Coastline evolution of Portuguese low-lying sandy coast in the last 50 years: an integrated approach

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Abstract.

Regional/~~global-scale~~ national-scale information on coastline rates of change and trends is extremely valuable, but ~~national-scale~~ these studies are scarce. A widely accepted standardized methodology for analysing long-term coastline change has been difficult to achieve, but is essential to conduct an integrated and holistic approach to coastline evolution and hence support coastal management actions. Additionally, databases providing knowledge on coastline evolution are of key importance to support both coastal management experts and users.

The main objective of this work is to present the first systematic, ~~global~~ national-scale and consistent long-term coastline evolution data of Portuguese mainland low-lying sandy coasts.

The methodology used quantifies coastline evolution using ~~an~~ a unique and robust coastline indicator (the foredune toe), which is independent of short-term changes.

The dataset presented comprises: 1) two polyline sets, mapping the 1958 and 2010 sandy beach-dune systems coastline, both optimized for working at 1:50 000 scale or smaller, ~~and~~ 2) one polyline set representing long-term change rates between 1958 and 2010, estimated at each 250 m~~. The~~ , and 3) a table with minimum, maximum and mean of evolution rates for sandy beach-dune systems coastline. All science data produced here are in Open Access at https://doi.pangaea.de/10.1594/PANGAEA.859136 and can be used in other studies.

Results show beach erosion as the dominant trend, with a mean change rate of -0.24 ±0.01 m/year for all mainland Portuguese beach-dune systems. Although erosion is dominant, this evolution is variable in signal and magnitude in different coastal sediment ~~cell~~ cells and also within each cell. The most relevant beach erosion issues were found in the coastal stretches of Espinho - Torreira and Costa Nova - Praia ~~da Mira, both at sub-cell 1b; Cova~~ de Mira, Cova da Gala - Leirosa ~~, at sub-cell 1c~~ and Cova do Vapor - Costa da Caparica~~, at cell 4. Cells 1 and 4~~ . The coastal segments Minho river - Nazaré and Costa da Caparica adjacent coast exhibit a history of major human interventions interfering with the coastal system, many of which originated and maintained a sediment deficit. In contrast, ~~cells 5 and 6~~ coastal segments Troia - Sines and Sines - cape S. Vicente have been less intervened and show stable or moderate accretion behaviour.

1 Introduction

The coastal zone is intrinsically dynamic, where changes occur at different temporal and spatial scales. Along any sandy coastal stretch, changes in coastline position (erosion or accretion) are expected and occur in response to variations in sea-level, sediment budget and hydrodynamic conditions. As human ~~demands~~ activities and occupation grow in coastal areas, management problems and challenges also increase, in order to accommodate both coastal change and occupation. Beach erosion is one of the leading management problems that coastal regions have to face worldwide (Phillips and Jones, 2006) and accurate information on coastline movement rates and trends is essential to support sustainable management strategies. This objective is particularly relevant in a climate change scenario, which may determine an increase in the intensity of coastal response (e.g. excess erosion induced by sea-level rise).

The idea that coastlines are under threat by climate change acceleration is relatively recent (Carter and Woodroffe, 1994) and has increased the demand for accurate knowledge on coastal evolution. This encouraged the development of numerous long-term (>30 years according to Fletcher *et al.* (2012)) studies worldwide which, in most cases, lack the broader scale perspective, evaluating change at micro/meso spatial scales and generally focusing only on known problematic areas.

Pioneer studies considering a national-scale approach to coastline change were promoted in the USA and Europe, in the early 21^{st} century, by the USGS (United States Geological Survey)(USGS, 2004) and the European Commission (European Commission, 2004). The United States launched the National Assessment of Coastline Change Project, which delivered a number of reports organized by coastal regions (e.g Fletcher *et al.*, 2012). The European counterpart is the EUROSION project framework (European Commission, 2004), which conducted a country by country evaluation of coastal erosion at European scale and delivered 3 main final products: 1) online reports, including major findings and recommendations, 2) a GIS database, which includes Europe's coastline vectors at 1:100 000 scale, and 3) a Coastline Management Guide.

Despite this effort, there is still no consensual coastline definition for reporting coastal evolution at national to global scale or to ensure comparability between datasets. Therefore, most of the coastline evolution works are still not adequate for inter-comparison.This fact is even more striking as the 2012 European Environment Agency (EEA) report on climate change (EEA, 2012) does not include coastline position as an EEA indicator on threats to the coastal zone, because regular updates of this type of information ~~is~~ are not expected.

In Portugal, coastline evolution studies are usually local to meso-scale in their spatial scope and essentially focus on problematic areas (e.g., Abecassis *et al.*, 1970; Barceló, 1971; Castanho *et al.*, 1974; Bettencourt and Ângelo, 1992; Ferreira, 1992; Oliveira, 2005; Pinto and Teixeira, 2005; Veloso-Gomes *et al.*, 2009; Taveira Pinto *et al.*, 2009; Rebêlo *et al.*, 2011; Silva *et al.*, 2013); and used different coastline proxies (e.g., European Commission, 2004; Oliveira, 2005; Ferreira *et al.*, 2006; Rebêlo *et al.*, 2011; Cenci *et al.*, 2013). Thus, these analyses can not provide a complete and unified approach for all the Portuguese territory.

From the above, one may conclude that an approach using metrics that are consistent from one coastal zone to another is essential to address coastal evolution in an integrated and holistic manner. A single and robust coastal indicator capable of representing long-term change is indispensable and should be evaluated at a national and broader scale.

This work aims at presenting the first systematic, ~~global~~ national-scale and consistent long-term coastline evolution study of Portuguese mainland low-lying sandy coast~~at a national scale~~. Coastline evolution is quantified using a single robust coastline indicator (foredune toe), which is, to a larger extent, independent of short-term morphodynamic changes. The coastline and evolution data are fully and freely available at http://doi.pangaea.de/10.1594/PANGAEA.853654 and can be used in other studies. This dataset comprises: 1) two polyline sets, mapping the 1958 and 2010 sandy beach-dune systems coastline, both optimized for working at 1:50 000 scale or smaller, and 2) one polyline set representing long-term change rates between 1958 and 2010, estimated at each 250 m.

2 Study area

Portuguese mainland coastline extends south from Minho river to west of Guadiana's river mouth (Figure 1) along *circa* 900 km (variable with the scale of representation). The coast includes a wide range of morpho-sedimentary environments, such as beaches, cliffs, estuaries, lagoons and barrier islands (Andrade and Freitas, 2002; Ferreira and Matias, 2013). Coastal districts house around 3/4 of the population and generate around 80% of the gross national product (Duarte Santos *et al.*, 2014b), with an increasing economic activity on these areas, especially from tourism.

~~According to Andrade and Freitas (2002) the coast of mainland Portugal is high-mesotidal and wave-dominated, with energy decreasing in sheltered West-East trending sections, which includes the Algarve south-facing littoral .~~ Tides along the Portuguese coast are semi-diurnal, meso-tidal and are unimportant to coastal processes except in the vicinity of inlets and tide-dominant basins (Andrade and Freitas, 2002). According to Andrade and Freitas (2002), Portuguese western and southern-facing coasts present asymmetric characteristics regarding wave energy and wave climate. The western coast is fully exposed to the dominant NW high energy swells (Andrade and Freitas, 2002). The south-facing coastal stretches are sheltered from the dominant waves, resulting in a milder wave regime (Ferreira and Matias, 2013). The high-energetic wave regime at the western coast induces a net potential littoral drift southward directed that can reach up to $10^6\ m^3/year$. This potential falls one or more orders of magnitude in linear coastal stretches somewhat rotated clockwise, along equilibrium arcuate embayments and sections sheltered from the prevailing NW waves; in these cases the residual drift may be annulled or even reversed in direction (Andrade and Freitas, 2002). At the south coast of Portugal, dominant waves drive an easterly directed littoral drift of *circa* 10^4 to $10^5\ m^3/year$, depending upon coastal orientation (Ferreira and Matias, 2013); exceptions are NW/SW coastal ribbons that face the prevailing swell and show almost null residues of longshore power and drift (Andrade and Freitas, 2002).

2.1 Sediment cells

According to EUROSION resolution 1 (European Commission, 2004), the sediment status must be accounted for each coastal sediment cell. Sediment cells are independent of each other in terms of sediment transfers, which means actions taken within a specific cell may impact sections of the same cell but will not significantly affect adjacent cells.

The works of Andrade and Freitas (2002) and later of Duarte Santos *et al.* (2014a) defined and characterized 8 sediment cells (Figure 1) along the Portuguese mainland littoral, according to its geomorphological characteristics and sedimentary dynamics:

Cell 1 - Minho river mouth to Nazaré. This cell is divided in 3 sub-cells: from Minho to Douro rivers (sub-cell 1a), from Douro river to cape Mondego (1b) and from cape Mondego to Nazaré (sub-cell 1c).

Sub-cell 1a is characterized by a low rocky coast, with numerous small sandy and gravel beaches, sometimes extensive, whose development is strongly associated with local sheltering effects, in the first case, and river estuaries in the latter. The low-lying sandy coast accounts for 50% of the total coastal stretch.

Sub-cell 1b coastline presents geomorphological characteristics similar to cell 1a at the north, and further south consists essentially of an extensive linear beach, backed by coastal dune systems and only interrupted by the Aveiro inlet. The southernmost section is constituted mainly by cliffs and sandy beaches. Beach-dune systems represent 75% of this sector total length.

Sub-cell 1c presents a rocky coast to the north, which becomes a highly developed sandy beach at Figueira da Foz, made by the retention effect of the Figueira da Foz port northern jetty. This sediment retention induced downdrift coastline retreat, which led to the construction of rigid structures, southern of Figueira da Foz port (Duarte Santos *et al.*, 2014a). Further south the coast is low, sandy and straight, culminating in cliffs bordered by narrow beaches, which extend until Nazaré neighbourhood. This sector presents 72% of its beaches backed by dunes.

Cell 2 - Nazaré to Peniche, which consists mainly of cliffs bordered by rocky platforms, north of Óbidos lagoon, and linear beaches, generally narrow, to the south that accounts for only 25% of all this coastal sector.

Cell 3 - Peniche to cape Raso. This section is dominated by cliffs presenting ~~numerously~~ numerous pocket beaches, with very different geometry. The wider and short beaches are often limited by small dune fields, and developed next to stream mouths, whereas linear and narrow beaches lacking dunes, sometimes with kilometric extent, are associated with the existence of natural headlands that provide limited sediment retention. This sector has one of the lowest percentage of beach-dune systems, a merely 6%.

Cell 4 - Cape Raso to cape Espichel. In terms of its geomorphological characteristics, this cell can be divided into two distinct sectors, separated by the Tejo river mouth. Northwest of Tejo estuary the coast is dominated by cliffs, with a set of small embedded beaches, limited landward by cliffs or artificial structures and sheltered from the dominant NW wave regime. South of Tejo, the coast adopts an arched configuration, suggesting an equilibrium bay, forming a continuous sandy coast from Costa da Caparica to Bicas. Further south, until cape Espichel, the coastline mainly develops in cliffs, occasionally interrupted by small sandy or gravelly pocket beaches. Half of the sector (50 %) is represented by beach-dune systems.

Cell 5 - Cape Espichel to Sines. The coast between cape Espichel and Sado inlet is sheltered from the prevailing wave regime and only few pocket beaches exist in indentations affecting the rocky plunging cliffs of the Arrábida chain. Between Troia peninsula and Sines, it is a continuous sandy coast, with an arched configuration, similar to that observed in Caparica-Espichel section. The beach is bordered by dunes in most of the sector, mainly north of Medronheiro; south of this point cliffs occur until Melides lagoon and, occasionally, between Sancha lagoon and Moinhos stream. This sector present 54% of its coast represented by low-lying sandy beaches.

Cell 6 - Sines to cape S. Vicente. This stretch is dominated by cliffs, generally high, carved in resistant Paleozoic and Mesozoic rocks. These cliffs are disturbed by Mira, Odeceixe and Aljezur estuaries and lowlands which, together with cliff indentations, accommodate sandy and gravelly beaches, usually with reduced width. The beaches developed on larger stream mouths are often backed by dune systems. Together with cell 3, this sector presents small percentage (3%) of beach-dune systems.

Cell 7 - between cape S. Vicente and Olhos de Água. This cell is characterized by an extremely varied morphology, where cliff segments alternate with beaches confined between resistant headlands or developed at stream mouths and in barriers separating small lagoons/estuaries from the open ocean. From Lagos to Olhos de Água the coast is extremely crenulated. Lagos and Armação de Pera bays include dune systems with significant size. This cell presents 12% of its coastline belonging to beach-dune system geomorphological type.

Cell 8 - from Olhos de Água to Guadiana river ~~mounth~~mouth. The coastline is mainly dominated by a barrier islands system (Ria Formosa) and the Manta Rota - Vila Real de Santo António coastal plain. The western end, between Olhos de Água and Garrão, comprises a sandy beach bordered by cliffs. The barrier island system, which separates the sea from the second larger Portuguese lagoon, includes, from West to East, two peninsulas (Ancão and Cacela), five barrier islands (Barreta, Culatra, Armona, Tavira and Cabanas) and six tidal inlets (Ancão, Faro-Olhão, Armona, Fuseta, Tavira and Cacela inlets). 66% of this sector beaches are backed by dunes.

3 Methods

3.1 Beach coastline indicator

In coastal evolution studies the selection of a suitable coastline definition is a primary issue. ~~Due~~ Long-term studies, such as the one presented, are based on discrete measurements that represent snapshots of the coastal system, usually separated by a large temporal gap. To obtain an unbiased measure of coastal evolution, the measurements should, therefore, be as independent as possible of both high frequency water level changes and the seasonal beach morphological cycle.

In this sense, we have considered the coastline concept (as given in Carapuço *et al.*, 2016) over the use of the shoreline (the physical interface of land and water) since is more conservative in spatial location. Notwithstanding, due to the extremely dynamic nature of this ~~concept~~feature, coastline mapping is generally based on an indicator which, according to ~~Boak and Turner (2005)~~Boak and Turner (2005), is a feature used as proxy to represent the "true" coastline position.

Coastline indicators may be physical coastal features such as the bluff top/cliff top, landward edge of shore protection structure, ~~berm crest, scarp edge,~~ foredune toe and seaward vegetation line. ~~Alternatively, other features representing the land/water interface may also be used: e.g. high water line, mean high water line, wet/dry line or runup maxima (swash lines) or the instantaneous water line.~~

~~Long-term coastal evolution studies are based on discrete measurements that represent snapshots of the coastal system, usually separated by a large temporal gap. To obtain an unbiased measure of coastal evolution, the indicator should, therefore, be independent of both high frequency water level changes and seasonal beach morphological cycle.~~

~~In this work, which focus on~~ Considering that this study targets low-lying sandy coasts backed by dunes, ~~coastline is considered as the landward limit of the backshore and is represented by the foredune toe. This morphological feature,~~ the coastline indicator used in this study was the foredune toe, and recognized as the morphological feature less affected by short-term (tidal) and medium-term (seasonal) changes ~~(Komar *et al*., 2001; Ferreira *et al*., 2006; Del Río and Gracia, 2013), is thus adequate to measure long-term variations.~~ (e.g., Komar *et al*., 2001; Ferreira *et al*., 2006; Del Río and Gracia, 2013).

The foredune toe indicator is described by either a slope break or the seaward limit of vegetation. The latter criteria was only used when the first was not clearly recognized. In cases where the beach is not backed by a dune (e.g. overwashed sections of sandy barriers, extensive blowouts in the backbeach) the afore-mentioned indicator could ~~no~~ not be mapped. These situations constitutes a limitation of the proposed methodology, and other methods should be used when analysing other geomorphological coastal types. Nevertheless, using this method was possible to map 92% and 95% of all the low-lying sandy coast of mainland Portugal for the years 1958 and 2010, respectively. The shoreline evolution assessment was conducted in 84% of the sandy coast, where both coastline information overlay.

3.2 Coastline mapping

3.2.1 Data sources

Two sets of data were used in the coastline extraction procedure:

1) digital aerial photographs from the USAF 1958 flight (photos taken in different days and no flight plan available to the authors) with 0.5 m of pixel resolution;

2) digital orthophotomaps of the year 2010 (IGEO, 2010) (photos taken in different days of 2010) with 0.2 m of pixel resolution.

3.2.2 Mapping procedures

Due to the unrectified nature of the 1958 aerial photographs, images were georeferenced using the 2010 orthophotomaps. The georeferencing procedure, consisting on the coordination of points on the image to be georeferenced with points on a geographically referenced dataset, was conducted according to Figure 2, in a GIS environment. The individual photos were grouped in mosaics covering continuous sandy coastal areas. A total of 158 photos were used to produce 56 mosaics, using the Photomerge capability of Photoshop®. This procedure finds the optimal borders between the images and creates seams based on those borders, requiring an image overlapping of 40 to 70 %. Mosaicking minimizes misalignments, especially visible in borders of two contiguous images ~~. Main~~ (Wan et al., 2013), main advantages includes image spatial continuity, allowing for coastline location on longer coastal stretches and facilitates the search for common ground control points (GPCs) (Verhoeven *et al.*, 2012).

Mosaics were georeferenced using GCPs, that corresponded to common elements in both datasets, evenly distributed along the coastline. Between 5 to 10 GCPs per km of coastline were used, accounting for availability of common elements, mosaicking distortions and terrain elevation. The georeferencing was based on a *Spline* adjustment method (a piecewise polynomial that maintains continuity and smoothness between adjacent polynomials).

The work of Rocchini and Di Rita (2005) showed that in flat areas georeferencing by polynomial fit is a very robust tool, with performance similar to those obtained by orthorectification, reporting significant increases of the error as terrain becomes more rugged. In this present work an independent study for accuracy assessment related to the georeferencing process and coastline vectorization was also conducted. Results from this evaluation will be used in coastline rates uncertainty assessment and are presented in the next section.

The coastline ~~digitazion~~ digitization process, which consisted in manually recognizing and digitizing the coastline indicator on the images, was conducted using a ranging visualization scale between 1:5 000 and 1:8 000. The coastline final position segments, for both analysed dates, were optimized for working at a 1:50 000 scale or smaller.

3.3 Coastline evolution

Coastline evolution rates of change (R) were calculated in a GIS environment using Digital ~~Coastline~~ Shoreline Analysis System (Thieler *et al.*, 2009) and Coastline Change Mapper (Psuty *et al.*, 2010), both ArcGIS extensions. Transects were placed every 250 m, roughly perpendicular to the coastline trend. Rate of change results were grouped together along the same littoral cell and maximum ($Max(R)$), mean ($\bar{R}$) and minimum ($Min(R)$) rates were assessed for each one. Results are presented for the overall sandy beach-dune systems coastline as well.

3.3.1 Position and rate uncertainty

Several sources of error affect the accuracy of coastline position and consequently coastline change rates. Measurement uncertainties include errors related to coastline digitization (E_d) (Fletcher *et al.*, 2003), image resolution (E_{ir}) (Coyne *et al.*, 1999; Catalão *et al.*, 2002) and image rectification (E_r) (Shoshany *et al.*, 1996; Fletcher *et al.*, 2003).

According to Fletcher *et al.* (2003) these errors are random and uncorrelated and can be represented by a single measure (U_p) calculated as the square root of the sum of the squares (Coyne *et al.*, 1999; Fletcher *et al.*, 2003):

$$U_p = \sqrt{E_d^2 + E_r^2 + E_{ir}^2} \tag{1}$$

Fletcher *et al.* (2003) states another physical components of error, representing short-term variability in coastline position. In this study, these sources of error were eliminated by adopting the foredune shoreward edge approach, in accordance to other works (e.g Del Río and Gracia, 2013).

The uncertainty related to the georeferencing procedures (E_r) of 1958 aerial photos was evaluated using 3 mosaics~~. Root mean square errors~~ , depicting different geomorphological settings. Validation with independent subset of control points (10% of the original GCPs) was used to assess root mean square error (RMSE) ~~were calculated for each one.~~ for each mosaic. This process assures an independent evaluation of the georeferencing errors that was considered representative for all other mosaics. Results show a maximum RMSE of 4.79 m for all 3 mosaics, hence, E_r was considered as 5 m. Uncertainties related to the vectorization process of the coastline indicator ~~by different operators~~ (E_d)~~were estimated as~~ , which were digitized by 3 different operators, resulted in a 7 m error. Image resolution is 0.5 m (E_{ir}). Thus, $U_{p,1958}$ was estimated as 8.6 m.

In a similar matter to the aerial photos, the uncertainties related to the use of orthophotomaps were estimated as: $E_r = 0$, due to its rectified nature, $E_d = 5$ m and $E_{ir} = 0.2$ m. Therefore, $U_{p,2010}$ was estimated as 5.0 m.

The coastline change rate uncertainty (U_R) is calculated, according to Fletcher *et al.* (2012), by using the uncertainty values for both coastlines ($U_{p,1958}$ and $U_{p,2010}$) and the time frame (t) between them~~as~~:

$$U_R = \frac{\sqrt{U_{p,1958}^2 + U_{p,2010}^2}}{t} \tag{2}$$

In this work, the uncertainty affecting coastline change rate was calculated as ±0.2 m/ year, for the 52 year period of analysis.

The uncertainty of a mean rate can be calculated, according to Fletcher *et al.* (2012), as the root sum of squares of rate uncertainties (U_R) at all transects divided by their total number (n):

$$U_{\bar{R}} = \frac{\sqrt{\sum_n^{i=1} U_{R,i}^2}}{n} \tag{3}$$

$U_{\bar{R}}$ was evaluated for each individual sediment cell taking into account the number of transects in each one, and the same procedure was applied to all low-lying sandy coastline of mainland Portugal. $U_{\bar{R}}$ values are shown in Table 1.

4 Results and Discussion

The coastline evolution dataset comprises: 1) two coastlines, an older one dated 1958 and a modern one dated 2010, and 2) long-term change rates between 1958 and 2010, which were estimated at 250 m interval assuming a linear rate of change. All science data are available as polylines and in Open Access at http://doi.pangaea.de/10.1594/PANGAEA.853654. These results have also been incorporated as an update of the EUROSION Project information on low-lying sandy coastal ribbons of mainland Portugal, ~~which will be made available by the EMODnet project (EMODnet, 2009),~~ in collaboration with IPMA (Instituto do Mar e da Atmosfera) agency, the EMODnet project portuguese partner on Geology (EMODnet, 2009). The dataset was incorporated into the Coastal Migration Map - Coastal Behaviour for all European countries and is currently available for visualization at http://194.66.252.216/geonetwork/srv/por/catalog.map.

Table 1 shows maximum, minimum and mean coastline evolution rates found in each sediment cell and for the total coastline of mainland ~~Portugal~~Portugal and is Open Access at https://doi.pangaea.de/10.1594/PANGAEA.859135. The total length occupied by sandy beach-dune systems corresponds to *circa* 40% of the total mainland Portuguese coastline.

Sub-cell 1a presents an erosion maximum of -1.84 ±0.2 m/year, mainly southward of the Lima estuary. An accretion maximum of +5.83 ±0.2 m/year is reached next to the same river mouth, due to interference of both harbour ~~jettys~~ jetties in sediment transport patterns. The mean rate of change is -0.29 ±0.02 m/year showing an erosive trend (Figure 3). According to Duarte Santos *et al.* (2014a) this pattern is related with the reduction in river sediment supply and harbour dredging.

Sub-cell 1b is dominated by an erosional trend with an average retreat rate of -0.91±0.01 m/year, this figure exceeding by a factor of 3 to 5 the average recession observed elsewhere along the same coast and the global average. Erosional trends extend almost continuously from the Douro river mouth to Torreira and also further south, from the Aveiro inlet to Praia ~~da~~ de

Mira, where a maximum rate of change (-7.38 ±0.2 m/year) is observed. Accretional trends are observed updrift of significant obstacles to littoral drift such as cape Mondego and Aveiro jetties (Figure 3). Similarly to sub-cell 1a the main factor driving erosion is the loss of fluvial sediment supply and sediment retention in artificial structures. This sub-cell contains the most vulnerable areas concerning the erosion risk in Portugal (Duarte Santos *et al.*, 2014a).

In sub-cell 1c, erosion is mainly concentrated in its northern section up to about 20 km southward of the Mondego river mouth, in relation with harbour development works, including dredging and jetties. Here the retreat rates locally reach a maximum of -3.77 ±0.2 m/year at Lavos. Further south, accretion dominates reaching a maximum of +1.39 ±0.2 m/year in the vicinity and updrift of Nazaré, related with sediment retention by a rocky headland. Mean coastline rates of change indicates a general erosional trend, with a value of -0.34 ±0.01 m/year (Figure 4).

Cell 2 presents a set of 5 discontinuous sandy beach-dune systems with a mean evolution rate of -0.17 ±0.03 m/year. Erosional coastal stretches are found at Nazaré-Salgados, Cova da Areia and Baleal embayment, east of Peniche. Accretion was detected in São Martinho do Porto bay and Óbidos sand barrier, with maximum of +1.63 ±0.2 m/year in the former case (Figure 4).

Cell 3 shows rare beach-dune systems confined to coastline indentations in relation to small river mouths. The signal and rate of change are site specific, with erosion at Consolação, Ponta da Lamporeira and Guincho (north of Cape Raso) (-0.49, -0.22 and -0.65 ±0.2 m/year, respectively), and accretion at Areia Branca, Santa Rita and Ponta da Lamporeira (+0.74, +1.06 and +0.23 ±0.2 m/year) (Figure 4). The mean coastline rate of change (+0.02 ±0.04 m/year) is within the method uncertainty, indicating no significant long-term evolution. This result is compatible with negligible anthropogenic influence in sediment supply, thus the measured changes essentially reflect the coastal system natural variability.

Cell 4 northern sector, trending East-West, contains only small pocket beaches limited by either cliffs or artificial structures and were not considered in this study. The southern sector (extending from Cova do Vapor ~~until~~ to Bicas) is dominated by one continuous sandy beach-dune system, north of Lagoa de Albufeira, and by beaches backed by cliffs to the south. Coastal change was not measured at Costa da Caparica due to the existence of a seawall. Likewise, in places between Costa da Caparica and Lagoa de Albufeira, where the lack of dune vegetation and overexposure of the 1958 photographs precluded the coastline indicators identification, coastal change was not measured. In this sector, two contrasting trends were found: 1) an intense erosional trend with a maximum of -4.57 ±0.2 m/year, southward and next to the Tejo river mouth, north of Costa da Caparica and 2) south of Costa da Caparica, a mild accretional trend alternating with stable stretches, reaching a maximum of +1.20 ±0.2 m/year at Meco (Figure 5). Globally, this sector presents a slight erosive trend with a ~~+0.04~~ -0.04 ±0.03 m/year of mean rate, despite the strong erosive tendency north of Costa da Caparica. The erosional process north of Costa da Caparica has been aggravated in the second quarter of the XXth century due to sand deficit in relation to intensive dredging; in response, a seawall and a groyne field were built (Appendix I - Duarte Santos *et al.*, 2014a). More recently the beaches were object of artificial nourishment (Appendix VI - Duarte Santos *et al.*, 2014a). Coastal retreat rates reported here would have been higher in the absence of beach nourishment.

The geomorphological settings of cells 5 and 4 are broadly homothetic, but the intensity and spatial distribution of erosion/accretion rates are different. In cell 5, the northern tip of Troia sand spit presents the largest accretion trend (+8.18 ±0.2

m/year). The erosion maximum, located immediately southward of the accretion area, is -1.09 ±0.2 m/year (Figure 5). In this sector, mean coastline rates of change reveals the highest accretional trend for all sediment cells in mainland Portugal (+0.45 ±0.01 m/year).

Cell 6, which presents geomorphological similarities with cell 3, shows both the maximum erosive trend (~~-1.32~~ -0.95 ±0.2 m/year) and the maximum accretion trend (+~~3.11~~ 1.32 ±0.2 m/year) close to Vila Nova de Milfontes. The mean rate of change in beach-dune systems is +0.28 ±0.06 m/year, translated in an overall accretional trend of the few beach-dune systems stretches (Figures 5).

In the western south facing Algarve coast, ~~Cell~~ cell 7 shows a maximum erosion rate of -0.66 ±0.2 m/year at Armação de Pera bay and a maximum rate of accretion of +1.96 ±0.2 m/year at Lagos bay. The mean rate of change is +0.28 ±0.03 m/year, revealing an overall accretional trend (Figures 6).

Cell 8 presents a complex evolution pattern, with sections in erosion alternating with sections in accretion. This pattern is mostly related with the morphological evolution of Ria Formosa tidal inlets, determined by either natural or artificial causes (Figure 7). The maximum and minimum values should be interpreted with caution because they represent localized effects of inlet-barrier tip morphological readjustments. Moreover, retention effects induced by jetties also contributed to high values of change (e.g Faro and Guadiana inlets). The erosion maximum of -8.96 ±0.2 m/year is observed at the western tip of Cacela barrier and the accretion maximum of +12.99 ±0.2 m/year at the eastern boundary of Armona inlet (Figure 6). The mean ~~evolution~~ rate of change for this section falls within the uncertainty range (+0.01 ±0.01 m/year), which indicates an overall balanced coastal sediment budget. Additionally, Ferreira et al. (2016) highlights a relevant retreat of the cliffed coast between Olhos de Àgua and Ancão, particularly in the decads of 1970s to 1990s, induced by the construction of the Vilamoura jetties. The same author also state that it is presently controlled by artificial nourishment actions.

Although a thorough review of the many Portuguese coastline (and shoreline) evolution studies is beyond the scope of this analysis, some results reported by other authors for areas prone to erosion are briefly summarized. However, a word of caution is needed when comparing the results obtained in the scope of the present work with those presented in the literature,as they were obtained using different methodologies and using distinct time-frames. SENER (2012) reported for 1958-2007 a maximum evolution rate of: -4.4 m/year at Esmoriz; -5.6 m/year at Ovar; +5.7 m/year at S. Jacinto; -5.8 m/year near Costa Nova and -3.5 near Praia de Mira. Freire (1986) mentions a maximum of -12.5 m/year for the years 1958-1966 at Cova do Vapor/Costa da Caparica and Pinto *et al.* (2007) mention -3.3 m/year between 1999-2007. Ferreira and Matias (2013) acknowledge an important retreat of more than 3 m/year in the western part of Culatra Island, while the eastern half exhibit accretion, between 1958-1976. Ferreira et al. (2016) also mention that Ria Formosas' system evolution is dominated by tidal inlet dynamics, which has direct and indirect affected the entire system including barriers erosion/accretion. In general, at the areas where evolutions trends are reported by other authors the magnitudes are similar to the ones obtained in this study.

Figure 8 summarizes results of long-term coastline change assessment at a country scale. ~~40% of~~ Portuguese mainland coastal territory ~~is~~ occupied by sandy beach-dune systems~~depicting~~ , which represents 40% of the total extent, depict an overall erosional tendency of -0.24 ±0.01 m/year. This trend results from high erosion values located at specific coastal stretches. In fact only 46% of all transects exhibit erosion, with an average trend of -1.43 m/year. On the other hand, 54% of all analysed transects show either a stable/within-uncertainty values or an accretion tendency (+1.2 m/year at 34%). Although beach erosion is dominant in average, this evolution is variable in signal and magnitude along and within each of the 8 sediment cells ~~considered and within each cell~~ (Figure 8). ~~Cell 1, and particularly sub-cell 1b, stands out in this study by the intensity and extent of the erosional behaviour. This coastal ribbon has a long history of human interventions that originated and maintained a sediment deficit. In contrast, cells 5 and 6 have been less intervened and show stability or moderate accretion. Sandy beach front areas showing chronic coastal erosion are associated with man-induced deficit in the sediment budget.~~

5 Conclusions

This work characterizes coastline evolution of low-lying sandy coasts using a methodology that: 1) is consistent from one coastal region to another and 2) is independent of short-term change, as it quantifies change using a single robust coastline indicator (foredune-toe), adequate for applications at a national scale. Furthermore, a complete dataset derived with this methodology and applied to all sandy beach-dune systems in mainland Portugal are available in Open Access at https://doi.pangaea.de/10.1594/PANGAEA.859136.

The dataset ~~, comprising~~ comprises 2 coastline sets (1958 and 2010)~~and~~ , a long-term (52 years) change rates estimated every 250 m, and minimum, maximum and mean coastline evolution rates for each considered sediment cell and for all cells. These dataset is the first systematic, ~~global~~ national-scale and consistent long-term coastline evolution study of Portuguese mainland low-lying sandy coast. These data can be used in other studies, and thus represent an important tool to support both coastal experts and end-users.

Coastline evolution results showed an overall erosional tendency for the Portuguese mainland low-lying sandy coast, presenting a mean rate of -0.24 $\pm$0.01 m/year. Despite this result, sandy beach-dune systems display a variable evolution, both in signal and intensity, along and within the 8 coastal sediment cells of the studied coast. The most concerning beach erosion issues are located on cells 1 and 4, particularly on the coastal stretches of Espinho - Torreira, Costa Nova - Praia ~~da~~ de Mira, Cova da Gala - Leirosa and Cova do Vapor - Costa da Caparica. Cells standing out by the intensity and extent of the erosional behaviour exhibit major human interventions, many of which originated and maintained a sediment deficit. In contrast, cells 5 and 6 have been less intervened and show stable or moderately accretional behaviour. Thus, sandy beach front areas where coastal erosion is chronic are associated with man-induced deficit in the sediment budget.

Long-term coastal evolution studies should also integrate short-term analysis in order to assess acceleration patterns related to climate change effects and also evaluate management measures. The methodology proposed here can also be applied in the context of short-term analysis (<30 years), using smaller time-frames. This integration will be addressed in future works. Further investigation is necessary to extend this methodology to other coastal geomorphological contexts (e.g. beach backed by rocky coasts), which will also be the objective of future studies.

Author contributions. C. Ponte Lira, A. N. Silva, R. Taborda and C. F. Andrade developed the methodology, C. Ponte Lira and A.N. Silva tested, validated and apllied the methodology to all Portuguese mainland sand-dune systems. C. Ponte Lira wrote the manuscript with contributions from all co-authors.

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Table 1. Minimum ($Min(R)$), maximum ($Max(R)$) and mean ($\bar{R}$) of evolution rates (R) for sandy beach-dune systems (SBDS) coastline. Total coastline length (km) and SBDS coastline length (in km and in percentage). All values are presented for each sediment cell and for all mainland Portugal SBSD coastline. Values in parenthesis depict, respectively, (a) % of transects with $R \leqslant -0.2$, (b) % of transects with $-0.2 < R < 0.2$ and (c) $R \geqslant -0.2$.

Cell	Location [1] Start End	$Min(R) \pm U_R$ (m/year)	$Max(R) \pm U_R$ (m/year)	$\bar{R} \pm U_{\bar{R}}$ (m/year) (a) (b) (c)	[2]Total coastline length (km)	[3]SBDS coastline length (km)	[3]SBDS coastline length (%)
1a	41°51'47N / 8°52'13W 41°8'51N / 8°40'28W	-1.94±0.2	5.63 ±0.2	-0.29 ±0.02 (60)(19)(21)	95	48	50
1b	41°8'51N / 8°40'28W 40°11'11N / 8°54'31W	-7.38 ±0.2	4.67 ±0.2	-0.91 ±0.01 (60)(10)(30)	120	91	75
1c	40°11'11N / 8°54'31W 39°36'16N / 9°5'6W	-3.77 ±0.2	2.75 ±0.2	-0.19 ±0.01 (39)(26)(35)	69	49	72
2	39°36'16N / 9°5'6W 39°21'30N / 9°24'27W	-1.07 ±0.2	1.63 ±0.2	-0.17 ±0.03 (59)(31)(10)	54	13	24
3	39°21'30N / 9°24'27W 38°42'29N / 9°29'4W	-0.65 ±0.2	1.06 ±0.2	0.02 ±0.04 (30)(48)(22)	107	6	6
4	38°42'29N / 9°29'4W 38°24'50N / 9°13'19W	-4.57 ±0.2	1.20 ±0.2	-0.04 ±0.03 (11)(29)(60)	32	16	50
5	38°24'50N / 9°13'19W 37°57'14N / 8°53'14W	-1.09 ±0.2	8.18 ±0.2	0.45 ±0.01 (28)(28)(44)	99	53	54
6	37°57'14N / 8°53'14W 37°1'19N / 8°59'44W	-0.95 ±0.2	1.32 ±0.2	0.28 ±0.06 (36)(9)(55)	133	8	6
7	37°1'19N / 8°59'44W 37°5'23N / 8°11'4W	-0.66 ±0.2	1.96 ±0.2	0.23 ±0.03 (12)(56)(32)	94	11	12
8	37°5'23N / 8°11'4W 37°9'57N / 7°23'38W	-8.96 ±0.2	12.99 ±0.2	0.01 ±0.01 (45)(17)(38)	84	56	66
All	-60 518 / 244 795 64 870 / -277 252	-8.96 ±0.2	12.99 ±0.2	-0.24 ±0.01 (46)(20)(34)	887	350	40

[1] Latitude / Longitude in ETRS 89; [2]Total coastline length was estimated using the available EUROSION coastline (European Commission, 2004) for the Portuguese mainland littoral; [3]SBDS coastline length was calculated using the proposed 2010 Coastline.

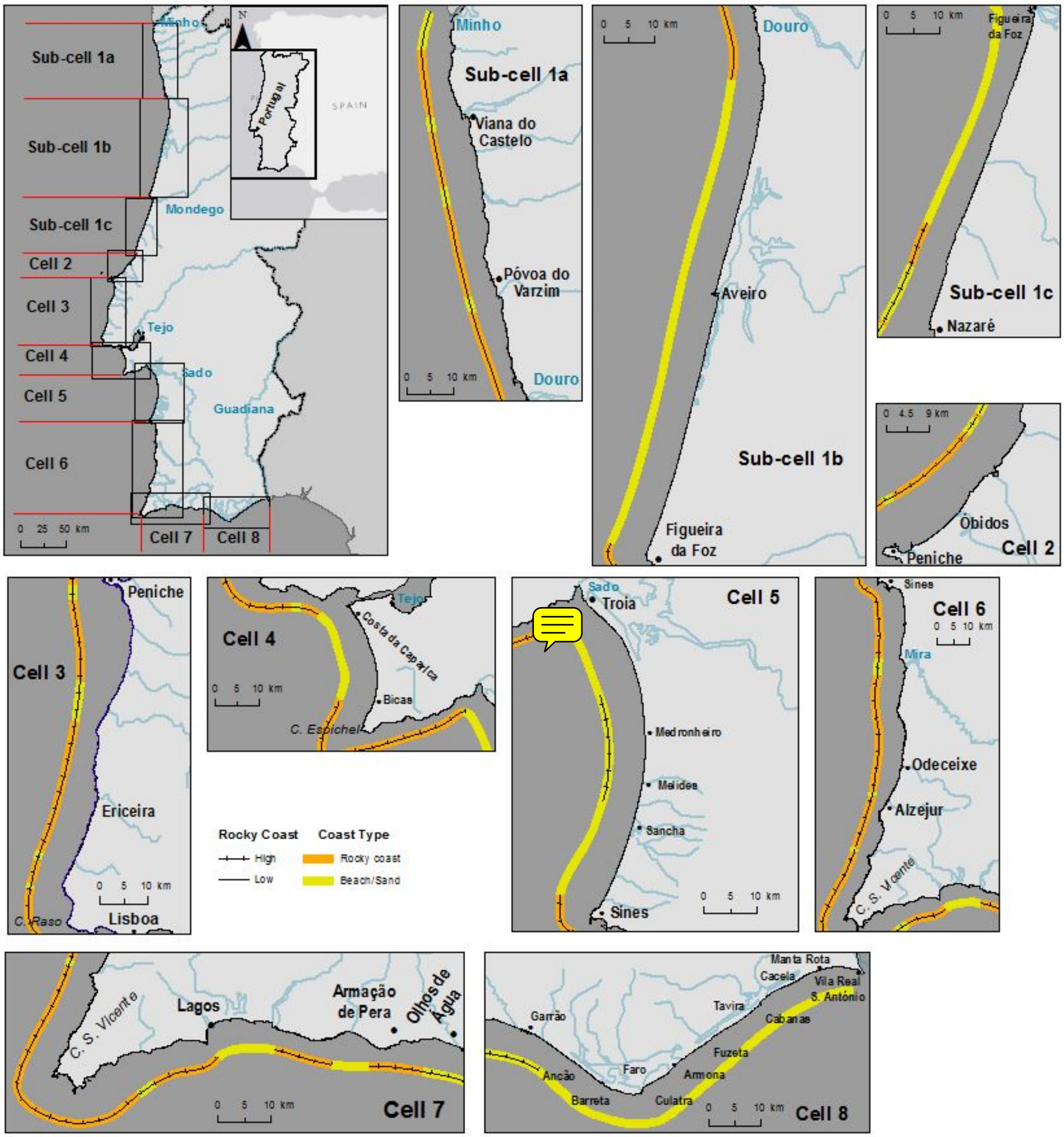

Figure 1. Sediment cells for the Portuguese mainland coast (cell limits in red) and coastal characterization.

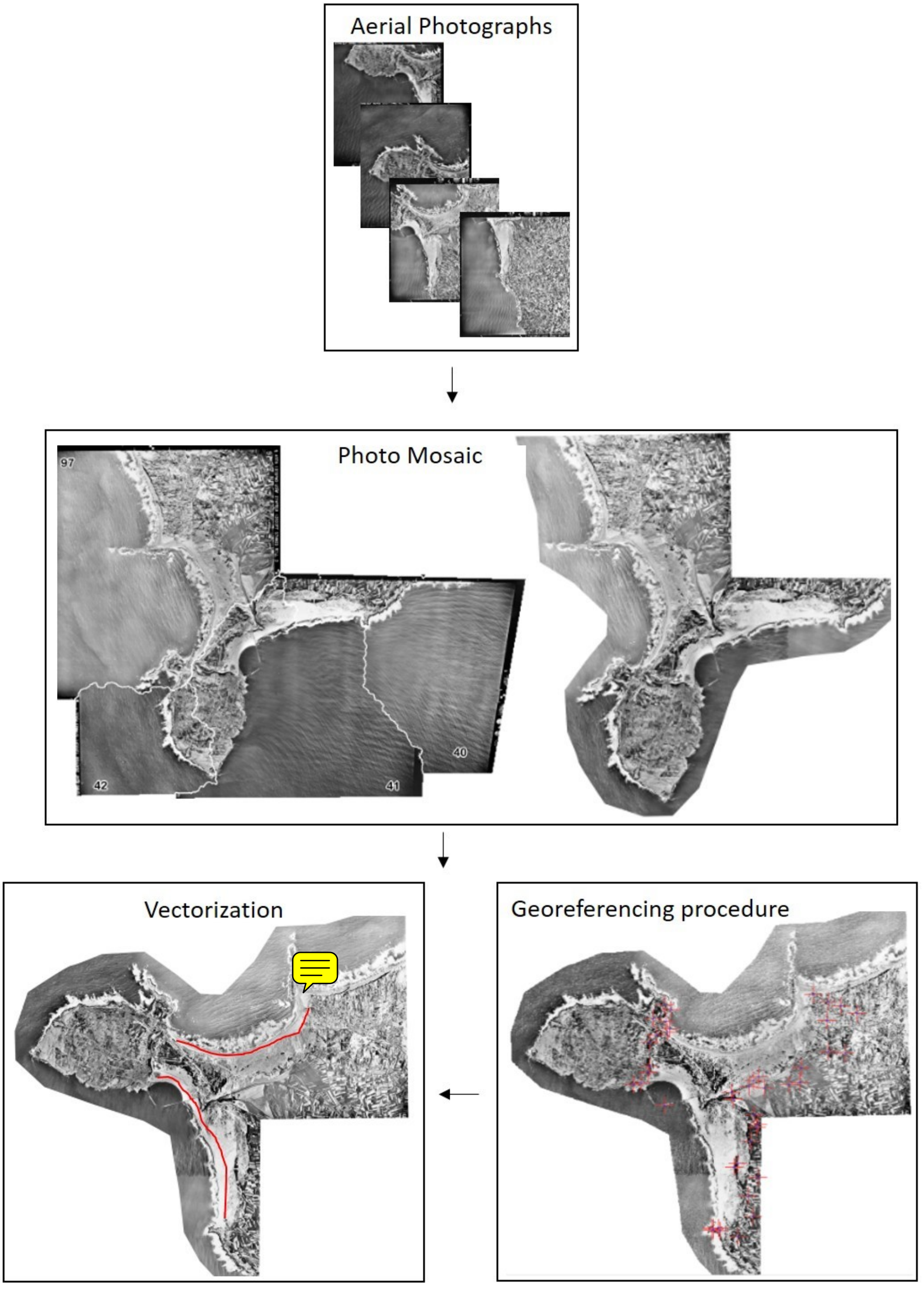

Figure 2. Flowchart procedures for using aerial photographs to extract coastline indicators.

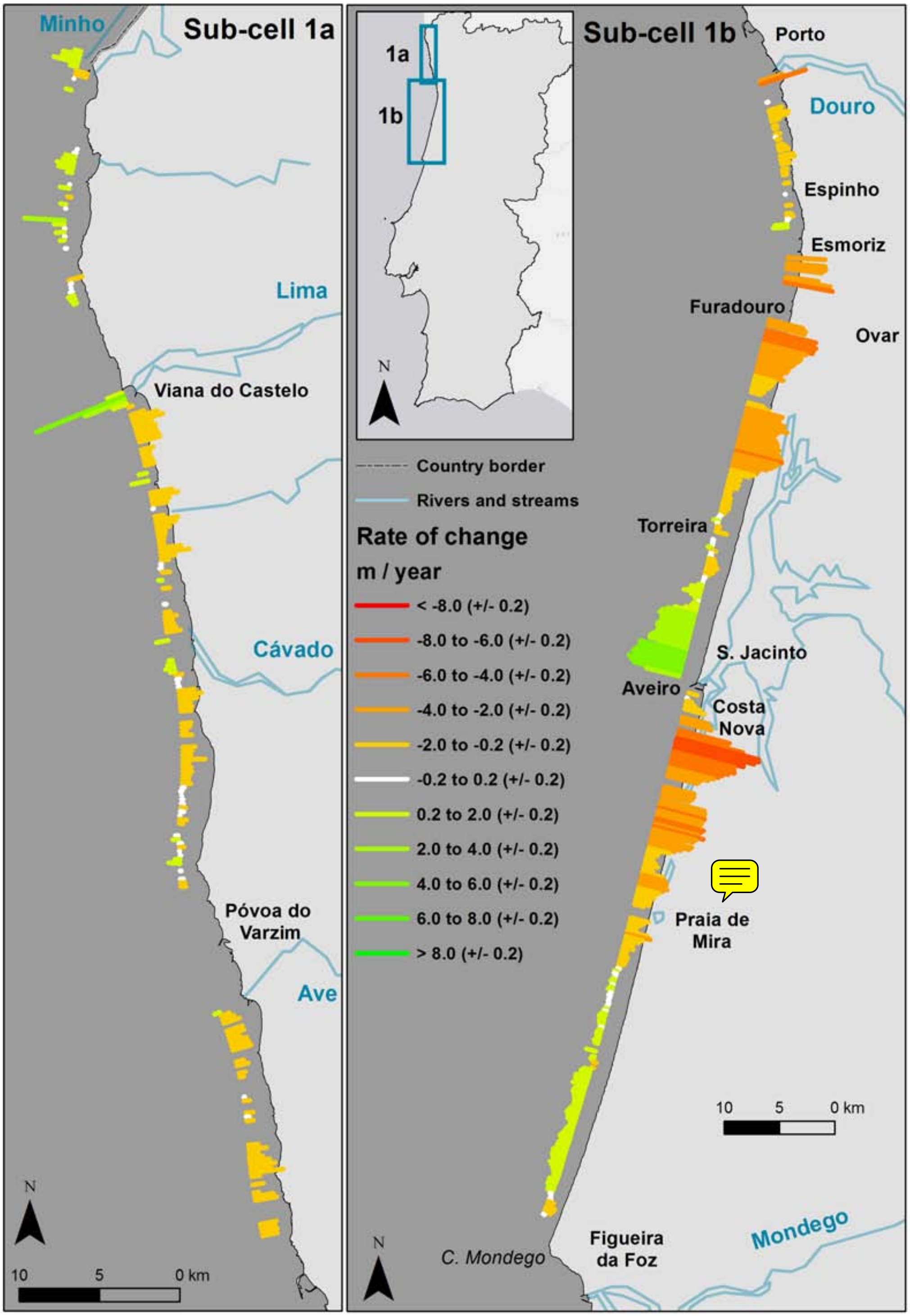

Figure 3. Long-term coastline rates of change in meters per year for sediment sub-cells 1a and 1b.

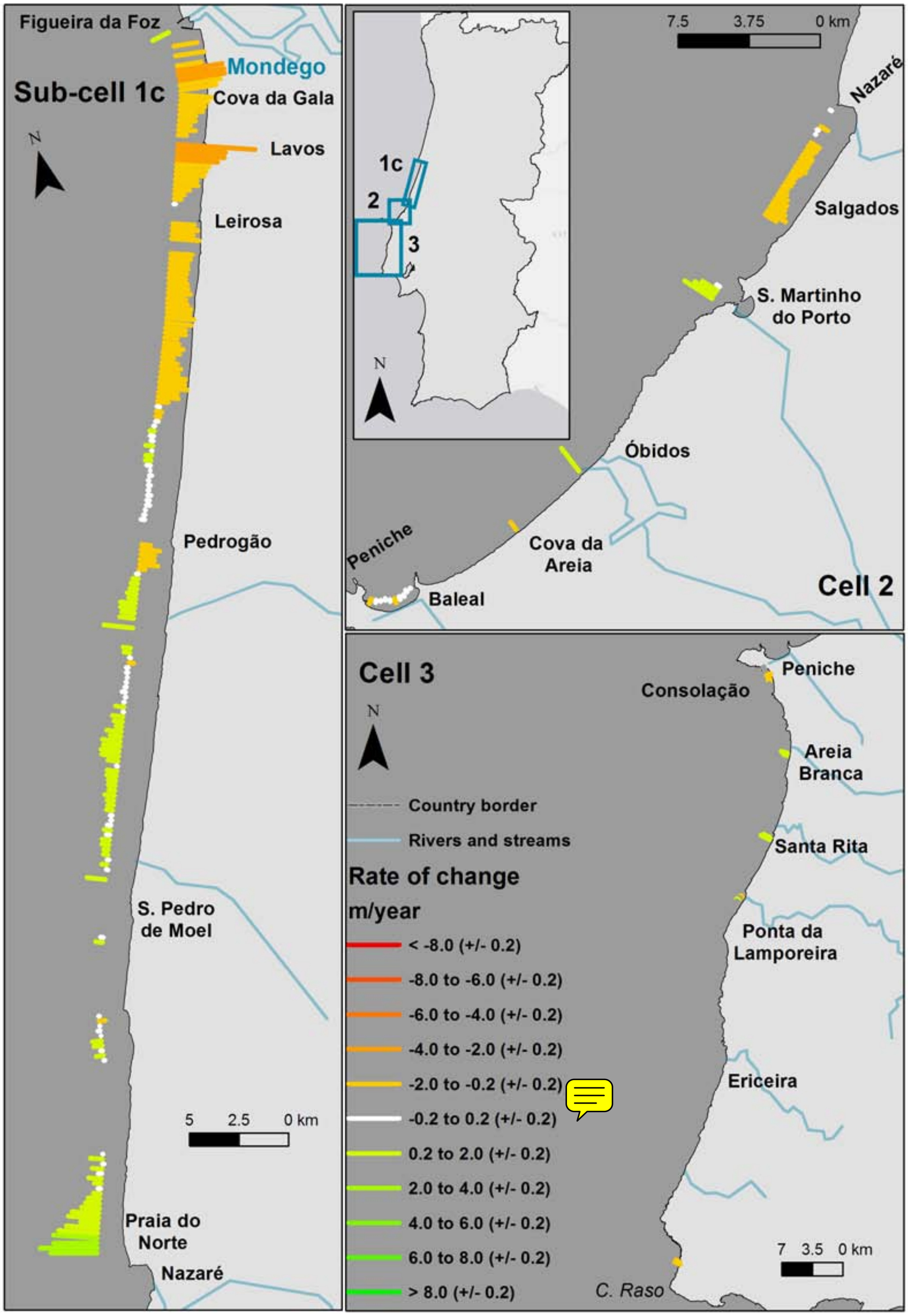

Figure 4. Long-term coastline rates of change in meters per year for sediment sub-cell 1c, cells 2 and 3. Note: Sub-cell 1c coast is represented with a 15^o rotation.

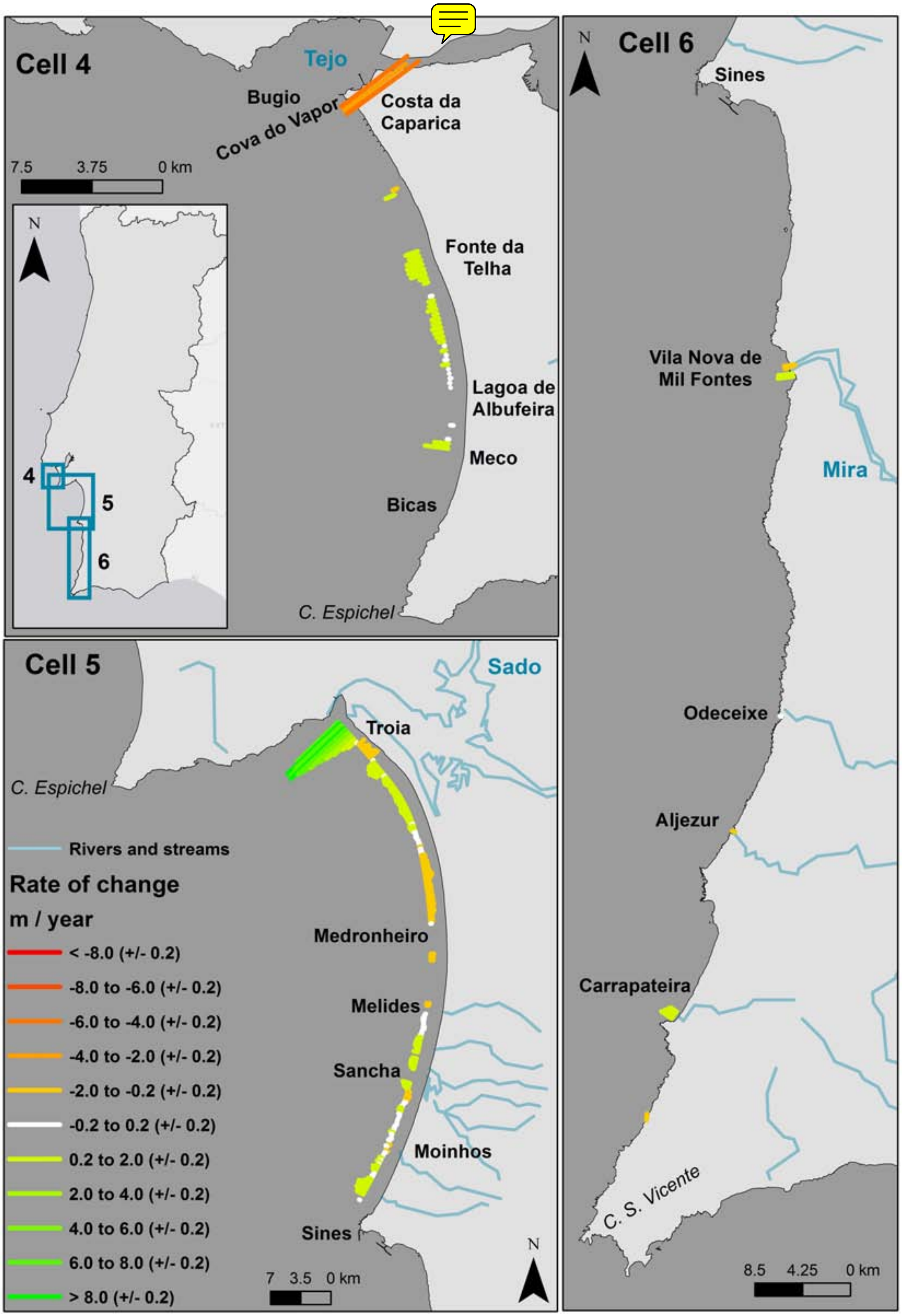

Figure 5. Long-term coastline rates of change in meters per year for sediment cells 4, 5 and 6.

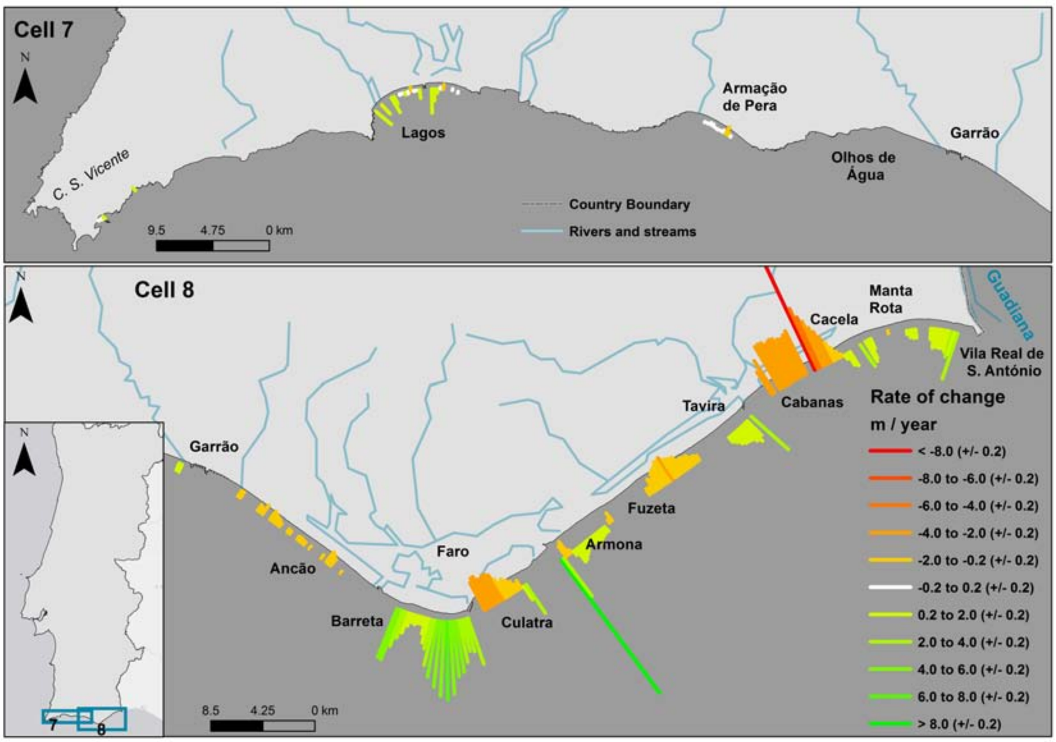

Figure 6. Long-term coastline rates of change in meters per year for sediment cells 7 and 8.

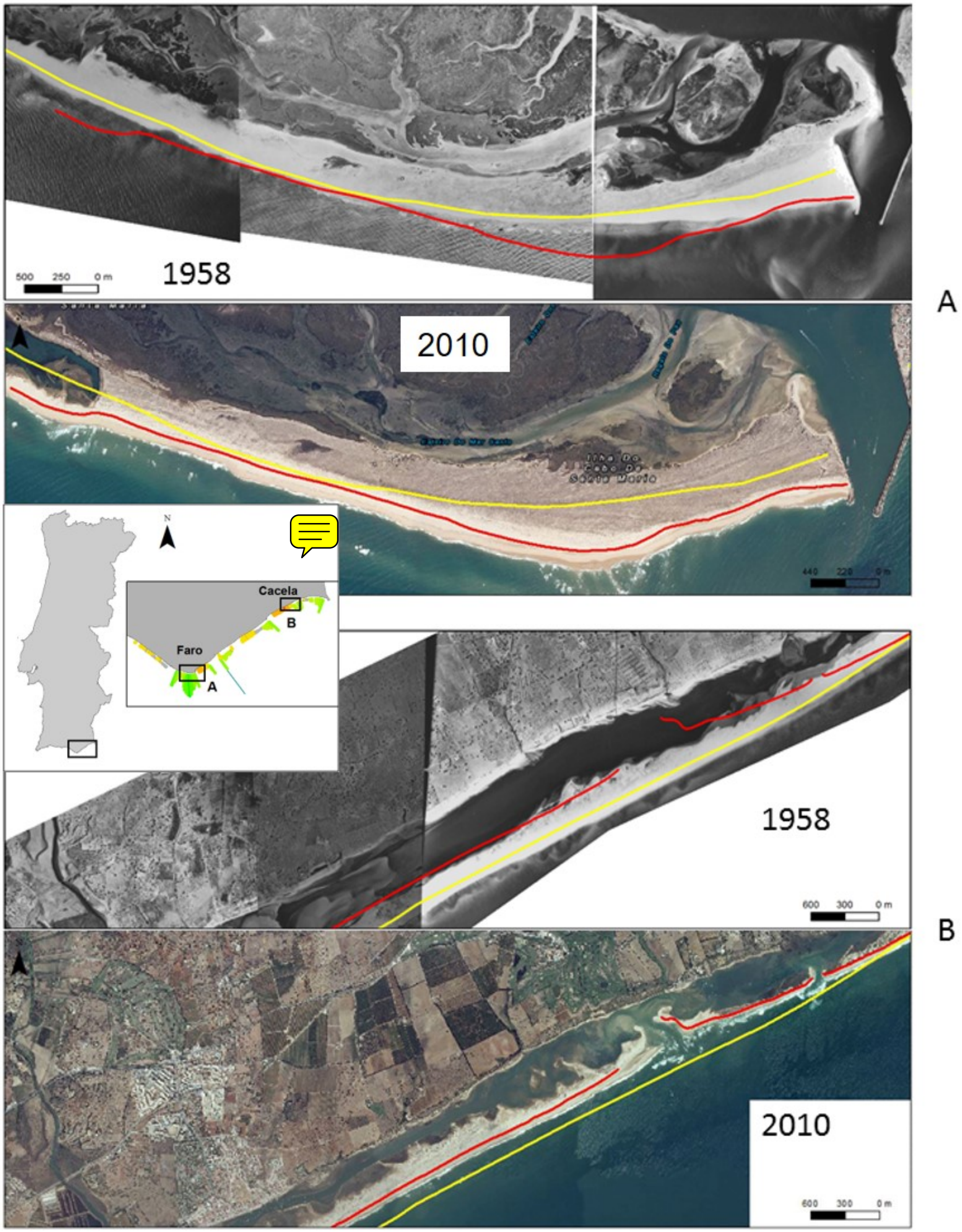

Figure 7. Detail of coastline change between 1958 (yellow) and 2010 (red) at A - Faro-Olhão inlet and B - Cacela inlet, both at the Ria Formosa barrier islands system.

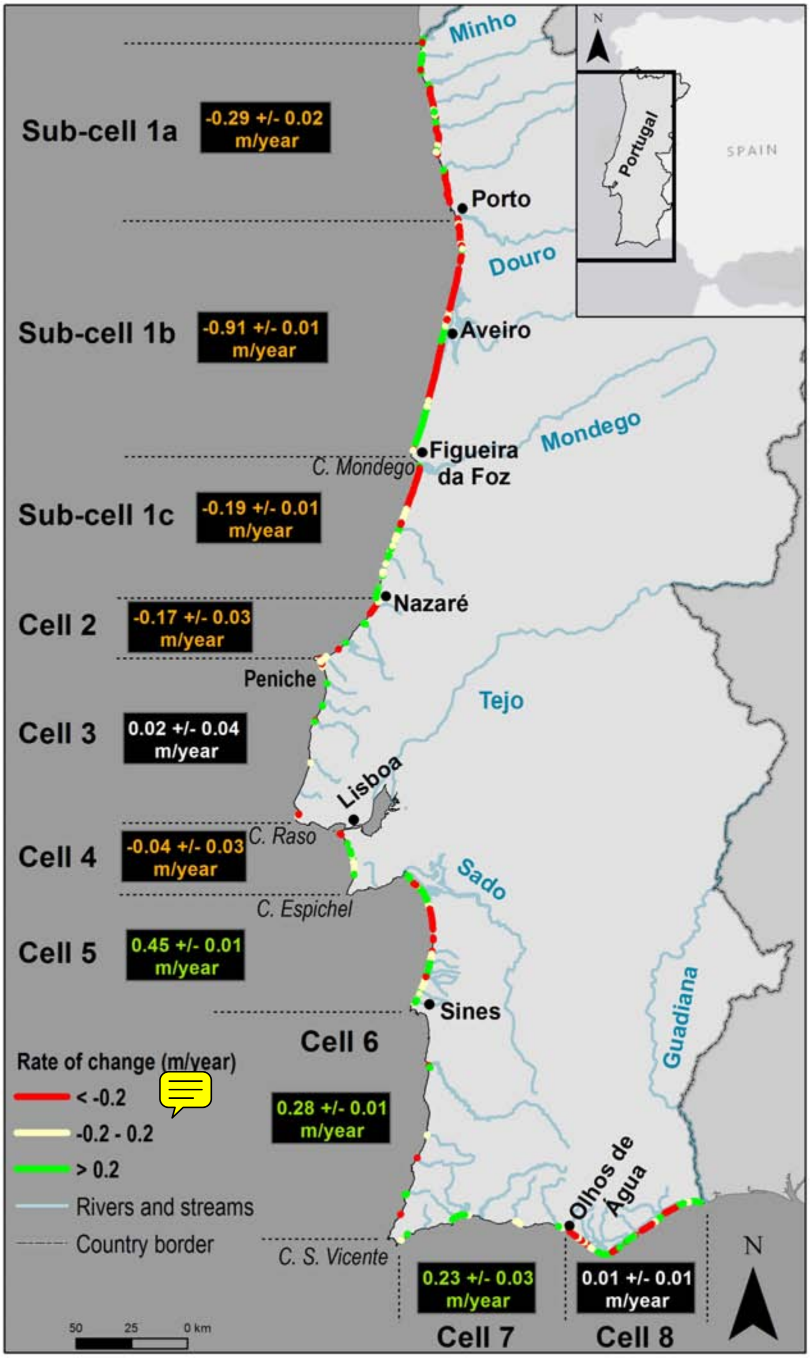

Figure 8. Rate of change map for the mainland Portuguese sandy beach-dune systems coastline. Represented in red are sandy coastal stretches with $R \leq -1$ m/year; in green are sections in accretion and in light yellow sections with $-1 < R < 0$ m/year. Boxed values refer to the mean coastline rate of change within each sediment cell (orange - erosion; green - accretion and white - within uncertainty measures).

~~Detail of coastline change between 1958 (yellow) and 2010 (red) at A - Faro-Olhão inlet and B - Cacela inlet, both at the Ria Formosa barrier islands system.~~