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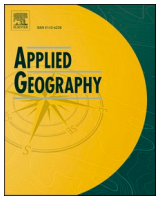

Resist or retreat? Beach erosion and the climate crisis in Italy: Scenarios, impacts and challenges

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ABSTRACT

The ongoing erosion of beaches due to anthropic pressure, together with the effects of sea level rise are expected to have devastating effects on sandy coastlines. This paper identifies the Italian beaches under threat and their regional distribution, examining the implications for beach-dependent activities and coastal management, based on the integration of various projections and datasets. As a result, by the year 2050 erosion is expected to affect 70% of Italian beaches. One-fifth of the current beaches' surface is likely to be almost completely submerged by 2050 and 45% by the end of the century, with the regions of Sardinia, Campania, Lazio, and Apulia likely to lose more than half of their equipped beaches. Although beaches naturally tend to migrate landward when subjected to erosion, and such shift can be favoured by managed retreat measures, these solutions are severely limited by the increasing urbanisation of back beaches. Adaptation in Italy is almost exclusively based on coastal protections, which exacerbate overall erosion and undermine beaches' natural resilience. A transformative and nature-based rethinking of the coastal management regime is needed to avoid the artificialization of a huge portion of the sandy coastline and increasing threats to coastal settlements and economies.

1. Introduction

The climate crisis poses significant threats to coastal areas. Increasing temperatures, sea level rise, and more frequent extreme weather events are reshaping coastal landscapes, particularly in low-lying areas, and impacting the livelihoods of millions of people (IPCC, 2023). In this context, sandy coastlines and beaches are both particularly vulnerable and extremely precious, since they are highly complex environments of significant environmental, social, and economic importance (de Andrade et al., 2019).

Beach erosion firstly threatens coastal ecology and ecosystems, further exacerbating beaches' vulnerability to climate-related stressors (Barredo et al., 2016). Secondly, it impacts beach-dependent human activities, as well as coastal settlements and infrastructure (Spencer et al., 2022), posing risks to human safety and inflicting substantial socioeconomic impacts (Alexandrakis et al., 2015).

Climate change and sea level rise are the most alarming consequences of the climate crisis, but not the only source of heightened coastal erosion. Anthropic pressure is already contributing to the erosion of more than 0.5 m/year of 24% of the world's sandy beaches (Luijendijk et al., 2018). Growing coastal populations and economies, and the construction of buildings and infrastructure close to the shoreline, disrupt natural processes, hindering sandy coasts' ability to adapt. Although they operate on different temporal and spatial scales, anthropic pressures can pose even greater distress than physical factors (Slott et al., 2010). These pressures, together with the effects of climate change, will likely result in the shrinkage of most beaches and, in some cases, in the complete submergence of the areas they currently occupy (Vitousek et al., 2017; Vousdoukas et al., 2020).

Forecasting the future evolution of coastal landscapes is therefore crucial for designing appropriate response strategies. However, the extent of the depth and pace of coastal change, as well as the ways we can prevent it and adapt to it, are still open questions. Available solutions need to be properly contextualised in light of predictable trends, the specific nature of each coastal system, and the complexity of actors and interests that influence response strategies and their impact upon coastal landscapes' resilience (Robert et al., 2023).

Several studies on the impacts of climate change on sandy beaches have been conducted both globally (Hinkel et al., 2013; Neumann et al., 2015; Ranasinghe, 2016) and at more local scales (Bon de Sousa et al., 2018; Cowley et al., 2022; Spencer et al., 2022), providing crucial evidence. These threats are particularly relevant for Italy and the

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Mediterranean. Because of its relatively small size, the Mediterranean is experiencing a more rapid increase in temperature, especially in its southern regions, where most of the low-lying and sandy coasts are intensely urbanised and touristified (Jeftic et al., 1992). Research conducted on Mediterranean coasts has emphasised their vulnerability (Da Lio & Tosi, 2019; Pranzini & Williams, 2013; Satta et al., 2017). For Italy, some studies have described the complexity of the natural and anthropic processes that influence the impacts of climate change on localised sandy beaches, as well as response strategies (De Falco et al., 2014; Perini et al., 2017). However, there is no comprehensive understanding of the implications of climate change for Italian beaches, with policymakers and stakeholders often lacking the necessary knowledge and awareness.

The goal of this study is to further investigate the sandy coastline dynamics examined at a global level by Vousdoukas et al. (2020) to provide a more specific assessment of the potential threats posed by both coastal erosion and sea level rise to sandy beaches in Italy. The first objective is to supplement the findings of Vousdoukas et al. (2020), since the authors did not identify the beaches under threat of submersion based on their actual size and shape, but simply assumed that they would be extinct if the retreat exceeded 100 m. The width of beaches in Italy, as will be discussed further on, can vary and be considerably below this threshold. To this end, the article provides more specific identification of the coastal areas and regions most prone to significant beach retreat in the next decades. Secondly, identification of the most vulnerable beaches will be coupled with analysis of their use for tourism and recreational purposes, based on the activities currently authorised on these beaches, to provide evidence on potential impacts in this regard. Finally, the article will reflect upon alternative adaptation strategies and the specific challenges these strategies face in the context of a country like Italy, since the effects of sea level rise and the dynamics of beach erosion are also crucially dependent on how sandy coasts are managed.

It is particularly important to consider that the projections presented in the next sections assume that the location of the beaches will remain unaltered. In fact, beaches tend to retreat and migrate landward when subject to erosion (Cooper et al., 2020). Pervasive urbanisation, however, impedes beach retreat. Moreover, many current coastal management practices tend to increase the rigidity of sandy coasts in an attempt to preserve the *status quo* (Robert et al., 2023), which may ultimately lead to aggravating the predicted dynamics, and to the almost complete artificialization of a huge portion of the Italian coastline.

2. Study area

The study area encompasses all coastal regions in Italy, along the Adriatic, Ionian, Tyrrhenian, and Ligurian Seas, extending 7500 km (Fig. 1). Two-thirds of this coast is low-lying, of which 70% is sandy, extending a total length of 3270 km and covering more than 120 km^2 of beaches (ISPRA, 2012). The coastline is home to a variety of ecosystems, including dunes, wetlands, and estuaries. This diverse coastal morphology and ecology makes it susceptible to various climate-related impacts.

The Italian coast is also heavily urbanised. Approximately 10% of the coastline is occupied by permanent infrastructure such as ports and other structures close to the shore or partially superimposed. Nearly a quarter of the land within 300 m of the coastline is covered by human-made structures, with peaks in the Liguria (47%) and Marche (45%) regions (ISPRA, 2023). The artificialization of the Italian coast has been increasing over the decades, notwithstanding the so-called 'Galasso Law' of 1985, which attempted to forbid new constructions within 300 m of the coastline (Falco, 2017). Pressures on many coastal settlements amplify considerably during the warm season due to extensive touristification.

This intense human presence and the associated infrastructure have worsened the problem of coastal erosion. According to ISPRA (2021),

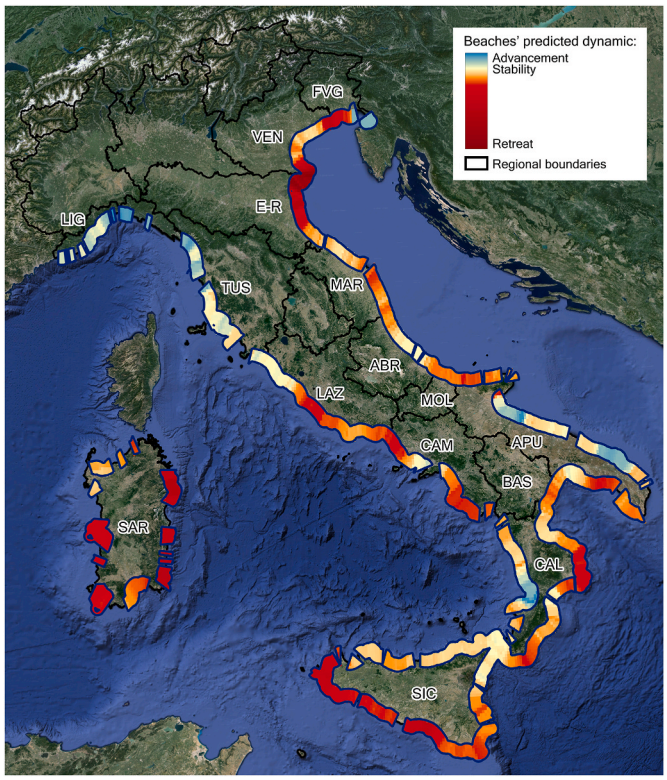

Fig. 1. Predicted sandy coastline dynamics up to the year 2050 along the Italian low-lying coastline. Spatial interpolation of the point predictions of Vousdoukas et al. (2020), 50th percentile, RCP 4.5. Labels indicate the Italian coastal regions: Liguria (LIG), Tuscany (TUS), Lazio (LAZ), Campania (CAM), Basilicata (BAS), Calabria (CAL), Sicily (SIC), Sardinia (SAR), Apulia (APU), Molise (MOL), Abruzzo (ABR), Marche (MAR), Emilia-Romagna (E–R), Veneto (VEN), and Friuli-Venezia Giulia (FVG).

approximately 18% of low-lying coastline in Italy has been eroding from 2006 to 2019, despite widespread use of coastal protections (see Section 6). Anthropic pressure poses challenges in managing climate change impacts, makes coastal regions more vulnerable to natural hazards, and amplifies social and economic risks for coastal communities and economies. Tourism facilities, in particular, are often located very close to the shoreline and, even when abandoned or unauthorised, are rarely removed. Unsustainable and often illegal development and occupation of coastal areas (Chiodelli et al., 2021) disrupts natural ecosystems and compromises coastal resilience. Moreover, management of coastal areas in Italy poses a highly intricate challenge due to institutional fragmentation and the overlapping of laws and regulations across national, regional, and municipal levels, which are often weakly enforced (Falco, 2017). It is essential to take all these specific factors into account when analysing the future impacts of climate change, making Italian coasts an excellent case study for assessing these impacts in similar settings.

3. Data and methodology

To provide an analytical and comprehensive assessment of potential future impacts, this study integrates and elaborates different projections and datasets. The main source is the estimate of the sandy coastline variation provided by Vousdoukas et al. (2020), which predicts the probability distributions of coastal advancement and retreat under two climate change scenarios (RCP 4.5 and 8.5) and for the years 2050 and 2100, on a global scale. A spatial interpolation of the Vousdoukas et al. point predictions for Italy is presented in Fig. 1.

The added value of the Vousdoukas et al. analysis is the fact that it considers two important long-term factors: i) shoreline changes driven

by long-term hydrological, geological, and anthropic dynamics (i.e. natural transitions or human interventions that alter the sediment budget and/or transport processes of coastal systems); ii) shoreline retreat due to coastal morphological adjustments to sea level rise. The authors estimate the first factor as probability density functions, based on previous estimations by Luijendijk et al. (2018) and Mentaschi et al. (2018), and extend the trends into the future to forecast shoreline dynamics. The second factor is based on an adjusted version of Bruun's rule (Bruun, 1988). In particular, Bruun's rule implies that the overall beach retreat is considerably above what would be expected from sea level rise alone. This method assumes that beach morphology tends to adapt to the prevailing wave climate and considers atmospheric conditions from six Coupled Model Intercomparison Project – Phase 5 (CMIP5) Global Climate Models (GCMs) (Mentaschi et al., 2017; Vousdoukas et al., 2017), together with a global dataset of active beach slopes (Athanasiou et al., 2019).

The database certainly presents limitations due to computational resources, data availability, and methodological abstraction imposed by the spatial and temporal scale of the analysis (Vousdoukas et al., 2020). For instance, it does not consider any physical limits to beach erosion, which may lead to overestimating the extent of potential shoreline retreat. Moreover, it does not account for the various sources, sinks, and availability of sediments due to limitations in terms of modelling capabilities and accessible data. A more refined understanding and prediction of coastal change would require complex morphological models and more detailed local analysis. Bruun's rule has also been criticised (Cooper et al., 2020). However, Vousdoukas et al. (2020) is currently the sole comprehensive dataset that makes it possible to estimate the potential loss of sandy beaches due to erosion and sea level rise for the whole country.

In this study, we elaborate the predictions of Vousdoukas et al. (2020) under the IPCC RCP 4.5 scenario, for the years 2050 and 2100, and for the 5th, 17th 50th, 83rd and 95th percentiles of probability. In the year 2050, variation of the Italian sandy shoreline is expected to range from a maximum retreat of 816m to a maximum advancement of 437m. For the year 2100, the scenario ranges from a maximum retreat of 1484m to a maximum advancement of 710m. For both scenarios, the median values are negative: 18.6m and −42.7m respectively.

To identify the extent and geographic distribution of beach surface loss and its implications, we processed and integrated the above-mentioned predictions with two main datasets. The first of these datasets is the Italian coast geodatabase of the Institute for Environmental Protection and Research (ISPRA, n.d.). The geodataset also provides the polygonal geometry for each beach, sourced from 2006, which serves as the primary data for the analysis. This also implies that the results might be underestimated, since they do not incorporate ongoing erosion dynamics beyond 2006. For the analysis, we divided the geometry of the beaches into smaller sections and calculated the beach width at each vertex of each section's polygon. Each section was then assigned the nearest point prediction from Vousdoukas et al. (2020), with an average distance of approximately 400m. To identify the beach surface under threat of erosion, we computed the difference between the maximum width of each beach section and the expected shoreline changes. This method allows us to obtain a detailed but also comprehensive identification of threatened beaches at various scales. Previous analyses relying on the same global predictions are instead based on an average estimation of beach width (Spencer et al., 2022), probably because information on the actual width of beaches is not available as secondary data. Other studies provide *ad-hoc* predictions, but are inevitably limited to specific study areas, as in the case of certain Hawaiian islands (Anderson et al., 2018; Tavares et al., 2020).

The second dataset, to which we linked the results of the previous step, is open data made available by the Italian Ministry of Infrastructure and Transport (MIT, n.d.). The dataset covers all 'maritime concessions' that were authorised in the year 2022, geolocated as point elements, which we further elaborated and verified to check for inaccurate or missing data. As mentioned in the introduction, the aim is to provide an estimate of the tourist, recreational and economic activities hosted by beaches that are under threat. Although beaches are state-owned assets that cannot be permanently ceded, they are temporarily licensed to operators for commercial purposes. Facilities that provide services and amenities to beachgoers are a defining characteristic of Italian coasts. Indeed, 'free' beaches without amenities are very rare, particularly in areas exposed to intense tourism pressures (Zanchini & Nanni, 2022). Consequently, the distribution of beach concessions can provide some useful indications about the intensity of the current social and economic use of beaches, and therefore of potential negative impacts in this regard.

4. Future shoreline retreat and beach surface loss

The results we obtained regarding the surface of the beaches currently under threat are summarised in Figs. 2 and 3. In particular, we calculated the extent of the beach sections for which 75% of the total area is expected to be submerged. We present these results for each probability level to capture the range of uncertainty associated with future scenarios. Given that the shape of beach sections is irregular, and that our computations are based on the maximum width of each section, the results should be considered underestimated, in line with the conservative approach behind the whole methodology. Results can refer to each beach, but we aggregate them at lower scales, since local predictions may be more affected by uncertainties as well as by potential inaccuracies in the underlying data.

At national level, the results suggest that at least three-quarters of the surface of between 9% and 44% of all Italian beaches is likely to be submerged by 2050. By 2100, the range will be from 28% to almost two-thirds. According to the 50th percentile projections, one-fifth of Italy's beaches might be submerged by 2050, and 45% by 2100. More precisely, by 2050, 14% of its beaches are expected to be completely submerged, 32% to be more than half-submerged, another 36% to be less than half-submerged, and only 31% will remain stable or advance.

Variability at the regional scale is particularly high for 2050. Five of the 15 Italian coastal regions are expected to lose less than 15% of their beaches under the 50th percentile scenario. Regions such as Sardinia (southern Italy) and Friuli-Venezia Giulia (north-eastern Italy), conversely, exhibit remarkably high median probability levels compared to the rest of Italy. In the worst-case scenarios, these two regions might lose two-thirds or more of their beaches as early as 2050, although there is a high range of uncertainty.

By the end of the century, under the 50th percentile scenario, the proportion of beaches remaining stable or advancing is forecast to be similar to the 2050 prediction (29%). The most significant difference lies in the sharp increase in the percentage of beaches that will be completely submerged (39%), more than three-quarters-submerged (45%), or more than half-submerged (55%). This suggests that even areas where beach retreat is not a prominent issue in the medium term will experience growing impacts in the long term. By 2100, there is still a wide range of predictions, but almost all regions are very likely to lose at least one-third of their beaches. The worsening of the situation compared to 2050 is particularly evident in Lazio and Campania, followed by Marche, Emilia-Romagna, and Apulia.

Many of the most vulnerable regions are located in Southern Italy. The ranking of the 20 most affected Italian provinces is also dominated by the South, with half of them located in Sardinia and Southern Sicily (Fig. 3). Sardinia stands out as the most vulnerable: under the 50th percentile scenario, the percentage of Sardinian beaches that would remain stable or advance will only change minimally (from 11% in 2050 to 9% in 2100), but the percentage of almost completely submerged beaches is projected to significantly increase.

The higher vulnerability of southern regions contrasts with the fact that the most devastating effects of sea level rise are expected in the North-Adriatic (i.e. eastern) coast. The vulnerability of southern regions

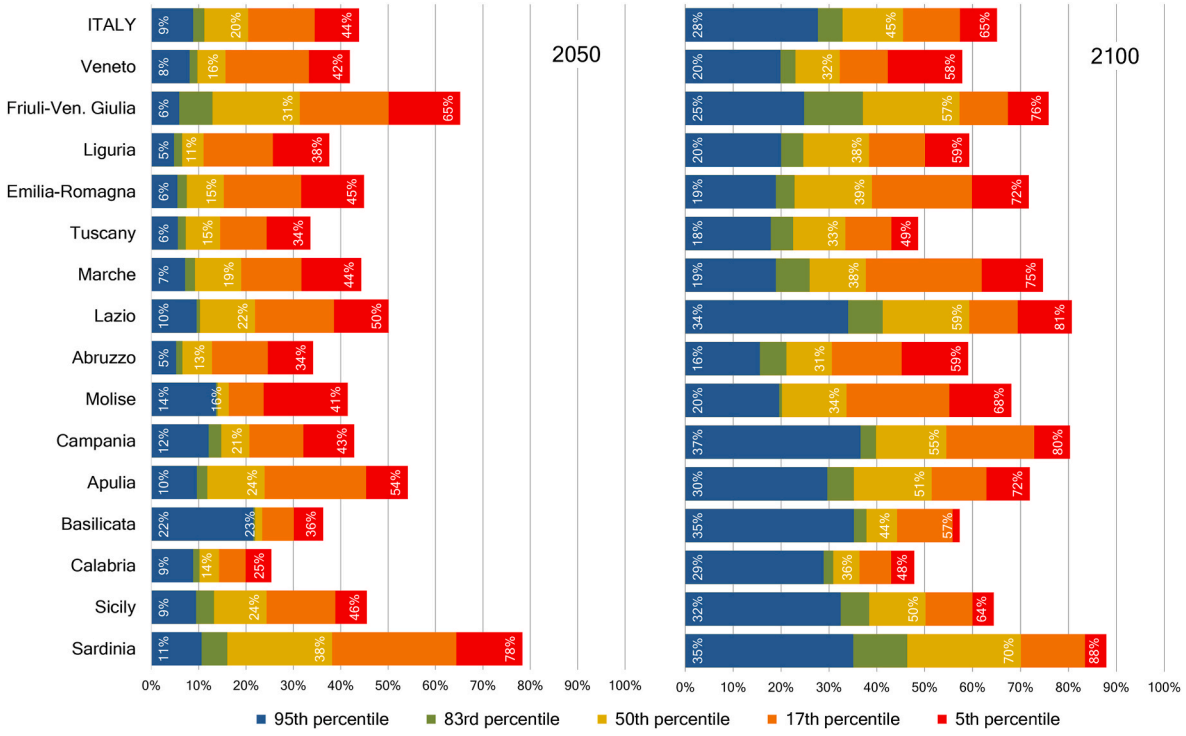

Fig. 2. Surface of beaches that are more than 75% under threat of submersion in Italian regions. Based on Vousdoukas et al. (2020), RCP 4.5 scenario, and ISPRA geodata. Labels indicate the prediction for the 5th, 50th and 95th percentile.

may be primarily due to the impact of already ongoing erosion processes, which increase in severity from north to south (Zanchini & Nanni, 2022). Erosion is particularly intense along coasts with a complex morphology and numerous bays and peninsulas, such as Sardinia, Sicily, southern Campania, and eastern Calabria.

The Adriatic basin, however, is also expected to suffer significant impacts. The Adriatic is a semi-enclosed and shallow basin, with a low-lying and flat topography, which amplifies the effects of rising sea levels. The Northern Adriatic coast also has a history of subsidence, where the land is gradually sinking. Indeed, along the Adriatic Sea – i.e. in the Friuli-Venezia Giulia, Veneto, Emilia-Romagna, Marche, Abruzzo, Molise, and Apulia regions – the proportion of stable or advancing beaches is the lowest. By 2050, the worst scenario in these regions is predicted for Friuli-Venezia Giulia, particularly in the Trieste area: the most affected of all Italian provinces. The province of Rovigo in Veneto is also one of the most affected, which can be attributed to the delta system of the Po River, Italy's longest river. As sea levels continue to rise, this deltaic region faces an increased threat of inundation. By 2100, in line with national trends, beach retreat is expected to worsen throughout the Adriatic region, particularly in the southern region of Apulia.

Lastly, the continental regions bordering the Ligurian and Tyrrhenian Seas – Liguria, Tuscany, Lazio, Campania, and western Calabria – show varying degrees of susceptibility to coastal variation. The worst scenario is in Campania, where approximately 85% of the beaches are expected to retreat by the year 2050 according to the 50th percentile scenario. Similar percentages are projected for the Lazio region, which shares Campania's notably high rate of coastal land artificialization, exacerbating shoreline retreat. Liguria and Tuscany are characterised by a relatively higher degree of stability. Approximately one-third and half of the beaches in Liguria and Tuscany, respectively, are stable or advancing. Interestingly, in the province of Lucca (Tuscany), all the beaches are expected to advance. In both regions, however, the portion of beaches projected to retreat will more than triple from 2050 to 2100, although remaining lower than the national average.

Impacts also depend on the different average widths of the beaches, which also explains the high vulnerability of Sardinia, southern Sicily, and Friuli-Venezia Giulia. The Pearson correlation coefficient between the portion of beaches at risk of inundation and their average width per Italian province is 0.5 for the year 2100, and highly significant. Such association is shown in Fig. 3, which also highlights some exceptions.

This analysis may also be applied to each of the 614 Italian coastal municipalities, albeit with higher uncertainties at this scale, as already mentioned. Overall, we estimate that around 6% of these municipalities may witness the submersion of all their beaches by over 95% by 2050, based on the 50th percentile scenario. These municipalities are primarily concentrated in Sardinia and Liguria. Although Liguria may not rank among the most affected regions on average, it could therefore experience significant localised impacts. This is due to Liguria's rugged coastline, characterised by small pocket beaches and gentle shore sections nestled between jutting headlands. Similarly, Sardinia features towering rocky coasts, often interspersed with secluded bays. In municipalities facing complete beach submersion, all beaches are typically just a few tens of meters wide, making them particularly vulnerable. By 2100, the number of municipalities in which all beaches are potentially submerged doubles, with the highest proportion in Campania (18 out of 59 municipalities), particularly in the Gulf of Naples. The semi-enclosed nature of the Gulf of Naples, combined with an urbanised coastline and relatively shallow depths, exacerbates the susceptibility to erosion of the few beaches that dot the coast. Additionally, the very high intensity of coastal urbanisation and the presence of important historical and cultural sites near the shoreline accentuate the negative impacts.

5. Implications for beach use and economy

What would be the consequences of the scenarios outlined in the previous section, in terms of the use of beaches and the activities they host? In monetary terms, Spencer et al. (2022) predicted that, in the Caribbean, an expected loss of approximately half of the beaches by 2100 would result in a 38% decrease in tourism revenues. For Italy, Cantasano et al. (2023) reported an average financial loss of 1600 euros for each square meter of lost sandy beach. If applied to the 50th

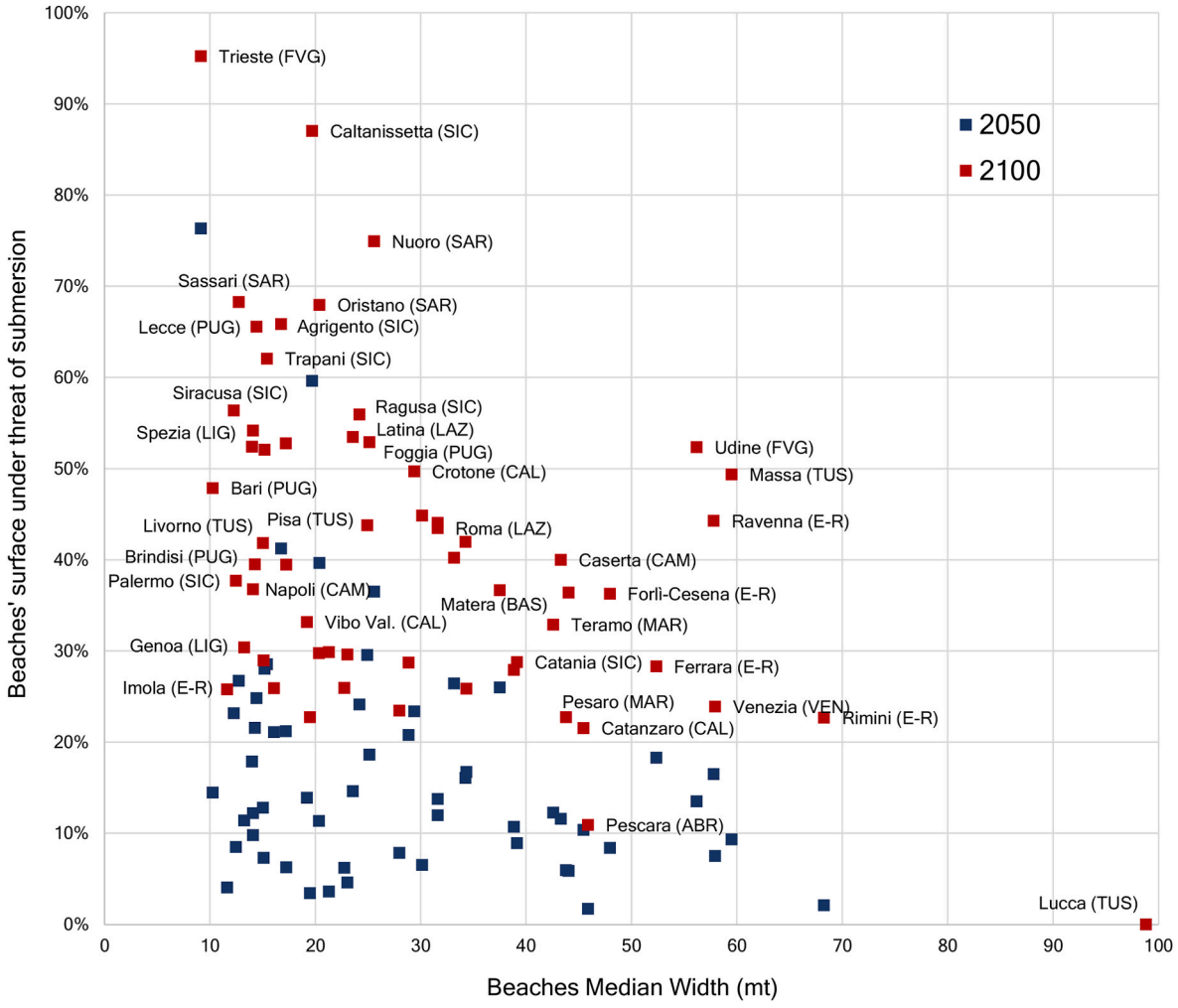

Fig. 3. Beaches under threat of submersion and beaches' average width in Italian provinces. Based on Vousdoukas et al. (2020), RCP 4.5 scenario, 50th percentile, and ISPRA geodata.

percentile prediction, and only for beaches expected to be almost completely submerged, this would imply an expected loss of 27 and 75 billion euros for the years 2050 and 2100 respectively.

As mentioned in Section 3, this study adopts a different approach. To provide evidence on how intensive is the use of sandy coastlines under threat, we analyse the geographical distribution of 'maritime concessions', i.e. tourism, recreational and economic activities that are currently authorised on beaches (Fig. 4 presents some examples). Italian beaches are well known and frequently accused of being over-occupied by a variety of services managed by private operators who receive a specific concession from the state in return for the payment of an annual fee. According to Legambiente (Zanchini & Nanni, 2022), 43% of the Italian sandy coast is occupied by 'beach establishments' (in Italian: '*stabilimenti balneari*') – designated portions of beach hosting services such as sunbed rental and food services (Fig. 4). 'Free' beaches, as already mentioned, are rare. In Liguria, Emilia-Romagna, and Campania approximately 70% of beaches' length is assigned under concession, with peaks between 80% and 100% in at least 28 municipalities (Zanchini & Nanni, 2022).

The procedures for the assignment of these concessions should be reformed and are currently being widely debated in Italy. In particular, the standard practice of reissuing beach concessions to their previous holders violates the European Union's so-called 'Bolkestein Directive' (Prada, 2022). This reform is encountering fierce resistance, mainly justified by the overtly pro-market rationale of the Bolkestein Directive. The main concerns are for the negative effects on local coastal businesses and the risk of their take-over by larger, even multinational, corporations. The current regime, on the other hand, has led to accusations of *de-facto* privatisation of most beaches, illegal restrictions on beach access, and quasi-monopolistic management of the beach economy, as well as allegations of favouritism and corruption in the concession system. It should be added that beach facilities, including when they are temporary, can aggravate coastal erosion.

According to a study conducted by Nomisma (2023), 95% of these concessions encompass areas of less than 10,000 square meters. In terms of geographical distribution, the Emilia-Romagna region leads the way with 15% of all Italian beach establishments, followed by Tuscany (13%) and Liguria (11.5%). One in five of these concessions were authorised in the last decade, particularly in southern regions. The cumulative fees for tourist and recreational concessions in 2022 exceeded 609 million euros, 70% of which are due to beach establishments, although current concession fees are accused of often being too low. According to Nomisma, each beach establishment generates an average annual revenue of 260,000 euros. The industry predominantly comprises small and very small businesses that employ around 60,000 workers, of whom approximately 43,000 are employees: roughly 6.5 employees per business (Nomisma, 2023). Maritime concessions can also be authorised for productive activities of various sorts, both onshore and offshore, as indicated in Fig. 4.

For this study, we only considered onshore concessions located within or very close to a beach, excluding those for which information is incomplete or inaccurate, and those whose operations are unlikely to be

Fig. 4. Examples of maritime concessions in Italy: Olbia harbour in Sardinia (upper figure); Cesenatico beach in Emilia-Romagna (lower figure). Based on MIT (n.d.).

impeded by beach erosion, such as nautical services. We have therefore considered a total number of approximately 18,000 concessions, of which 53% are for tourism and recreational purposes and, among those, 70% are classified as 'beach establishments'. Fig. 5 shows the numbers and the percentages of the activities located on beaches that are more than 75% under threat of submersion by 2050 and 2100. Fig. 6 only focuses on beach establishments and provides the same predictions for the 12 Italian regions for which information is available and complete.

In terms of typologies, the 50th percentile prediction consistently indicates that 17–25% of concessions are under threat of submersion for 2050, and 40–50% by 2100 (Fig. 5). Non-tourism businesses are expected to be the most affected. In terms of regions, focusing only on beach establishments, there is a wider range of variation (Fig. 6).

These results are obviously strongly correlated with the beach retreat prediction discussed in the previous section. It is more interesting to compare the expected impact on beach retreat with the impact on beach establishments (Fig. 7). The aim is to assess if and where the impact on 'free' beaches will be more intense than on 'equipped' beaches. In the case of the Molise region, for example, retreat is expected to disproportionally affect free beaches (+11%). The same applies, although to a lesser extent, to the other regions below the diagram's diagonal. By contrast, for the regions above the diagonal, the impact on equipped

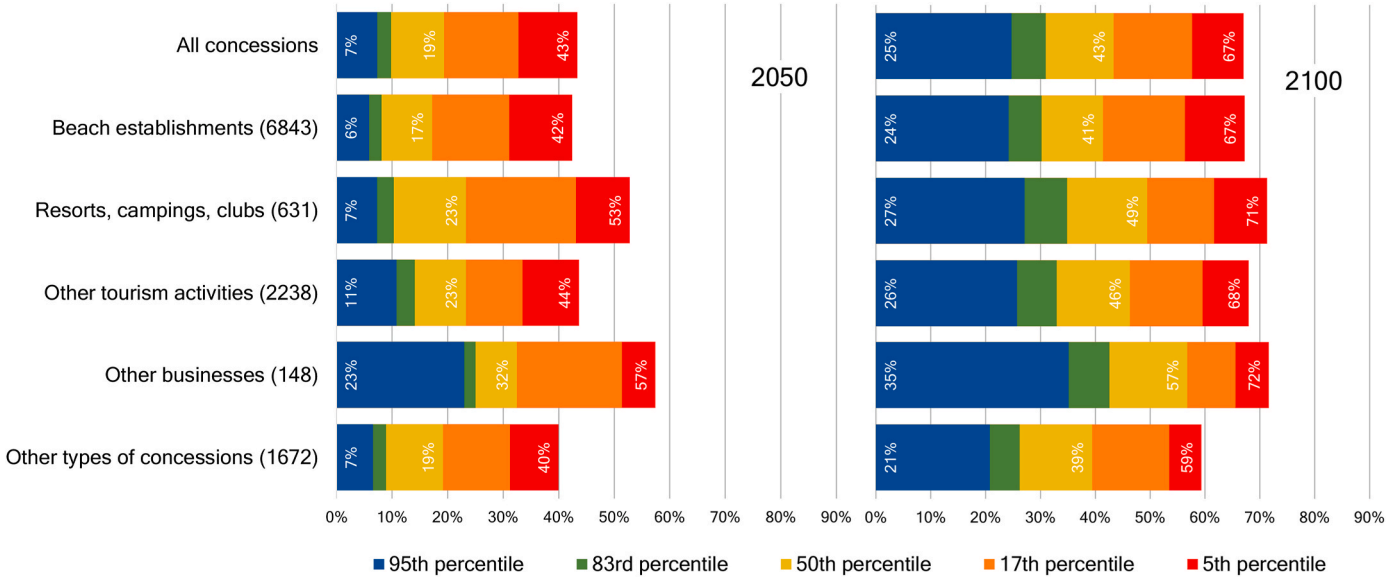

Fig. 5. Maritime concessions per typology in beaches more than 75% under threat of submersion, in different probability scenarios. Based on Vousdoukas et al. (2020), RCP 4.5 scenario, ISPRA, MIT. Labels indicate the prediction for the 5th, 50th and 95th percentile. The number in brackets indicates the total number of authorised beach concessions. Data for Sicily, Basilicata, and Friuli-Venezia Giulia is unavailable.

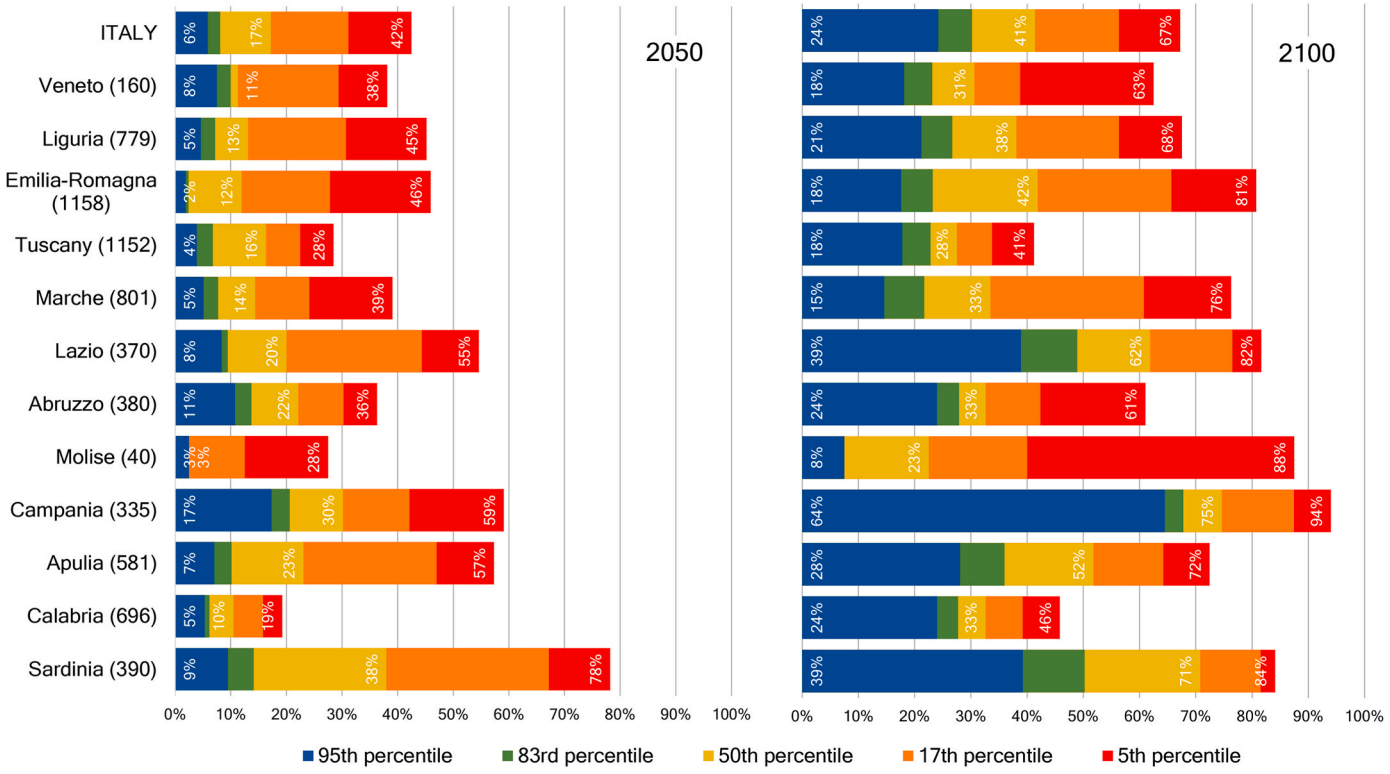

Fig. 6. Beach establishments authorised on beaches more than 75% under threat of submersion, in different probability scenarios and Italian regions. Based on Vousdoukas et al. (2020), RCP 4.5 scenario, ISPRA, MIT. Labels indicate the prediction for the 5th, 50th and 95th percentile. The number in brackets indicates the total number of authorised beach establishments. Data for Sicily, Basilicata, and Friuli-Venezia Giulia is unavailable.

beaches will be more intense. For example, the impact on equipped beaches in Campania in 2100 is expected to be the highest: 75% of Campania's equipped beaches are under threat, while the region ranks third in terms of overall beach retreat. On average, the impact in Italy is expected to be slightly higher for free beaches.

Applying these predictions to their current number of employees and revenues (Nomisma, 2023), Italian beach establishments are expected to lose approximately 10,000 and 25,000 workers and about 320 and 770 million euros of annual revenues by the year 2050 and 2100, respectively.

6. Resist or retreat? Implications and alternatives for coastal management

In the face of the challenges posed by the scenarios described in the previous sections, the debate on what should be done often revolves around the alternative between a resistance strategy through hard protections and an adaptation strategy through managed realignment or retreat.

A thorough analysis of the Italian policy scenario in these regards is beyond the scope of this paper. However, it is important to consider that the same effects of beach erosion and sea level rise will crucially depend on how we respond. In particular, as mentioned in the introduction, the predictions outlined in the previous sections assume that beaches' position and shape will not vary in the next decades, even in the event of severe erosive processes. This is obviously not the case: provided that space is available, beaches subject to erosion naturally tend to migrate landward. While this is generally true, such an expectation must be properly contextualised.

Along most of the coastline of a country such as Italy, adequate back beach space is simply unavailable due to its morphology or, more frequently, due to intense urbanisation and the presence of infrastructure that denaturalises and disconnects the beach from its inland (Martínez et al., 2014). According to our elaboration of ISPRA data (n. d.), approximately half of the back beach in Italy is artificial (Fig. 8). 39% of Italy's back beach space is urbanised, 7% is occupied by tourism facilities, and 4% by infrastructure. The situation varies along the Italian coastline (Fig. 8). In Abruzzo, Marche and Liguria, for example, beach erosion might be milder than elsewhere, but natural retreat is severely limited by the extensive artificialization of the back beach. The opposite is true for Sardinia and Apulia, in particular. The worst scenario, from this perspective, is in Friuli Venezia-Giulia, Lazio and Campania, where strong erosive processes will occur along intensively urbanised coasts.

Moreover, current coastal management strategies are strongly in favour of preserving the *status quo*, allocating vast resources to maintain beaches in their current position. When faced with erosive processes, these strategies tend to focus "solely on the very local, narrow thread of beach sand" (Burger et al., 2017, p. 513). The most common defensive strategy relies on hard protections such as dikes, embankments, sea walls and surge barriers. Italy is also an excellent case study in this regard. Approximately 1200 km of the Italian coast is defended by artificial structures, corresponding to more than one-quarter of the total length of sandy beaches (Pranzini, 2018). The length of the artificialized coast increased by +10.6% from 2010 to 2020 (Nanni et al., 2023). While such a strategy will prove increasingly ineffective in the medium term, it is unlikely to be abandoned in favour of more rational and longer-term adaptive strategies.

The pros and cons of such an approach are well-known (Cantasano et al., 2023). On the one hand, hard protections are relatively cheap and provide predictable levels of safety in the short term (Oppenheimer et al., 2019). For this reason, they are especially favoured in urbanised coasts and in areas that heavily rely on beach tourism. On the other hand, such interventions lead to substantial denaturalisation and deterioration of the coastal landscape, as well as of water quality. Worse still, hard protections often aggravate overall beach erosion, particularly in adjacent areas, leading to their continuous extension. Protections also

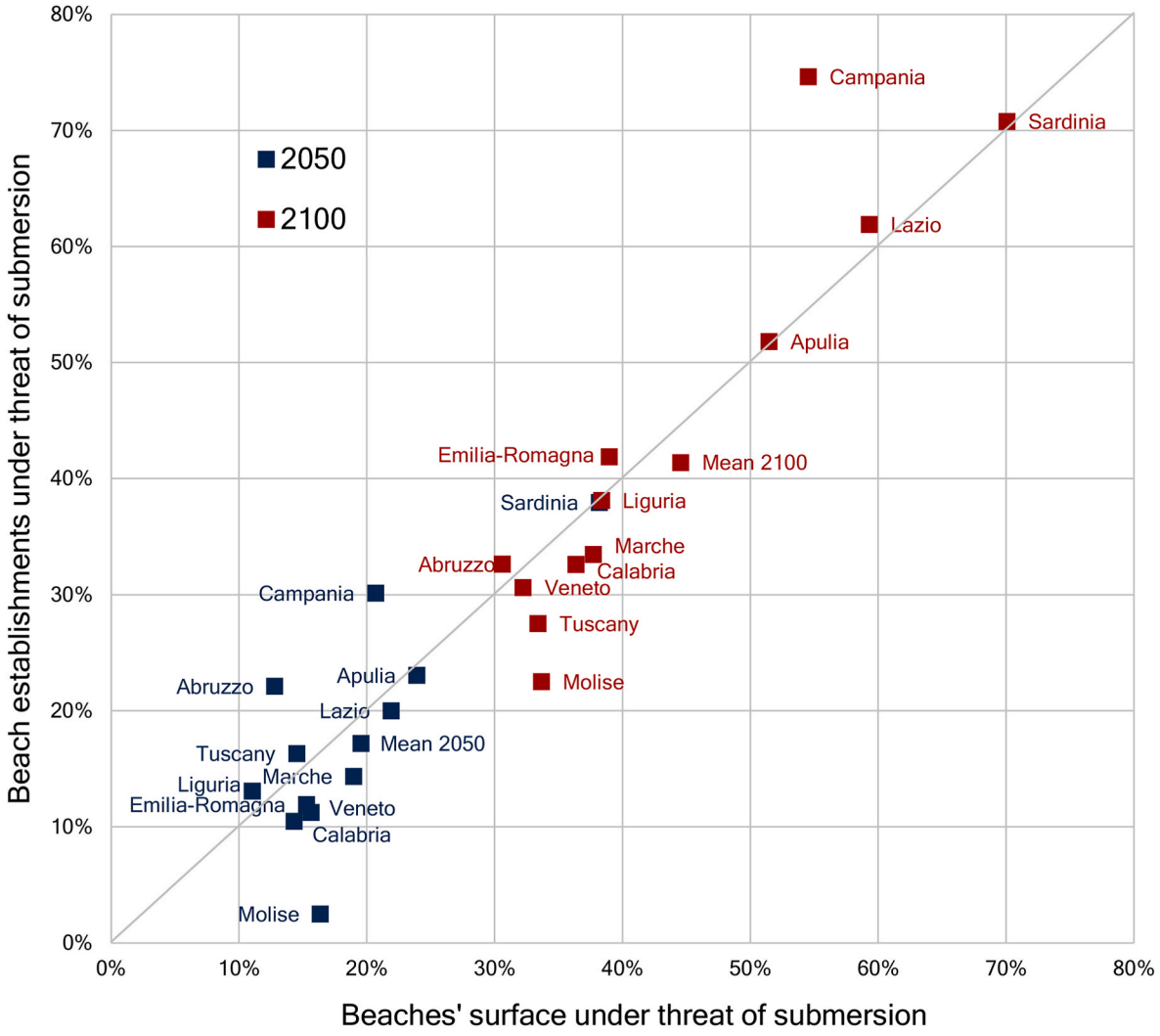

Fig. 7. Surface of beaches more than 75% under threat of submersion and the number of beach establishments on beaches under threat of submersion in Italian regions. Based on Vousdoukas et al. (2020), RCP 4.5 scenario, ISPRA, MIT. Data for Sicily, Basilicata, and Friuli-Venezia Giulia is unavailable.

limit beaches' natural resilience, increase their rigidity and vulnerability, and hinder their natural tendency to migrate landward, intensifying the risk of flooding and leading to increased exposure in the long term (Oppenheimer et al., 2019). In a scenario such as that outlined in the previous sections, this strategy is expected to have severe limits in terms of its effectiveness. The foreseeable outcome is the continuous reinforcement and extension of hard protections, leading to the almost complete artificialization of a vast portion of Italy's sandy coastline.

For this reason, many scholars and environmental advocacy groups have been proposing more 'natural' adaptation strategies, such as managed realignment and retreat. Managed realignment is a soft engineering approach aimed at creating space for enhancing coastlines' natural adaptive capacity through landward shoreline realignment (Esteves, 2014). This is part of growing attempts at 'building with nature' to improve the environmental and socio-economic sustainability of coastal management. When managed realignment aims to favour coastal migration or retreat, it often implies the removal or natural breaching of artificial protections to allow the coast to naturally adapt to erosion (Esteves & Williams, 2017; Turner et al., 2007). Managed retreat implies "moving away from the coast rather than fortifying in place" (Hino et al., 2017, p. 1), meaning the landward relocation of people, assets, infrastructures, and activities away from high-risk areas. This is a necessary complement to managed realignment in areas that are urbanised or occupied by human-made structures.

Managed realignment, besides having various positive environmental benefits, is more economically efficient than hard protections in the medium term (Turner et al., 2007), particularly in light of rising sea levels and because it involves lower maintenance costs (Hino et al., 2017). However, the few managed realignment projects in Europe are rather small and limited to a very small portion of the areas at risk (Esteves & Williams, 2017; Siders, 2019). They frequently encounter obstacles that limit their applicability either to non-urbanised/unexploited areas or to the aftermath of a disaster (Oppenheimer et al., 2019). Their implementation is hindered by barriers such as public acceptance, funding constraints, land availability, and uncertainties related to the coastal evolution and future climate conditions (Esteves & Williams, 2017).

Managed retreat is even more challenging and often faces fierce resistance (Hino et al., 2017). Barriers to its implementation are both psychological - it tends not to be accepted by the local population and economic operators, partly due to some sort of '*status quo*' or 'optimism bias' - and institutional, since those local actors who are primarily responsible for coastal management tend to favour resistance and the perpetuation of purely defensive strategies (Siders, 2019).

In some places, managed retreat may be simply physically impossible or incredibly expensive due to, as mentioned, the urbanisation and artificialization of the coast. Implementation typically involves the preliminary acquisition by the state of the assets that must be retreated

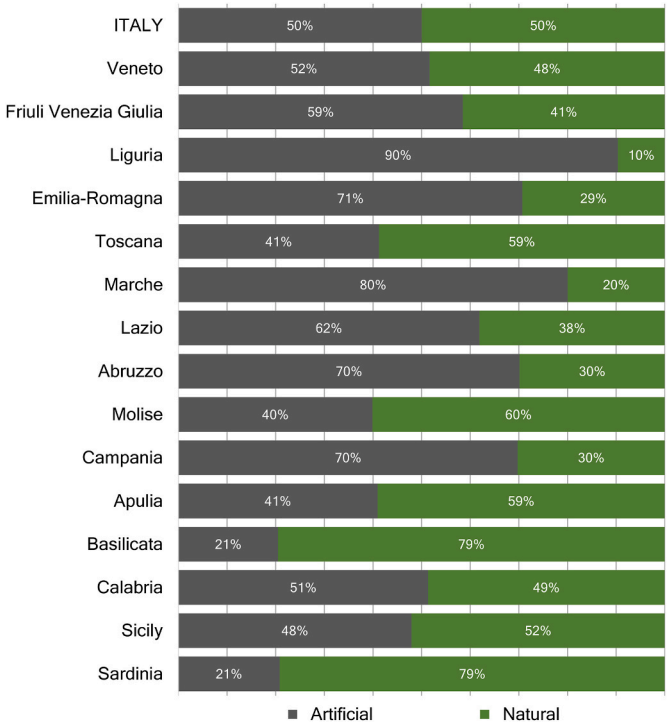

Fig. 8. Back beach characteristics in Italian regions. Based on ISPRA (n.d.).

(Siders, 2019), and therefore the alteration of private property rights (O'Donnell, 2019; 2023). Public acceptance of such measures is problematic in any case, and their costs and benefits may be inequitably distributed among different social groups and vested interests (Siders, 2019). The key to addressing these challenges is to promote local ownership of these strategies, properly involving different sectors and levels of government, and consensus building, with particular attention to social and spatial fairness (Hurlimann et al., 2014).

However, the applicability of management retreat is inevitably limited in Italy where, as already mentioned, resistance prevails, associated with increasingly pervasive and expensive beach nourishment interventions. It was estimated that from 1996 to 2017, approximately 21 million m^3 of offshore sediments were used for large beach nourishment projects in different Italian regions (Pranzini, 2018).

These ambivalent but customary coastal management practices risk simply perpetuating themselves, partly due to the so-called 'levee effect' feedback loop, whereby the construction of structural protections spurs further development behind them, amplifying the motivation for their continuation (Hino et al., 2017, p. 1). Moreover, a peculiar coalition of interests encompassing tourism operators, local public authorities, and the businesses employed in these interventions are strongly in favour of preserving the *status quo* (Pranzini, 2018) and well positioned to exert an influence on coastal management.

From the standpoint of private operators, retreat certainly implies uncertainties and a restriction to their activities due to more rigid norms and rules, which strikingly contrasts with the *laissez-faire* and *de-facto* privatised regime that currently prevails along Italian coasts. Coastal protections, on the other hand, reassure operators that their activities will continue and their assets will not be devalued, since these activities and assets are anchored to the specific locations they currently occupy. However, such reassurance in the mid-term will prove illusory for many of them. One way to address this could be to introduce concession or licensing regimes that account for the constantly changing shoreline, as well as to invest in more adaptable infrastructure and the diversification of services (Burger et al., 2017).

It should also be added that coastal development in Italy – particularly in its southern regions – is frequently illegal or informal, although largely tolerated. Existing laws and regulations are weakly enforced. The demolition of unauthorised buildings or settlements – even when they significantly contribute to landscape degradation, environmental vulnerability, and even risks – is rare (Chiodelli et al., 2021; Falco, 2017). The prospect of proper, preemptive, effective planning is therefore extremely unlikely.

In this context, favouring the adoption of the 'best' adaptation strategy cannot be solely based on an abstract and technical analysis of the cost-effectiveness of the available alternatives, but upon a more profound and transformative rethinking of current regimes.

7. Conclusions

The climate crisis will dramatically accelerate sea level rise and beach erosion in the next decades, severely impacting Italy's already problematic coastal environment. If the predictions upon which this article is based are confirmed (Vousdoukas et al., 2020), and according to a relatively optimistic projection, the portion of Italian beaches suffering retreat is expected to shift from the current 18%–70% as early as 2050. According to the most probable scenario, one-fifth of the current beaches are under threat of being almost completely submerged in 2050. By 2100 this portion is expected to increase to 45%, with peaks in the Sardinia (38% in 2050, 70% in 2100), Lazio (22%, 59%), Friuli-Venezia Giulia (31%, 57%), Campania (21%, 55%), Apulia (24%, 51%), and Sicily (24%, 50%) regions. These dynamics will severely impact the Italian coasts' vulnerable and precious environment, as well as their intense use for tourism and recreational purposes. Italy could potentially lose around 40% of its equipped and more intensively used beaches by 2100.

These figures should be considered with caution, particularly due to potential inaccuracies in the data and methods we used – which we described in the previous sections – as well as to the uncertainty of the underlying projections. Moreover, as discussed in the previous section, foreseeable effects must be considered in light of beaches' natural resilience, their tendency to migrate landward when subject to erosion, and the possibility of favouring such a shift through managed realignment.

However, in the context of Italy, approximately half of the current back beach space is denaturalised, artificial, and urbanised. In some regions, including those where the impact of the aforementioned scenarios will be most severe, the back beach artificialization rate reaches peaks of 60–90%.

The standard and pervasive response to erosion is beach nourishment interventions and the construction of coastal protections. Hard defences aggravate overall erosion and compromise the natural resilience of coastal landscapes. This coastal management strategy has been proven to be inefficient in the medium term, and its shortcomings will be exacerbated by the climate crisis, but is unlikely to be abandoned in favour of more pro-adaptive and nature-based solutions.

Ultimately, the risk is almost complete artificialization and denaturalisation of a huge portion of Italy's most precious coasts, the disappearance of thousands of beaches, and increased threats to coastal infrastructure, settlements and economies.

A profound and transformative rethinking of current coastal planning regimes is required, favouring nature-based solutions. The first step would be to carefully identify beaches where management realignment is currently possible, or where the backshore space could more easily permit managed retreat interventions. The second step would be to address the many barriers to nature-based adaptation, together with the pre-existing anthropic causes of erosion and of the decreasing resilience, as well denaturalisation of coastal landscapes. These include urbanisation, over-exploitation, land consumption and degradation, the ineffectiveness and ambivalence of current coastal management and planning regimes, illegal and illicit development, and the prevalence of private and economic interests over collective and environmental goals.

Some authors have regarded managed retreat as an inherently

transformative planning practice (Kates et al., 2012), or at least as having the potential to change societal perceptions of climate risk, challenging techno-optimistic and conservative adaptation approaches (Siders et al., 2021). Managed retreat can also restore natural habitats and therefore increase the attractiveness and value of the coastal landscape. However, even when policymakers express a clear preference against hard structures, the perpetration of protective measures may be favoured by the legislative and funding framework (Robb et al., 2019), or by inertia and vested interests, coupled with the above-mentioned 'levee effect' feedback loop.

It is crucial to regain public control over coastal management and development, as well as to prioritise collective, long-term, environmental goals over private, short-term, and economic goals, in light of proper awareness of the implications of the climate crisis. It may not be too late, but it will certainly be incredibly challenging.

CRediT authorship contribution statement

Filippo Celata: Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Formal analysis, Data curation, Conceptualization. **Eleonora Gioia:** Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Formal analysis, Data curation, Conceptualization.

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