available topo-bathymetric measurements did not allow for a storm-scale calibration which would have been much more relevant given that the study analyzes three historical storm events. However, several relevant parameters were calibrated and led to promising values of the BSS index, indicating a good performance of the model in the study area.

Overall, the study demonstrated the ability of seagrass and the artificial dune to mitigate coastal impacts, and especially underscored how their integration can produce significant improvements in contrasting storm impacts on the beach. It must be taken into account that the presence of both the NBS on a coastal stretch depends on the combination of different factors, i.e., waves, bottom and seabed light conditions suitable for the seagrass growth and regeneration, a beach environment that is as natural as possible that allows the foredune building, stabilization and growth, avoiding the disturbance of seaside infrastructure and urbanized areas.

These aspects were not considered and discussed in this study, which instead approached the problem from a modeling point of view.

The study aims to demonstrate the possible benefits of the two coastal nature-based protections by imparting the research community/coastal engineers with possible ideas for improving coastal management by adopting natural, eco-sustainable solutions with low economic and social impact where possible.

5. Conclusions

The purpose of this study was to investigate the role of two NBSs (seagrass meadows and an artificial dune built completely with natural materials) in reducing coastal risks in terms of coastal erosion and inundation. In contrast with other studies (Bao, 2011; John et al., 2016; Gesing, 2019; Schweiger and Schuettrumpf, 2021) the integration of the two NBS was also investigated through numerical simulations with XBeach.

Table 6

Shoreline retreat (m) and eroded volumes (m) at the cross-shore indicated in Fig. 10 for the REF runs (without costal defenses) and the DUNE runs (with the artificial dune) for each modeled storm (S1,S2,S3). The percentage attenuation of both shoreline retreat and eroded volumes is also presented for each DUNE simulation with respect to the REF run.

	Shoreline retreat (m)		att_{shore} (%)	Eroded volume (m³/m)		att_{ero} (%)
	REF	DUNE		REF	DUNE	
S1	35	35	0 %	55	50	9 %
S2	29	29	0 %	38	38	0 %
S3	42	26	38 %	60	39	35 %

Table 7

Percentage attenuation in the flooding area and the max inundation depth in the lagoon area. Results of INT runs (which integrate the seagrass and the artificial dune effects) are presented in the first two columns for the three storms studied (S1,S2, S3). The benefits observed by the integration runs (INT cases) with respect to the DUNE and VEG cases (considered alone) are also detailed in terms of percentage increase of the benefit in mitigating the flooding area and the max inundation depth.

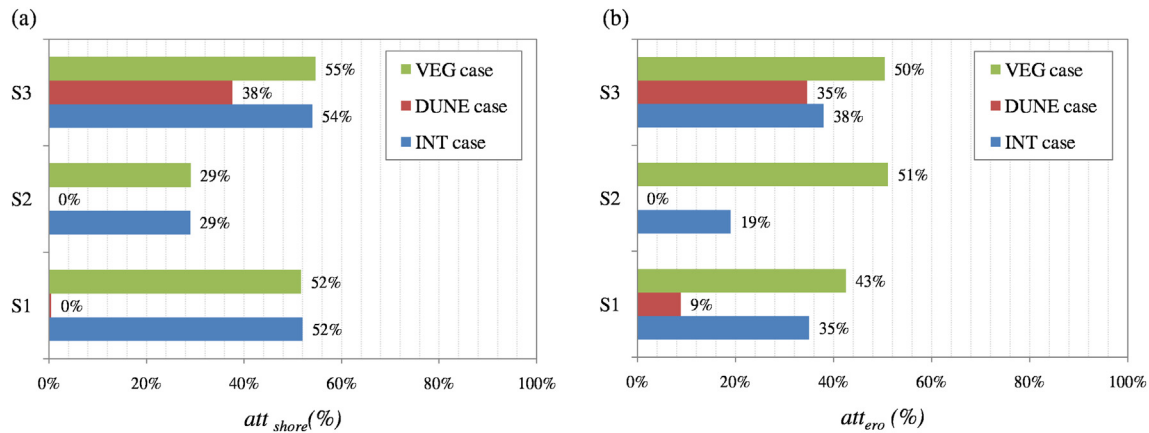|	INT case		INT vs DUNE		INT vs VEG	
	att_{flood} (%)	att_{IDmax} (%)	att_{flood} (%) benefit	att_{IDmax} (%) benefit	att_{flood} (%) benefit	att_{IDmax} (%) benefit
S1	77 %	96 %	+ 3 %	+ 1 %	+ 45 %	+ 38 %
S2	76 %	99 %	+ 1 %	0 %	+ 39 %	+ 59 %
S3	65 %	79 %	+ 14 %	+ 5 %	+ 65 %	+ 65 %

Fig. 13. Percentage attenuation in shoreline retreat and eroded volumes of the subaerial beach during the three storms S1,S2 and S3 for: simulations with the seagrass (VEG), simulations with the artificial dune (DUNE) and simulations with the integration of the two NBS (INT).

The study demonstrated that seagrass is efficient in attenuating incoming wave intensity, in terms of significant wave height, with a maximum reduction of 89 % and an average attenuation at the storm's peak of 32 %. As expected, this attenuation results in a mitigation in the extent of the lagoon flooding in the range of 0 % - 37 % due to seagrass meadows, compared to the reference case (REF) without any coastal protections. The highest attenuation of inundation was achieved with the artificial dune (51 % - 75 %) due to its ability to increase the beach's elevation. The dune acts as a barrier against marine ingression and induces a limitation of the landward subaerial beach erosion at the dune's foot. In fact, it avoids any morphological variation within the lagoon. On the other hand, seagrass is effective in reducing the flooded area and the maximum inundation depths (14 % - 58 %) but it does not prevent the lagoon from flooding. However, due to its ability to mitigate incoming waves, seagrass meadows help contrast erosion preventing up to 30 m of beach from eroding.

While the dune has been demonstrated effective in limiting landward beach erosion at the dune's foot, totally avoiding any morphological variation behind it, the seagrass was found to be more effective in reducing the storms' impact on the foreshore in terms of erosion and landward shoreline movement, with maximum attenuation of 50 % and 55 %, respectively.

Another important aspect brought to light by the study is that both the shoreward and seaward margins of the meadow were buried after the storm events. The seagrass in the meadows traps the sand, thus preventing the loss of materials seaward, caused by the undertow currents.

This is particularly important when the seagrass is integrated with the artificial dune (INT cases), and will result in an important sediment supply for the beach under future extreme storm conditions, leading to a redistribution of sediment within the beach system.

The combined use of seagrass and the dune as a synergic solution compared to their separate deployment showed encouraging results, especially with respect to coastal inundation. This is true in particular with regard to the seagrass runs, with a maximum benefit of 65 % in attenuating the inundation area and the maximum inundation depths, both occurring during the most energetic historical storm (S3). Therefore, an important conclusion is that the integration of the two NBS produces the best benefit in terms of inundation during the worst storm conditions.

A further benefit of the artificial dune with respect to the seagrass consists in reducing the landward limit of the erosion at the dune's foot, preventing any morphological variations or inundation of the lagoon (i.e. acting as a barrier against marine ingression, increasing the beach's elevation, limiting the landward erosion). In contrast, due to the considerable attenuation of incoming waves, seagrass benefits the dune preserving its stability and functionality over the time.

The study demonstrated that the integration of the NBS to mitigate coastal risks will not only result in mitigating functions (i.e., attenuation of coastal flooding and erosion) but also in supporting actions (i.e., habitat for organisms, flora and coastal species) which will lead to significant social value of the natural ecosystem composed of seagrass and the artificial dune thanks to tourism, recreation, education and research.

Overall, these results suggest that the integrated application of NBS at Lido di Spina (Italy) is highly recommended to mitigate coastal risk. XBeach with NBS demonstrated high potential in assessing the vulnerability of beaches to coastal erosion considering historical high storm conditions. Hence this integrated approach can support coastal engineers/ managers/ planners in decision making and thereby aid in warning of possible erosion/ structural damage and the associated threat to human life and property. Future studies comprising sustainable management of coastal ecosystems must consider integrating coastal vegetation with infrastructure design (van Zelst et al., 2021) which is considered as a sustainable and cost-effective way in preserving the global coastlines. The study can act as a base for replication in other coastal regions where the changes in the prevailing wave and sea level conditions must be considered.

CRediT authorship contribution statement

Conceptualization: SU, AV; Data Curation: SU, UPA, AV, MA; Software: SU, UPA, JA; Formal analysis: SU, AV; Investigation: SU, MA, AV; Methodology: SU, AV, MA, UPA; Project Supervision: AV; Visualization: SU, MA, LGB, AV, UPA; Writing original draft: SU; Writing - Review & Editing: All.

Data availability

Data will be made available on request.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

Aguzzi, M., Costantino, R., De Nigris, N., Morelli, M., Romagnoli, C., Unguendoli, S., Vecchi, E., 2020. Stato del litorale emiliano-romagnolo al 2018. I quaderni di Arpae.

Aguzzi, M., Bacci, M., Nigris, N.De, Leo, L.S., Morelli, M., Pulvirenti, B., Robello, P., Ruggieri, P., Tavaroli, F., Unguendoli, S., Cacciamani, C., 2021. Designand Pre-assessment of NBS for Coastal Erosion and Marine Flooding: A Case Study.

Alves, J., Ardhuin, F., 2016. User manual and system documentation of WAVEWATCH III (R) version 5. 16 National Weather Service National Centers for Environmental Prediction 5830 University Research Court Technical Note Marine Modeling and Analysis Branch, pp. 10–14.

Andrews, D.G., Mcintyre, D.M.E., 1978. An exact theory of nonlinear waves on a Lagrangian-mean flow. J. Fluid Mech 4, 609–646.

Armaroli, C., Duo, E., 2018. Validation of the coastal storm risk assessment framework along the Emilia-Romagna coast. Coast. Eng. 134, 159–167. https://doi.org/10.1016/J. COASTALENG.2017.08.014.

Armaroli, C., Ciavola, P., Caleffi, S., Gardelli, M., 2007. Morphodynamicsof Nearshore Rhythmic Forms: An Energy-based Classification, pp. 4009–4021 https://doi.org/10.1142/ 9789812709554_0337.

Armaroli, C., Ciavola, P., Perini, L., Calabrese, L., Lorito, S., Valentini, A., Masina, M., 2012. Critical storm thresholds for significant morphological changes and damage along the Emilia-Romagna coastline, Italy. Geomorphology 143–144, 34–51. https://doi.org/10. 1016/j.geomorph.2011.09.006.

Armaroli, C., Grottoli, E., Harley, M.D., Ciavola, P., 2013. Beach morphodynamics and types of foredune erosion generated by storms along the Emilia-Romagna coastline, Italy. Geomorphology 199, 22–35. https://doi.org/10.1016/j.geomorph.2013.04.034.

Arnold Van Rooijen, A., 2019. Wave and Current Induced Flows in Aquatic Vegetation Canopies.

Bao, T.Q., 2011. Effect of mangrove forest structures on wave attenuation in coastal Vietnam. Oceanologia 53, 807–818. https://doi.org/10.5697/oc.53-3.807.

Bart, L.J., 2017. Long-termModelling With XBeach: Combining Stationary and Surfbeat Mode in an IntegratedApproach, pp. 1–108.

Bendoni, M., Georgiou, I.Y., Roelvink, D., Oumeraci, H., 2019. Numerical modelling of the erosion of marsh boundaries due to wave impact. Coast. Eng. 152, 103514. https://doi. org/10.1016/J.COASTALENG.2019.103514.

Berard, N.A., Mulligan, R.P., da Silva, A.M.F., Dibajnia, M., 2017. Evaluation of XBeach performance for the erosion of a laboratory sand dune. Coast. Eng. 125, 70–80. https:// doi.org/10.1016/J.COASTALENG.2017.04.002.

Bertin, X., Bruneau, N., Breilh, J.F., Fortunato, A.B., Karpytchev, M., 2012. Importance of wave age and resonance in storm surges: the case xynthiaBay of Biscay. Ocean Model. 42, 16–30. https://doi.org/10.1016/J.OCEMOD.2011.11.001.

Beudin, A., Kalra, T.S., Ganju, N.K., Warner, J.C., 2017. Development of a coupled wave-flow-vegetation interaction model. Comput. Geosci. 100, 76–86. https://doi.org/10.1016/J. CAGEO.2016.12.010.

Boudouresque, C.F., Bernard, G., Pergent, G., Shili, A., Verlaque, M., 2009. Regression of Mediterranean seagrasses caused by natural processes and anthropogenic disturbances and stress: a critical review. Bot. Mar. 52, 395–418. https://doi.org/10.1515/BOT.2009.057.

Boudouresque, C.F., Blanfuné, A., Pergent, G., Thibaut, T., 2021. Restoration of seagrass meadows in the mediterranean sea: a critical review of effectiveness and ethical issues. Water 13, 1034. https://doi.org/10.3390/W13081034 2021, Vol. 13, Page 1034.

Bugajny, N., Furmańczyk, K., Dudzińska-Nowak, J., Paplińska-Swerpel, B., 2013. Modelling morphological changes of beach and dune induced by storm on the southern Baltic coast using XBeach (case study: dziwnow Spit). J. Coast. Res. 65, 672–677. https://doi. org/10.2112/SI65-114.1.

Chen, W.L., Muller, P., Grabowski, R.C., Dodd, N., 2022. Green nourishment: an innovative nature-based solution for coastal erosion. Front. Mar. Sci. 8, 2054. https://doi.org/10. 3389/FMARS.2021.814589/BIBTEX.

Church, J., Clark, P., Cazenave, A., Gregory, J., Jevrejeva, S., Levermann, A., Merrifield, M., Milne, G., Nerem, R., Nunn, P., Payne, A., Pfeffer, W., Stammer, D., Alakkat, U., 2013. ClimateChange 2013 The Physical Science Basis Working Group I Contribution to the FifthAssessment Report of the Intergovernmental Panel on Climate Change WG IIntergovernmental Panel on Climate Change.

Ciavola, P., Armaroli, C., Chiggiato, J., Valentini, A., Deserti, M., Perini, L., Silvani, V., 2007. 2007.

Ciavola, P., Ferreira, O., Haerens, P., Van Koningsveld, M., Armaroli, C., Lequeux, Q., 2011. Storm impacts along european coastlines. Part 1: the joint effort of the MICORE and ConHaz projects. Environ. Sci. Policy 14, 912–923. https://doi.org/10.1016/J.ENVSCI. 2011.05.011.

Clay, P.M., Colburn, L.L., Seara, T., 2016. Social bonds and recovery: an analysis of hurricane Sandy in the first year after landfall. Mar. Policy 74, 334–340. https://doi.org/10.1016/ J.MARPOL.2016.04.049.

Coelho, C., Narra, P., Marinho, B., Lima, M., 2020. Coastal management software to support the decision-makers to mitigate coastal erosion. J. Mar. Sci. Eng. 8, 37. https://doi.org/ 10.3390/jmse8010037.

Cohen-Shacham, E., Walters, G., Janzen, C., Maginnis, S., 2016. Nature-based solutions to address global societal challenges. xiii + 97ppNature-basedSolutions to Address Societal Challenges. IUCN, Gland, Switzerland.

Conte, D., Lionello, P., 2013. Characteristics of large positive and negative surges in the Mediterranean Sea and their attenuation in future climate scenarios. Glob. Planet. Change 111, 159–173. https://doi.org/10.1016/J.GLOPLACHA.2013.09.006.

Creel, L., 2003. Ripple Effects : Population and Coastal Regions. 2003. WorldCat.org. http:// www.worldcat.org/it/title/ripple-effects-population-and-coastal-regions/oclc/56343213. (Accessed 20 September 2022).

D'Alessandro, F., Tomasicchio, G.R., Francone, A., Leone, E., Frega, F., Chiaia, G., Saponieri, A., Damiani, L., 2020. Coastal sand dune restoration with an eco-friendly technique. Aquat. Ecosyst. Health Manag. 23, 417–426. https://doi.org/10.1080/14634988.2020. 1811531.

Da Ros, Z., Corinaldesi, C., Dell'Anno, A., Gambi, C., Torsani, F., Danovaro, R., 2021. Restoration of Cymodocea nodosa seagrass meadows: efficiency and ecological implications. Restor. Ecol. 29, e13313. https://doi.org/10.1111/REC.13313.

Danish, T., Authority, C., 2012. Analysisand Modelling of Extreme Localised Dune Erosion Events Along Denmark's NorthSea High Water Dune Barrier, pp. 1–12.

Danjon, A., 1960. 2030 agenda for sustainable development. Trans. Int. Astron. Union 10, 22–37.

Danovaro, R., Nepote, E., Martire, M.Lo, Carugati, L., Da Ros, Z., Torsani, F., Dell'Anno, A., Corinaldesi, C., 2020. Multiple declines and recoveries of adriatic seagrass meadows over forty years of investigation. Mar. Pollut. Bull. 161, 111804. https://doi.org/10. 1016/J.MARPOLBUL.2020.111804.

De Vries, S., Harley, M.D., De Schipper, M.A., Ruessink, G., 2015. Dune growth due to aeolian sediment transport and the role of the beach and intertidal zone. https://doi.org/10. 1142/9789814689977_0043.

Duarte, C.M., Losada, I.J., Hendriks, I.E., Mazarrasa, I., Marbà, N., 2013. The role of coastal plant communities for climate change mitigation and adaptation. Jacob S.M. vanNat. Clim. Chang. 311 (3), 961–968. https://doi.org/10.1038/nclimate1970.

European Commission, 1992. Council Directive 92/43/ECC. Off. J. Eur. Union. 94, pp. 40–52.

Faivre, N., Fritz, M., Freitas, T., de Boissezon, B., Vandewoestijne, S., 2017. Nature-based solutions in the EU: innovating with nature to address social, economic and environmental challenges. Environ. Res. 159, 509–518. https://doi.org/10.1016/J.ENVRES.2017.08. 032.

Ferreira, O., Viavattene, C., Jiménez, J.A., Bolle, A., das Neves, L., Plomaritis, T.A., McCall, R., van Dongeren, A.R., 2018. Storm-induced risk assessment: Evaluation of two tools at the regional and hotspot scale. xiii + 97ppCoast. Eng. 134, 241–253. https://doi.org/10. 1016/j.coastaleng.2017.10.005.

Ferreira, Ó., Plomaritis, T.A., Costas, S., 2019. Effectiveness assessment of risk reduction measures at coastal areas using a decision support system: findings from Emma storm. Sci. Total Environ. 657, 124–135. https://doi.org/10.1016/J.SCITOTENV.2018.11.478.

Gallotti, G., Santo, M.A., Apostolidou, I., Alessandri, J., Armigliato, A., Basu, B., Debele, S., Domeneghetti, A., Gonzalez-Ollauri, A., Kumar, P., Mentzafou, A., Pilla, F., Pulvirenti, B., Ruggieri, P., Sahani, J., Salmivaara, A., Basu, A.S., Spyrou, C., Pinardi, N., Toth, E., Unguendoli, S., Pranavam Ayyappan Pillai, U., Valentini, A., Varlas, G., Zaniboni, F., Di Sabatino, S., 2021. On the management of nature-based solutions in open-air laboratories: new insights and future perspectives. Resour. 10, 36. https://doi.org/10.3390/RE-SOURCES10040036 2021, Vol. 10, Page 36.

Gambi, M.C., Nowell, A.R.M., Jumars, P.A., 1990. Flume observations on flow dynamics in Zostera marina (eelgrass) beds. Mar. Ecol. Prog. Ser. 61, 159–169.

Ganguli, P., Merz, B., 2019. Extreme coastal water levels exacerbate fluvial flood hazards in northwestern Europe. Sci. Reports 91 (9), 1–14. https://doi.org/10.1038/s41598-019-49822-6 2019.

Gesing, F., 2019. The politics of artificial dunes: sustainable coastal protection measures and contested socio-natural objects. Erde 150, 145–157. https://doi.org/10.12854/ERDE-2019-423.

Gracia, A., Rangel-Buitrago, N., Oakley, J.A., Williams, A.T., 2018. Use of ecosystems in coastal erosion management. Ocean Coast. Manag. 156, 277–289. https://doi.org/10. 1016/J.OCECOAMAN.2017.07.009.

Hanley, M.E., Hoggart, S.P.G., Simmonds, D.J., Bichot, A., Colangelo, M.A., Bozzeda, F., Heurtefeux, H., Ondiviela, B., Ostrowski, R., Recio, M., Trude, R., Zawadzka-Kahlau, E., Thompson, R.C., 2014. Shifting sands? Coastal protection by sand banks, beaches and dunes. Coast. Eng. 87, 136–146. https://doi.org/10.1016/J.COASTALENG.2013.10.020.

Harley, M.D., Ciavola, P., 2013a. Managing local coastal inundation risk using real-time forecasts and artificial dune placements. Coast. Eng. 77, 77–90. https://doi.org/10.1016/j. coastaleng.2013.02.006.

Harley, M.D., Ciavola, P., 2013b. Managing local coastal inundation risk using real-time forecasts and artificial dune placements. Coast. Eng. 77, 77–90. https://doi.org/10.1016/j. coastaleng.2013.02.006.

Harley, M.D., Armaroli, C., Ciavola, P., Ferrara, U., 2011. Evaluation of XBeach predictions for a real-time warning system in. Methods 1861–1865.

Harley, M.D., Valentini, A., Armaroli, C., Ciavola, P., Perini, L., Calabrese, L., Marucci, F., 2012. An early warning system for the on-line prediction of coastal storm risk on the Italian coastline. Coast. Eng. Proc. 1, 77. https://doi.org/10.9753/icce.v33.management.77.

Harter, C., Figlus, J., 2017. Numerical modeling of the morphodynamic response of a low-lying barrier island beach and foredune system inundated during hurricane ike using XBeach and CSHORE. Coast. Eng. 120, 64–74. https://doi.org/10.1016/J. COASTALENG.2016.11.005.

Hirst, A.J., Giri, K., Ball, D., Lee, R.S., 2017. Determination of the physical drivers of zostera seagrass distribution using a spatial autoregressive lag model. Mar. Freshw. Res. 68, 1752–1763. https://doi.org/10.1071/MF16252.

Houser, C., Trimble, S., Morales, B., 2014. Influence of blade flexibility on the drag coefficient of aquatic vegetation. Estuaries Coasts 382 (38), 569–577. https://doi.org/10.1007/ S12237-014-9840-3.

James, R.K., Lynch, A., Herman, P.M.J., van Katwijk, M.M., van Tussenbroek, B.I., Dijkstra, H.A., van Westen, R.M., van der Boog, C.G., Klees, R., Pietrzak, J.D., Slobbe, C., Bouma, T.J., 2021. Tropical biogeomorphic seagrass landscapes for coastal protection: persistence and wave attenuation during major storms events. Ecosystems 24, 301–318. https://doi.org/10.1007/S10021-020-00519-2.

John, B.M., Shirlal, K.G., Rao, S., Rajasekaran, C., 2016. Effect of artificial seagrass on wave attenuation and wave run-up. Int. J. Ocean Clim. Syst. 7, 14–19. https://doi.org/10. 1177/1759313115623163.

Kantha, L., 2013. Classification of hurricanes: Lessons from Katrina, Ike, Irene, Isaac and Sandy. https://doi.org/10.1016/j.oceaneng.2013.06.007.

Karunarathna, H., Brown, J., Chatzirodou, A., Dissanayake, P., Wisse, P., 2018. Multi-timescale morphological modelling of a dune-fronted sandy beach. Coast. Eng. 136, 161–171. https://doi.org/10.1016/j.coastaleng.2018.03.005.

Keesstra, S., Nunes, J., Novara, A., Finger, D., Avelar, D., Kalantari, Z., Cerdà, A., 2018. The superior effect of nature based solutions in land management for enhancing ecosystem services. Sci. Total Environ. 610–611, 997–1009. https://doi.org/10.1016/J. SCITOTENV.2017.08.077.

Kirwan, M.L., Megonigal, J.P., 2013. Tidal wetland stability in the face of human impacts and sea-level rise. Nat. 504 (5047478), 53–60. https://doi.org/10.1038/nature12856 2013.

Kulp, S.A., Strauss, B.H., 2019. New elevation data triple estimates of global vulnerability to sea-level rise and coastal flooding. Nat. Commun. 101 (10), 1–12. https://doi.org/10.1038/s41467-019-12808-z 2019.

Kumar, P., Debele, S.E., Sahani, J., Aragão, L., Barisani, F., Basu, B., Bucchignani, E., Charizopoulos, N., Di Sabatino, S., Domeneghetti, A., Edo, A.S., Finér, L., Gallotti, G., Juch, S., Leo, L.S., Loupis, M., Mickovski, S.B., Panga, D., Pavlova, I., Pilla, F., Prats, A.L., Renaud, F.G., Rutzinger, M., Basu, A.S., Shah, M.A.R., Soini, K., Stefanopoulou, M., Toth, E., Ukonmaanaho, L., Vranic, S., Zieher, T., 2020. Towards an operationalisation of nature-based solutions for natural hazards. Sci. Total Environ. 731, 138855. https://doi.org/10.1016/J.SCITOTENV.2020.138855.

Kumar, P., Debele, S.E., Sahani, J., Rawat, N., Marti-Cardona, B., Alfieri, S.M., Basu, B., Basu, A.S., Bowyer, P., Charizopoulos, N., Gallotti, G., Jaakko, J., Leo, L.S., Loupis, M., Menenti, M., Mickovski, S.B., Mun, S.J., Gonzalez-Ollauri, A., Pfeiffer, J., Pilla, F., Pröll, J., Rutzinger, M., Santo, M.A., Sannigrahi, S., Spyrou, C., Tuomenvirta, H., Zieher, T., 2021. Nature-based solutions efficiency evaluation against natural hazards: modelling methods, advantages and limitations. Sci. Total Environ. 784. https://doi.org/10.1016/J.SCITOTENV.2021.147058.

Lee, H.S., Choi, Y.J., Woo, S.B., 2021. Numerical models in coastal hazards and coastal environment. 2021J. Mar. Sci. Eng. 9, 494. https://doi.org/10.3390/JMSE9050494 Vol. 9, Page 494.

Lemauviel, S., Gallet, S., Rozé, F., 2003. Sustainable management of fixed dunes: example of a pilot site in Brittany (France). C. R. Biol. 326. https://doi.org/10.1016/S1631-0691(03)00056-8.

Lin, N., Emanuel, K., Oppenheimer, M., Vanmarcke, E., 2012. Physically based assessment of hurricane surge threat under climate change. Nat. Clim. Chang. 26 (2), 462–467. https://doi.org/10.1038/nclimate1389 2021, Vol. 13, Page 1034.

Lindemer, C.A., Plant, N.G., Puleo, J.A., Thompson, D.M., Wamsley, T.V., 2010. Numerical simulation of a low-lying barrier island's morphological response to hurricane Katrina. Coast. Eng. 57, 985–995. https://doi.org/10.1016/j.coastaleng.2010.06.004.

Lionello, P., Boldrin, U., Giorgi, F., 2007. Future changes in cyclone climatology over Europe as inferred from a regional climate simulation. Clim. Dyn. 306 (30), 657–671. https://doi.org/10.1007/S00382-007-0315-0.

de los Santos, C.B., Krause-Jensen, D., Alcoverro, T., Marbà, N., Duarte, C.M., van Katwijk, M.M., Pérez, M., Romero, J., Sánchez-Lizaso, J.L., Roca, G., Jankowska, E., Pérez-Lloréns, J.L., Fournier, J., Montefalcone, M., Pergent, G., Ruiz, J.M., Cabaço, S., Cook, K., Wilkes, R.J., Moy, F.E., Trayter, G.M.R., Arañó, X.S., de Jong, D.J., Fernández-Torquemada, Y., Auby, I., Vergara, J.J., Santos, R., 2019. Recent trend reversal for declining European seagrass meadows. Nat. Commun., 10 https://doi.org/10.1038/S41467-019-11340-4.

van der Lugt, M.A., Quataert, E., van Dongeren, A., van Ormondt, M., Sherwood, C.R., 2019. Morphodynamic modeling of the response of two barrier islands to Atlantic hurricane forcing. Estuar. Coast. Shelf Sci. 229, 106404. https://doi.org/10.1016/J.ECSS.2019.106404.

Martínez, M.L., Intralawan, A., Vázquez, G., Pérez-Maqueo, O., Sutton, P., Landgrave, R., 2007. The coasts of our world: ecological, economic and social importance. Ecol. Econ. 63, 254–272. https://doi.org/10.1016/J.ECOLECON.2006.10.022.

Masselink, G., Castelle, B., Scott, T., Dodet, G., Suanez, S., Jackson, D., Floc', H.F., 2016. Extreme wave activity during 2013/2014 winter and morphological impacts along the Atlantic coast of Europe. Geophys. Res. Lett. 43, 2135–2143. https://doi.org/10.1002/2015GL067492.

Maul, G.A., Duedall, I.W., 2019. Demography of Coastal Populations, pp. 692–700 https://doi.org/10.1007/978-3-319-93806-6_115.

Maza, M., Lara, J.L., Losada, I.J., 2013. A coupled model of submerged vegetation under oscillatory flow using Navier-Stokes equations. Coast. Eng. 80, 16–34. https://doi.org/10.1016/J.COASTALENG.2013.04.009.

Mazzella, L., Guidetti, P., Lorenti, M., Buia, M.C., Zupo, V., Scipione, M.B., Rismondo, A., Curiel, D., 1998. (PDF) Biomass partitioning in Adriatic seagrass ecosystems (Posidonia oceanica, Cymodocea nodosa, Zostera marina). Rapp. Comm. Int. Mer Médit. 35, 562–563.

McCall, R.T., Thiel, Van, de Vries, J., Plant, N.G., Van Dongeren, A., Roelvink, J.A., Thompson, D.M., Reniers, A.J.H.M., 2010. Two-dimensional time dependent hurricane overwash and erosion modeling at Santa Rosa Island. Coast. Eng. 57, 668–683. https://doi.org/10.1016/j.coastaleng.2010.02.006.

McGranahan, G., Balk, D., Anderson, B., 2007. TheRising Tide: Assessing the Risks of Climate Change and Human Settlements in LowElevation Coastal Zones. 19, pp. 17–37. https://doi.org/10.1177/0956247807076960.

Mendez, F.J., Losada, I.J., 2004. An empirical model to estimate the propagation of random breaking and nonbreaking waves over vegetation fields. Coast. Eng. 51, 103–118. https://doi.org/10.1016/J.COASTALENG.2003.11.003.

Mendoza, E.T., Jiménez, J.A., 2005. Factors Controlling Vulnerability to Storm Impacts Along the Catalonian Coast, pp. 3087–3099 https://doi.org/10.1142/9789812701916_0249.

Mentaschi, L., Vousdoukas, M.I., Pekel, J.F., Voukouvalas, A., Feyen, L., 2018. Global long-term observations of coastal erosion and accretion. Sci. Reports 81 (8), 1–11. https://doi.org/10.1038/s41598-018-30904-w 2018.

Miani, M., Dissanayake, P., Lamberti, A., Archetti, R., 2015. Sand Dune Breaching Along the Emilia-Romagna Littoral Zone : A Deterministic Approach, pp. 1–6 https://doi.org/10.1364/AO.48.006973.

Montblanc, T.F., Duo, E., Ciavola, P., 2020. DuneReconstruction and Revegetation as a Potential Measure to Decrease Coastal Erosionand Flooding Under Extreme Storm Conditions. https://doi.org/10.1016/j.ocecoaman.2019.105075.

Moraes, R.P.L., Reguero, B.G., Mazarrasa, I., Ricker, M., Juanes, J.A., 2022. Nature-based solutions in coastal and estuarine areas of Europe. Front. Environ. Sci. 10, 928. https://doi.org/10.3389/FENVS.2022.829526/BIBTEX.

Morris, R.L., Konlechner, T.M., Ghisalberti, M., Swearer, S.E., 2018. From grey to green: efficacy of eco-engineering solutions for nature-based coastal defence. Glob. Chang. Biol. 24, 1827–1842. https://doi.org/10.1111/GCB.14063.

Muller, H., Van Rooijen, A., Idier, D., Pedreros, R., Rohmer, J., 2017. Assessing Storm Impact on a French Coastal Dune System Using Morphodynamic Modeling. 33, pp. 254–272. https://doi.org/10.2112/JCOASTRES-D-15-00102.

Narayan, S., Beck, M.W., Reguero, B.G., Losada, I.J., Van Wesenbeeck, B., Pontee, N., Sanchirico, J.N., Ingram, J.C., Lange, G.M., Burks-Copes, K.A., 2016. The effectiveness, costs and coastal protection benefits of natural and nature-based defences. PLoS One 11, 1–17. https://doi.org/10.1371/journal.pone.0154735.

Nederhoff, C.M.(Kees), 2014. Modelling the effects of hard structures on dune erosion and overwash. Hindcasting the Impact of Hurricane Sandy on New Jersey with XBeach. 188. https://doi.org/10.1126/science.282.5396.2012.

Nepf, H.M., Vivoni, E.R., 2000. Flow structure in depth-limited, vegetated flow. J. Geophys. Res. Ocean. 105, 28547–28557. https://doi.org/10.1029/2000JC900145.

Nesshöver, C., Assmuth, T., Irvine, K.N., Rusch, G.M., Waylen, K.A., Delbaere, B., Haase, D., Jones-Walters, L., Keune, H., Kovacs, E., Krauze, K., Külvik, M., Rey, F., van Dijk, J., Vistad, O.I., Wilkinson, M.E., Wittmer, H., 2017. The science, policy and practice of nature-based solutions: an interdisciplinary perspective. Sci. Total Environ. 579, 1215–1227. https://doi.org/10.1016/J.SCITOTENV.2016.11.106.

Nunn, P.D., Klöck, C., Duvat, V., 2021. Seawalls as maladaptations along island coasts. Ocean Coast. Manag. 205, 105554. https://doi.org/10.1016/J.OCECOAMAN.2021.105554.

Ondiviela, B., Losada, I.J., Lara, J.L., Maza, M., Galván, C., Bouma, T.J., van Belzen, J., 2014. The role of seagrasses in coastal protection in a changing climate. Coast. Eng. https://doi.org/10.1016/j.coastaleng.2013.11.005.

Oppenheimer, M., Glavovic, B.C., Hinkel, J., van de Wal, R., Magnan, A.K., Abd-Elgawad, A., 2019. Chapter 4: Sea Level Rise and Implications for Low-Lying Islands, Coasts and Communities — Special Report on the Ocean and Cryosphere in a Changing Climate [WWW Document]. 2019… (Accessed 20 September 2022).

van Ormondt, M., Nelson, T.R., Hapke, C.J., Roelvink, D., 2020. Morphodynamic modelling of the wilderness breach, Fire Island, New York. Part I: model set-up and validation. Coast. Eng. 157. https://doi.org/10.1016/j.coastaleng.2019.103621.

Passeri, D.L., Long, J.W., Plant, N.G., Bilskie, M.V., Hagen, S.C., 2018. The influence of bed friction variability due to land cover on storm-driven barrier island morphodynamics. Coast. Eng. 132, 82–94. https://doi.org/10.1016/j.coastaleng.2017.11.005.

Pauleit, S., Hansen, R., Rall, E.L., Zölch, T., Andersson, E., Luz, A.C., Szaraz, L., Tosics, I., Vierikko, K., 2017. Urban landscapes and green infrastructure. Oxford Res. Encycl. Environ. Sci. https://doi.org/10.1093/ACREFORE/9780199389414.013.23

Pergent, G., Bazairi, H., Bianchi, C.N., Boudouresque, C.F., Buia, M.C., Clabaut, P., Harmelin-Vivien, M., Mateo, M.A., Montefalcone, M., Morri, C., Orfanidis, S., Semroud, R., Serrano, O., Pergent-Martini, C., 2012. Mediterranean Seagrass Meadows: Resilience and Contribution to Climate Change Mitigation, p. 40.

Perini, L., Calabrese, L., Deserti, M., Valentini, A., Ciavola, P., Armaroli, C., 2011. Le mareggiate e gli impatti sulla costa in Emilia-Romagna 1946-2010.

Perini, L., Calabrese, L., Lorito, S., Luciani, P., 2015a. Il rischio da mareggiata in Emilia-Romagna : l'evento del 5–6 febbraio 2015. Geol. 53, 8–17.

Perini, L., Calbrese, L., Lorito, S., Luciani, P., 2015. Costal Flood Risk in Emilia-Romagna (Italy): The Sea Storm of February 2015, pp. 225–230 https://doi.org/10.5150/CMCM.2015.044.

Plomaritis, T.A., Costas, S., Ferreira, Ó., 2018. Use of a bayesian network for coastal hazards, impact and disaster risk reduction assessment at a coastal barrier (Ria Formosa, Portugal). Coast. Eng. 134, 134–147. https://doi.org/10.1016/j.coastaleng.2017.07.003.

Potouroglou, M., Bull, J.C., Krauss, K.W., Kennedy, H.A., Fusi, M., Daffonchio, D., Mangora, M.M., Githaiga, M.N., Diele, K., Huxham, M., 2017. Measuring the role of seagrasses in regulating sediment surface elevation. xiii + 97ppSci. Reports 71 (7), 1–11. https://doi.org/10.1038/s41598-017-12354-y.

Procaccini, G., Buia, M.C., Gambi, M.C., Perez, M., Pergent, G., Pergent-Mertini, C., Romero, J., 2003. The seagrasses of the western Mediterranean. In: Green, E.P., Short, F.T. (Eds.), World Atlas of Seagrasses. University of California, Berkeley. USA.

Ranasinghe, R., 2016. Assessing climate change impacts on open sandy coasts: a review. Earth-Sci. Rev. 160, 320–332. https://doi.org/10.1016/J.EARSCIREV.2016.07.011.

Reguero, B.G., Losada, I.J., Díaz-Simal, P., Méndez, F.J., Beck, M.W., 2015. Effects of climate change on exposure to coastal flooding in Latin America and the Caribbean. PLoS One 10, e0133409. https://doi.org/10.1371/JOURNAL.PONE.0133409.

van Rijn, L.C., 2007. Unified view of sediment transport by currents and waves. I: initiation of motion, bed roughness, and bed-load transport. J. Hydraul. Eng. 133, 649–667. https://doi.org/10.1061/(ASCE)0733-9429(2007)133:6(649).

van Rijn, L.C., Wasltra, D.J.R., Grasmeijer, B., Sutherland, J., Pan, S., Sierra, J.P., 2003. The predictability of cross-shore bed evolution of sandy beaches at the time scale of storms and seasons using process-based profile models. Coast. Eng. 47, 295–327. https://doi.org/10.1016/S0378-3839(02)00120-5.

Rodriguez, A.B., Fodrie, F.J., Ridge, J.T., Lindquist, N.L., Theuerkauf, E.J., Coleman, S.E., Grabowski, J.H., Brodeur, M.C., Gittman, R.K., Keller, D.A., Kenworthy, M.D., 2014. Oyster reefs can outpace sea-level rise. Nat. Clim. Chang. 46 (4), 493–497. https://doi.org/10.1038/nclimate2216 2014.

Roelvink, D., Reniers, A., van Dongeren, A., van Thiel de Vries, J., McCall, R., Lescinski, J., 2009. Modelling storm impacts on beaches, dunes and barrier islands. Coast. Eng. 56, 1133–1152. https://doi.org/10.1016/j.coastaleng.2009.08.006.

Roelvink, D., Mehvar, S., Nederhoff, K., Dastgheib, A., 2018. Improving predictions of swash dynamics in XBeach: the role of groupiness and incident-band runup. Coast. Eng. 134, 103–123. https://doi.org/10.1016/J.COASTALENG.2017.07.004.

van Rooijen, A.A., van Thiel de Vries, J.S.M., McCall, R.T., van Dongeren, A.R., Roelvink, J.A., Reniers, A.J.H.M., 2015. Modeling of wave attenuation by vegetation with XBeach. E-proceedings 36th IAHR World Congr, p. 7.

Ruíz, J.M., Boudouresque, C.F., Enríquez, S., 2009. Mediterranean seagrasses. Bot. Mar. 52, 369–381. https://doi.org/10.1515/BOT.2009.058/MACHINEREADABLECITATION/RIS.

Schambach, L., Grilli, A.R., Grilli, S.T., Hashemi, M.R., King, J.W., 2018. Assessing the impact of extreme storms on barrier beaches along the Atlantic coastline: application to the

southern Rhode Island coast. Coast. Eng. 133, 26–42. https://doi.org/10.1016/J.COASTALENG.2017.12.004.

Schoonees, T., Gijón Mancheño, A., Scheres, B., Bouma, T.J., Silva, R., Schlurmann, T., Schüttrumpf, H., 2019. Hard structures for coastal protection, towards greener designs. Estuar. Coasts 42, 1709–1729. https://doi.org/10.1007/S12237-019-00551-Z/TABLES/3.

Schweiger, C., Schuettrumpf, H., 2021. Considering the effect of land-based biomass on dune erosion volumes in large-scale numerical modeling. J. Mar. Sci. Eng. 9. https://doi.org/10.3390/jmse9080843.

Schweiger, C., Kaehler, C., Koldrack, N., Schuettrumpf, H., 2020. Spatial and temporal evaluation of storm-induced erosion modelling based on a two-dimensional field case including an artificial unvegetated research dune. Coast. Eng. 161, 103752. https://doi.org/10.1016/j.coastaleng.2020.103752.

Shahrizal, M., Razak, A., Arriffah, N., Mohd Nor, Z., 2018. XBeach Process-based Modelling of Coastal Morphological Features Near Breakwater. https://doi.org/10.1051/matecconf/201820301007.

Simmons, J.A., Marshall, L.A., Turner, I.L., Splinter, K.D., Cox, R.J., Harley, M.D., Hanslow, D.J., Kinsela, M.A., 2015. A more rigorous approach to calibrating and assessing the uncertainty of coastal numerical models. Australas. Coasts Ports Conf. 2015, 7.

Simmons, J.A., Splinter, K.D., Harley, M.D., Turner, I.L., 2019. Calibration data requirements for modelling subaerial beach storm erosion. Coast. Eng. 152, 103507. https://doi.org/10.1016/J.COASTALENG.2019.103507.

Splinter, K., Palmsten, M., 2011. Comparison of measured and modeled run-up and resulting dune erosion during a lab experiment. Coast. Eng. 1–14. https://doi.org/10.19070/2332-287X-1500027.

Splinter, K.D., Palmsten, M.L., 2012. Modeling dune response to an East Coast low. Mar. Geol. 329–331, 46–57. https://doi.org/10.1016/j.margeo.2012.09.005.

Statistical Office of the European Communities, European Commission, 2011. Eurostat Regional Yearbook 2011.

Sutherland, J., Peet, A.H., Soulsby, R.L., 2004. Evaluating the performance of morphological models. Coast. Eng. 51, 917–939. https://doi.org/10.1016/J.COASTALENG.2004.07.015.

Sutton-Grier, A.E., Wowk, K., Bamford, H., 2015. Future of our coasts: the potential for natural and hybrid infrastructure to enhance the resilience of our coastal communities, economies and ecosystems. Environ. Sci. Policy 51, 137–148. https://doi.org/10.1016/J.ENVSCI.2015.04.006.

Suzuki, T., Zijlema, M., Burger, B., Meijer, M.C., Narayan, S., 2012. Wave dissipation by vegetation with layer schematization in SWAN. Coast. Eng. 59, 64–71. https://doi.org/10.1016/j.coastaleng.2011.07.006.

Syvitski, J.P.M., Kettner, A.J., Overeem, I., Hutton, E.W.H., Hannon, M.T., Brakenridge, G.R., Day, J., Vörösmarty, C., Saito, Y., Giosan, L., Nicholls, R.J., 2009. Sinking deltas due to human activities. Nat. Geosci. 2, 681–686. https://doi.org/10.1038/NGEO629.

Tanino, Y., Nepf, H.M., 2008. Laboratory investigation of mean drag in a random Array of rigid, emergent cylinders. J. Hydraul. Eng. 134, 34–41. https://doi.org/10.1061/(ASCE)0733-9429(2008)134:1(34).

Temmerman, S., Meire, P., Bouma, T.J., Herman, P.M.J., Ysebaert, T., De Vriend, H.J., 2013. Ecosystem-based coastal defence in the face of global change. Nat 5047478 (504), 79–83. https://doi.org/10.1038/nature12859 2013.

The European Union, 2010. Directive 2009/147/EC of the European Parliament and of the council of 30 November 2009 on the conservation of wild birds. Off. J. Eur. Union 53, 7–25.

Thiel de Vries, J.S.M.van, 2009. Jacob S.M. vanDune Erosion During Storm Surges, p. 202.

Umesh, P.A.P., Pinardi, N., Alessandri, J., Federico, I., Causio, S., Unguendoli, S., Valentini, A., Staneva, J., 2022. A digital twin modelling framework for the assessment of seagrass nature based solutions against storm surges. Sci. Total Environ. 847, 157603. https://doi.org/10.1016/j.scitotenv.2022.157603.

Van Rooijen, A.A., Mccall, R.T., Van Thiel De Vries, J.S.M., Van Dongeren, A.R., Reniers, A.J.H.M., Roelvink, J.A., 2016. Modelingthe Effect of Wave-vegetation Interaction on Wave Setup. https://doi.org/10.1002/2015JC011392.

Vitousek, S., Barnard, P.L., Fletcher, C.H., Frazer, N., Erikson, L., Storlazzi, C.D., 2017. Doubling of coastal flooding frequency within decades due to sea-level rise. Sci. Reports 71 (7), 1–9. https://doi.org/10.1038/s41598-017-01362-7 2017.

Vousdoukas, M., Almeida, L., Ferreira, Ó., 2011. Modelling storm-induced beach morphological change in a meso-tidal, reflective beach using XBeach. J. Coast. Res. 1916–1920.

Vousdoukas, M.I., Ferreira, Ó., Almeida, L.P., Pacheco, A., 2012. Toward reliable storm-hazard forecasts: XBeach calibration and its potential application in an operational early-warning system. Ocean Dyn. 62, 1001–1015. https://doi.org/10.1007/s10236-012-0544-6.

Vousdoukas, M.I., Mentaschi, L., Voukouvalas, E., Bianchi, A., Dottori, F., Feyen, L., 2018. Climatic and socioeconomic controls of future coastal flood risk in Europe. Nat. Clim. Chang. 89 (8), 776–780. https://doi.org/10.1038/s41558-018-0260-4 2018.

Vousdoukas, M.I., Mentaschi, L., Voukouvalas, E., Verlaan, M., Jevrejeva, S., Jackson, L.P., Feyen, L., 2018b. Global probabilistic projections of extreme sea levels show intensification of coastal flood hazard. Nat. Commun. 9, 1–12. https://doi.org/10.1038/s41467-018-04692-w.

Yizhaq, H., Ashkenazy, Y., Tsoar, H., 2009. Sand dune dynamics and climate change: a modeling approach. J. Geophys. Res. Earth Surf. 114, 1023. https://doi.org/10.1029/2008JF001138.

van Zelst, V.T.M., Dijkstra, J.T., van Wesenbeeck, B.K., Eilander, D., Morris, E.P., Winsemius, H.C., Ward, P.J., de Vries, M.B., 2021. Cutting the costs of coastal protection by integrating vegetation in flood defences. Nat. Commun. 121 (12), 1–11. https://doi.org/10.1038/s41467-021-26887-4 2021.