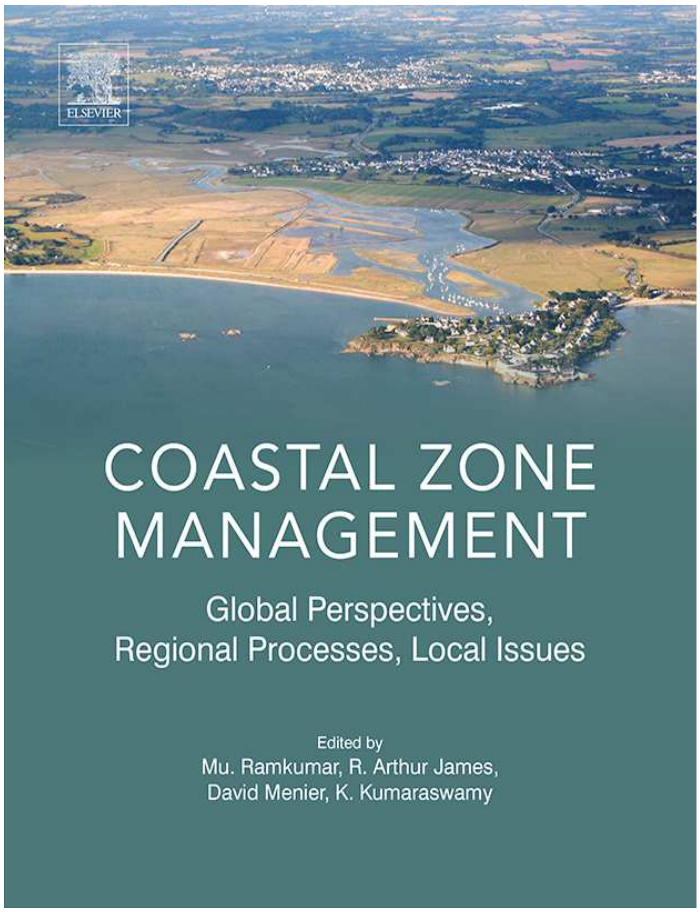

Soazig Pian and David Menier, Spatial and Statistical Analyses of Clifftop Retreat in the Gulf of Morbihan and Quiberon Peninsula, France: Implications on Cliff Evolution and Coastal Zone Management. In: Mu. Ramkumar, R. Arthur James, David Menier and K. Kumaraswamy (eds.) Coastal Zone Management. Burlington: Elsevier, 2019. pp. 131-153.
ISBN: 978-0-12-814350-6

CHAPTER 6

Spatial and Statistical Analyses of Clifftop Retreat in the Gulf of Morbihan and Quiberon Peninsula, France: Implications on Cliff Evolution and Coastal Zone Management

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1 Introduction

Most coastal research studies deal with the geomorphological and morphodynamic behavior of beach systems, while a few others focus on cliff evolution (Naylor et al., 2010). However, cliff retreat processes play an important role in the behavior of coastal systems by providing sediment sources (Dornbusch et al., 2008). Cliff failure and coastline retreat rates are assessed using a wide range of methods, based on both field and remote sensing data (Quinn et al., 2010). Long-term cliff retreat is often assessed using historical topographic maps or aerial photographs (Moore and Giggs, 2002; Dornbusch et al., 2008). Cliff retreat can be related to a wide range of processes, as reviewed by Sunamura (1992) and Dong (2009), including numerous factors such as cliff lithology, geological constraints, susceptibility of rocks to wave impacts and freshwater processes, soil layer width, vegetation cover, cliff exposure to prevailing winds and waves, protective beach width, sea-level rise rates, and also anthropogenic pressures such as footpath location or an increase of artificial areas (French, 2001). In sheltered areas, clifftop retreats are mainly driven by subaerial weathering processes (Robinson and Jerwood, 1987; Sallenger et al., 2002). Subaerial mechanisms can outweigh marine processes, in which case cliff failures are mainly related to rainfall and rock resistance (Young et al., 2009). Anthropogenic pressures exerted on clifftop areas also interact with weathering processes, leading to considerable coastline recession (Adriani and Walsh, 2007; Kumar et al., 2009). At the same time, the recession of coastal cliffs leads to significant risks to persons and property (Lee et al., 2001): coastline retreat contributes to triggering human activities, thus affecting infrastructure and

Coastal Zone Management. https://doi.org/10.1016/B978-0-12-814350-6.00006-9

tourist resorts, and could represent significant losses of land area. Recent studies (Del Rio and Gracia, 2009; Nunes et al., 2009) used Geographical Information Systems (GIS) to assess the risks of cliff retreat. These studies highlight the need to achieve a global understanding of cliff retreat processes to improve the efficiency of cliff retreat management (Fall, 2009).

This chapter combines the application of GIS with spatial and statistical analysis to assess the role of both natural and anthropogenic factors likely to drive clifftop retreat. This approach aims at identifying the main factors associated with differing rates of clifftop retreat in order to produce an effective set of data for coastal managers. The study focuses on two cliff systems located in South Brittany (France): the sheltered and weathered low cliffs of the Gulf of Morbihan, and the rocky cliffs of the Quiberon Peninsula. From the 1950s, these systems have been subject to subaerial weathering processes leading to clifftop retreat rates of more than 0.03 m/year (Pian, 2010). Both of these cliff systems are associated with highly important consequences for tourism, and thus an understanding of their evolution over a long time scale (50 years) may help plan coastal management for the study areas and elsewhere.

2 Study Area

The South Brittany coast is located in the western part of France (Fig. 1), which experiences westerly and southerly winds (Lemasson, 1999). The dominant waves are characterized by a height ranging from 0.5 to 2.5 m with a period of 5 to 9 seconds, and directed mainly from the northwest and west (Tessier, 2006).

2.1 The Gulf of Morbihan Cliffs

The Gulf of Morbihan is a sheltered coastal system where hydrodynamic conditions are predominately influenced by tidal currents. The waters in this Gulf interact with the Atlantic Ocean only though a pass at Port Navalo, which does not exceed 900 m in width. Numerous small islands are scattered in the Gulf. The two largest islands are the Ile aux Moines and the Ile d'Arz. The propagation of the tidal pulse is controlled, to a large extent, by the general shape of the Gulf, the location of the islands, and the bathymetry. In the west of the Gulf, around the Port Navalo pass, the maximum water depth reaches 30 m in tidal creeks. Toward the east, the water depths decrease, ranging from 10 to 1 m east of the Ile d'Arz. As a consequence, tidal currents are stronger at the Port Navalo pass, where they reach 9 *knots* during high spring tides (Pian and Regnauld, 2007). Tidal speeds of currents decrease between the Ile aux Moines and Ile d'Arz, and both flood and ebb currents reach their lowest values east of the Ile d'Arz. Due to these low-energy hydrodynamic conditions, tidal flats and salt marshes are well developed in the Gulf, especially in the eastern part. Most of the Gulf coastline is composed of small weathered cliffs no more than 10 m high. Cliff heights range from less than 0.50 m to a maximum of 10 m, with a mean height ranging between 1.5 and 4 m. The cliffs are composed of highly weathered

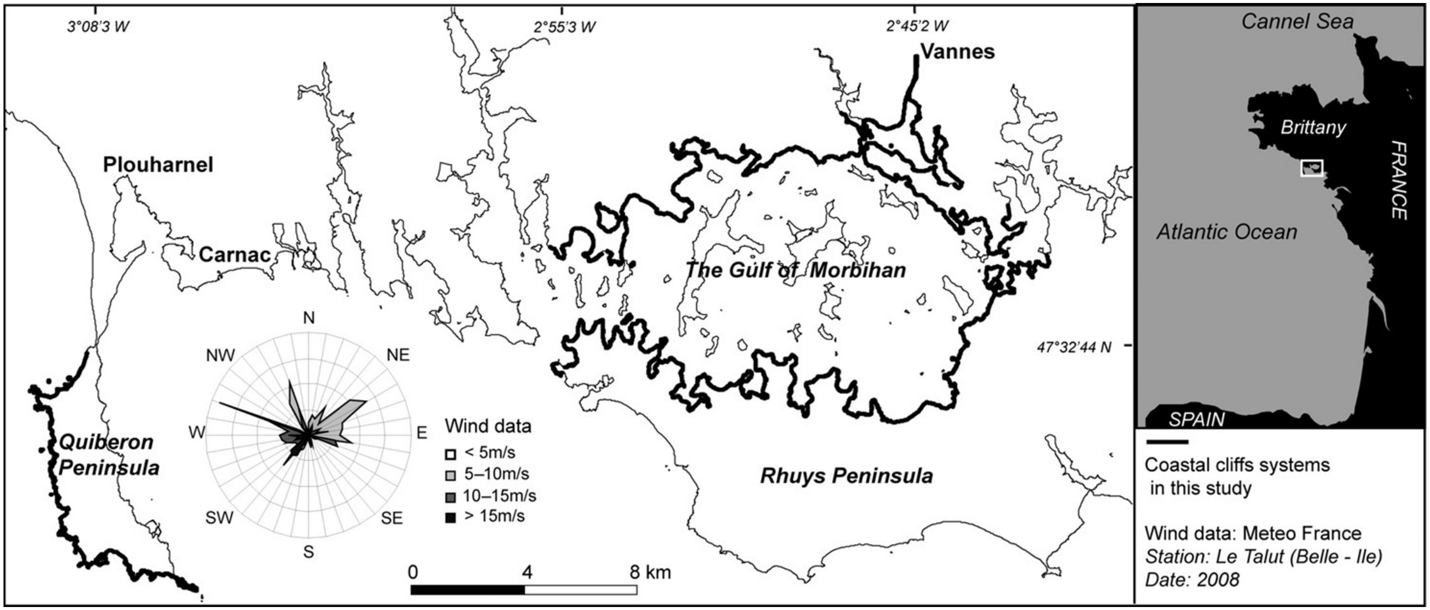

Fig. 1
Study area.

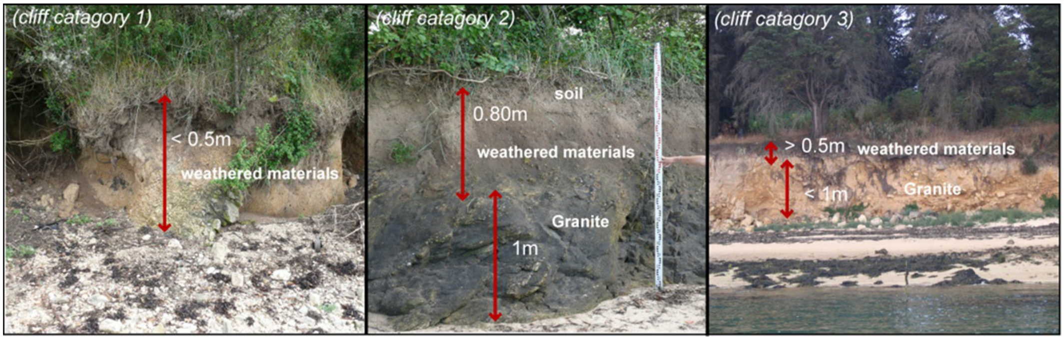

Fig. 2
Various types of soft rock cliffs within the Gulf of Morbihan.

materials derived from granite rocks (Fig. 2). A fine soil layer, which does not exceed 0.50 m in thickness, overlies the weathered layer and is colonized by different vegetation types such as grass, shrubs, or trees (Pian and Regnauld, 2007). Anthropogenic pressures on the cliffs are mainly linked to the presence of a footpath running along the top of the cliffs. In addition, numerous private properties associated with residential areas have been developed. Rigid structures such as sea walls are constructed to protect these properties from cliff recession.

2.2 The Quiberon Peninsula Cliffs

The Quiberon Peninsula is mainly composed of weathered rocky cliffs, orientated toward the west and exposed to prevailing winds and waves. This cliff system is located in a much higher energy environment than the Gulf of Morbihan. At the northern and southern extremities of the peninsula, cliffs with heights not exceeding 4 m are developed in highly weathered materials and are based on a hard rock shore platform. On the central part of the peninsula, cliffs are cut in granite and metamorphic rocks. These hard rock cliffs are capped by a weathered layer (Fig. 3). Cliff heights range from 15 to 5 m, and decrease from the north to the south. A former highly eroded climbing dune is established on the clifftop. A few small pocket beaches partly fed by cliff retreat occur at the foot of the cliffs. These beaches are composed of material of heterogeneous grain size ranging from pebbles to medium sands (Pian, 2010).

Relatively strong anthropogenic pressures are exerted on the cliffs tops: the Quiberon peninsula is one of the most important tourist resorts of South Brittany. It records the highest variations in population during the summer months. A large number of footpaths run along the clifftops, and there are numerous car parks in the vicinity. The cliffs are visited throughout the year.

3 Materials and Methods

To map a clifftop retreat, a combined set of field and aerial photograph data are utilized and integrated within a spatial database. The spatial database was constructed using ESRI ArcCatalog (Pirot and Saint-Gérand, 2005). A personal geodatabase was set up to store and

Fig. 3
Hard rock cliffs of the Quiberon Peninsula.

analyze different layers of spatial data dealing with the clifftop retreat, along with the characteristics of natural and anthropogenic factors.

3.1 Measuring Clifftop Retreat From Analysis of Aerial Photographs

Cliff retreat on a regional scale was measured from aerial photographs. The use of vertical aerial photographs in coastal studies has been widely discussed (Williams et al., 2001; Moore and Giggs, 2002; Graham et al., 2003; Fletcher et al., 2003). The oldest aerial photographs used in the present study date back to 1952. They were scanned with a spatial resolution of 12,000 dpi and geo-rectified, using ArcGis9.2 software. For each geo-rectified photograph, the RMS error was around 4, and the cell sizes varied from 0.68 to 0.8 m (Table 1). Once the photographs were geo-rectified, all the aerial photographs covering each site for 1952 were assembled into a mosaic using Envi3.0 software. Parallax was taken into account by conserving only the central parts of the aerial photographs and by measuring the offset between two fixed features (car parks) located on the clifftops, which were plotted onto the 1952 mosaic as well as the 2004 orthophotography.

The clifftop position was then determined by means of a geomorphological indicator whose migration during the considered time interval is assumed to represent the evolution of the shoreline (Parker, 2003). In this study, the clifftop position was assigned to the break of slope at the top of the cliff (Moore and Giggs, 2002). It was plotted on the orthophotographs of 2004, as

Table 1 Characteristics of the aerial photographs

	Cell Size (m)	Root Mean Square Error (RMS) (m)
Orthophotography 2004	0.50	
Aerial photographs 1952 (Gulf of Morbihan)	0.80	4.50
Aerial photographs 1952 (Quiberon Peninsula)	0.69	4.05

well as the on the aerial photographs dating from 1952, as a polyline using the ArcGis Editor tool. Then, for each site, polylines representing the shoreline positions in 1952 and 2004 were merged into a new layer using ArcGis toolbox functions and converted into a polygon layer (Levin and Benn Dor, 2004; Rodriguez et al., 2009). The values of the error margins associated with the geo-rectification and digitalization processes were extracted from the polygons (Table 1). To estimate the maximum amount of cliff retreat (outside error margins), the width of a rectangle was measured whose length was parallel to the coastline, and which included the whole polygon, using the polygon area and perimeter. Because cliff failure is constrained by faults and fractures orthogonal to the coastline, the polygon shape is a good approximation of the rectangle shape, so this method allowed an automatic quantification of clifftop retreats from aerial photographs. Cliff retreat rates were then estimated using the effective end point rate method (Doland et al., 1991), by dividing clifftop retreat values for each site by the number of years of the studied time interval.

3.2 Construction of the Spatial Database

The compilation of the spatial database (Fig. 4) was carried out in several steps, including the identification, classification, and digitization of natural and anthropogenic factors, and spatial data layer intersection.

As mechanical resistance of rocks, soil depth, or vegetation cover represent natural factors likely to control subaerial weathering processes (Robinson and Jerwood, 1987; French, 2001; Sallenger et al., 2002), we focus here on these factors to explain cliff retreat in both the Gulf of Morbihan and Quiberon Peninsula. For the more exposed Quiberon Peninsula cliffs, the orientation of the coastline to prevailing winds and waves was also taken into account, because erosion by wave action also controls cliff recession (Sunamura, 1977; Hapke and Richmond, 2002).

First, different categories of cliff and vegetation cover were mapped from field data and aerial photographs to characterize each stretch of the studied coastlines. The cliff classification used here is based on the previous studies of Emery and Kuln (1982) and Claytone and Shamonn (1998), and uses the following criteria: cliff orientation to prevailing winds and waves, cliff

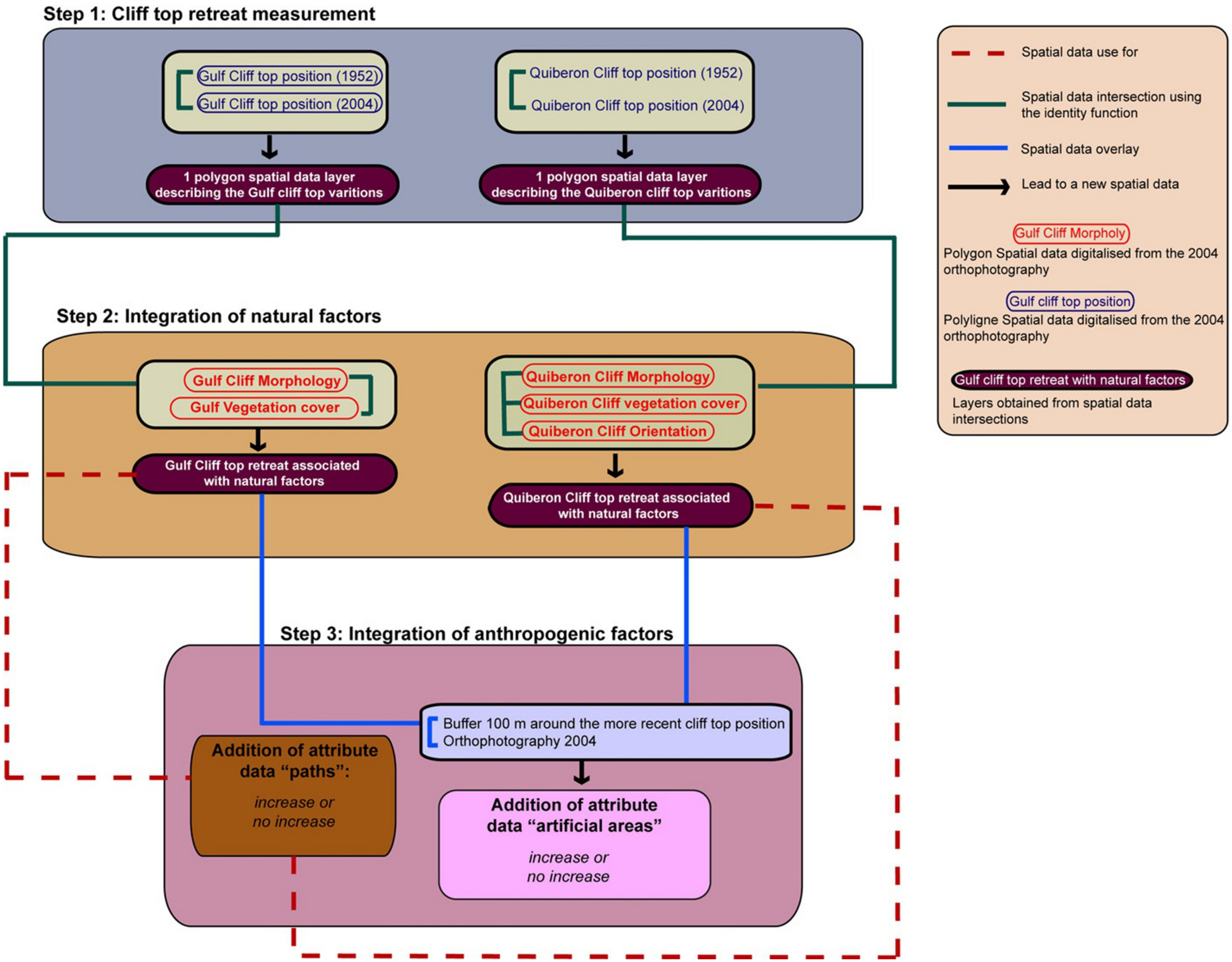

Fig. 4
Compilation of the spatial database.

height, presence/depth of weathered layer, presence/depth of soil layer, and resistance of the rock to weathering processes (soft rock vs. hard rock). From the aerial orthophotographs of 2004, a number of sites were selected and visited at least twice, at low and high tides. Between June 2006 and July 2009, nine sites were visited along the cliffs of the Quiberon Peninsula. A total of 46 sites were visited in the Gulf, where two field trips were carried out by boat. The choice of sites was based on screening and visual analysis of aerial photographs, which provided an overview of the different types of cliff morphology. For each site, a field index card was drawn up containing a picture of both the 2004 orthophotography and the survey map, as well as a description of the cliff and vegetation cover obtained by visual analysis of aerial photographs. For each site, this description was completed in the field: the resistance of the rock was assessed, the depths of the weathered and soil layers were measured, clifftop vegetation cover was checked, and cliff height was measured using D-GPS data.

The first cliff category includes microcliffs, no more than 1 m high, that are cut in weathered materials or salt marshes. They are widespread throughout the Gulf, especially in the east where low-energy hydrodynamic conditions favor the development of mudflats and saltmarshes. At high tide, the retreat of microcliffs could be partly related to tidal currents; however, their evolution is mainly controlled by subaerial weathering processes (Fig. 2). The second cliff category corresponds to low weathered cliffs, whose height ranges from 1 to 4–5 m (Fig. 2). The weathered layer makes up at least one half of the total cliff height. Sometimes, it lies on top of hard metamorphic or highly fractured granitic rocks. The weathered layer was found to be capped by a soil layer not exceeding a depth of 0.50 m. Because these types of cliffs are located in sheltered areas, the main processes controlling their retreat are driven by subaerial weathering. Such cliffs are found along the Gulf coastline and the south-eastern extremity of the Quiberon Peninsula. The third cliff category (Fig. 2) is composed of high weathered cliffs that can reach a height of 10 m. Unlike the previous type, the weathered layer represents less than half of the total cliff height, but overlies the same fractured metamorphic or granite rocks. These cliffs are located in sheltered areas within the Gulf, as well as along the more exposed coastlines, such as the north of the Quiberon Peninsula. Thus, their retreat is the result of both subaerial processes and wave action. The fourth cliff category concerns the exposed rocky cliffs of the Quiberon Peninsula (Fig. 3), which range in height from 10 to 15 m. The weathered layer is much thinner than in the previous types. The soil layer is very thin and often absent.

Three categories of vegetation cover were recognized on the orthophotographs of 2004, and then validated in the field: grass, scrubs, and tree vegetation. A fourth category was added to describe areas where soil layers and vegetation are absent.

To store these factors as spatial data layers within the geodatabase, the cliff coastlines were divided into different segments according to cliff and vegetation cover categories (Nunes et al., 2009). These segments were digitalized as polygons from the aerial photographs taken in 2004. Nominative attributes describing the four categories of cliffs and vegetation cover were assigned to each polygon. The Quiberon cliff coastline was also divided according to its orientation. Five orientations were recognized along the coastline: southeast, south, southwest, west, and northwest. Each segment was digitalized as a polygon at a scale of 1:25,000. An attribute value was assigned to each polygon in order to store the information related to the orientation.

Then, these spatial data layers were intersected with the polygon layers describing clifftop variations using the *identity* function provided by the ESRI ArcGis9.3 software (Fig. 4). As a result, for each stretch of the coastline in the Gulf of Morbihan and the Quiberon Peninsula, a spatial data layer defining a value of clifftop retreat in meters, as well as the location of a set of natural factors controlling cliff weathering and erosion was obtained. Then, two anthropogenic factors affecting clifftops and likely to interact with subaerial erosion processes were added to the spatial database (Fig. 4). The first factor refers to the addition of a pathway between 1952 and 2004. It was assessed by screening and visual analysis of aerial photographs. When a pathway was added on the clifftop, and intersected a polygon describing clifftop retreat, it was recorded within the spatial database in terms of nominative attribute values (*0 = no footpath increase or 1 = footpath increase*). The second anthropogenic factor takes into account the increase of artificial areas—that is, car parks—established on the clifftops within the same time interval. To identify this last factor, a 100 m wide buffer zone was created around the polygons representing clifftop retreat. Any increase of artificial area between 1952 and 2004 within this buffer zone was also recorded within the spatial database in terms of nominative attribute values (*0 = no artificial area increase or 1 = artificial area increase*).

3.3 Spatial and Statistical Analysis

To explain the spatial variations of clifftop retreat, a series of spatial and statistical analyses were carried out and are detailed herein.

3.3.1 Spatial analysis

First, spatial analysis was carried out to assess the spatial relationships between the distributions of clifftop retreat values along the coastlines, as well as the characteristics of the analyzed factors likely to control these changes (Pian, 2010). Such analyses rely on the assumption that the spatial distribution of geographic objects is related to their characteristics (O' Sullivan and Unwin, 2003), owing to the spatial auto-correlation principle that allows us to quantify the relationship between the proximity of different places and their degree of resemblance (Pumain and Saint-Julien, 2004). In the scope of this study, the geographic objects refer to the polygon representing clifftop retreat, and their characteristics are described within the spatial database as attribute values. A nearest-neighbor analysis was performed with the aim of assessing the distance between the density of different clifftop retreat values recorded along the coastline, and the density of certain factor characteristics contained within the spatial database. Indeed, this analysis attempts to identify certain spatial associations that group together a given factor (i.e. tree vegetation cover) with a specific clifftop behavior (i.e., high clifftop retreats values).

The density of the different factor characteristics was mapped using the ESRI *create vector grid tool* to create regular grids from spatial features contained in a spatial data layer source, while taking into account specific attribute values (Fig. 5). Cell sizes were determined according to the areal extent of spatial data layers and contain at least two polygons. Cell resolution is 1000 m for the Gulf of Morbihan, but decreases to 500 m for the Quiberon Peninsula due to the smaller spatial extent. Polygon attribute values contained in a given cell were assigned to the cell as new attribute data. Selected attribute values were added, and the sum weighted by the polygon areas. For each cliff coastal system, a grid was created for each attribute value related to each studied factor. Finally, the different grids were superimposed onto the spatial data layer describing the spatial variations of clifftop retreat values.

3.3.2 *Statistical analysis*

To complete the spatial analysis, the statistical relationships between the different factors contained within the spatial database were assessed through multivariate statistical analysis using XlStat software. First, a multiple component analysis (MCA) was carried out. The MCA allowed us to assess the statistical relationships between all the modalities of the set of nominative variables (Minvielle and Souiah, 2003). Clifftop retreat values are expressed in m and refer to quantitative data. To be incorporated within the MCA, these values were grouped

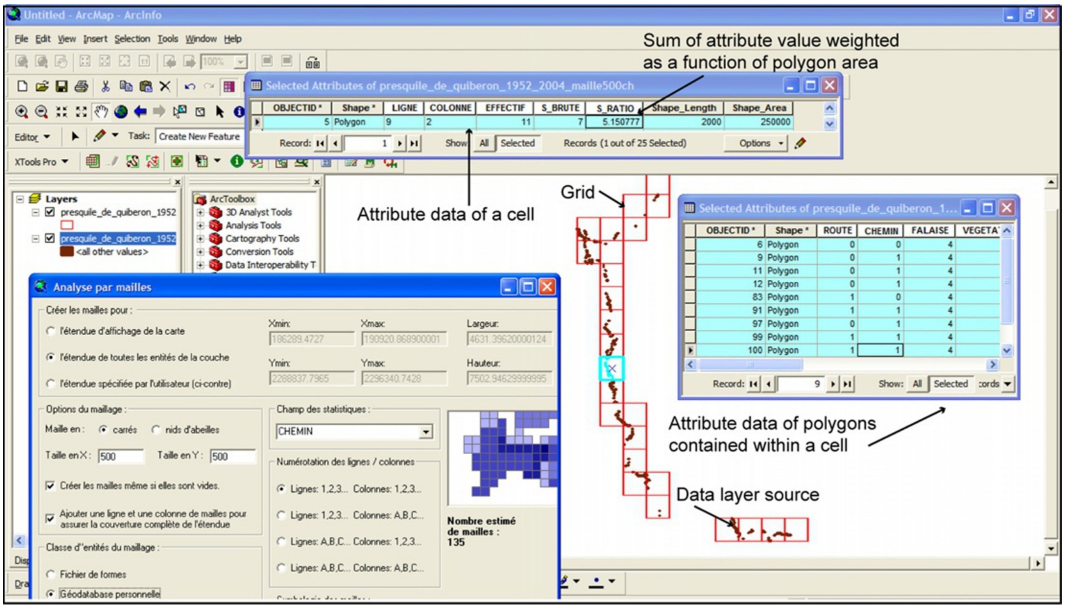

Fig. 5
Mapping density.

into five classes using a natural break classification that allowed us to define classes of similar numbers of data, and which does not distort the statistical analysis (Escoffier and Pagès, 1998).

It was followed by a hierarchical clustering analysis (HCA) on the coordinates of modalities provided by the MCA. The HCA aims at establishing a typology of the studied objects (clifftop retreat sites) by clustering them on the basis of their resemblance. Resemblance is defined as the sharing of a large number of the same modalities (Escoffier and Pagès, 1998), and can be assessed using Euclidian distance.

4 Results

4.1 Clifftop Retreat Mapping

Fig. 6 presents the spatial distribution of clifftop retreat values along the Gulf of Morbihan coastline between the years 1952 and 2004. While retreat rates higher than 0.02 m/year are less common, the four other clifftop retreat classes are well represented, and their distribution is relatively homogeneous. This inference implies that spatial variations of hydrodynamic conditions do not control the spatial distribution of clifftop retreat, or, alternatively, hydrodynamic conditions play a lesser role in clifftop retreat. At this juncture, the dominant role of other factors, such as subaerial weathering, can be assumed. This presumption is affirmed as detailed herein.

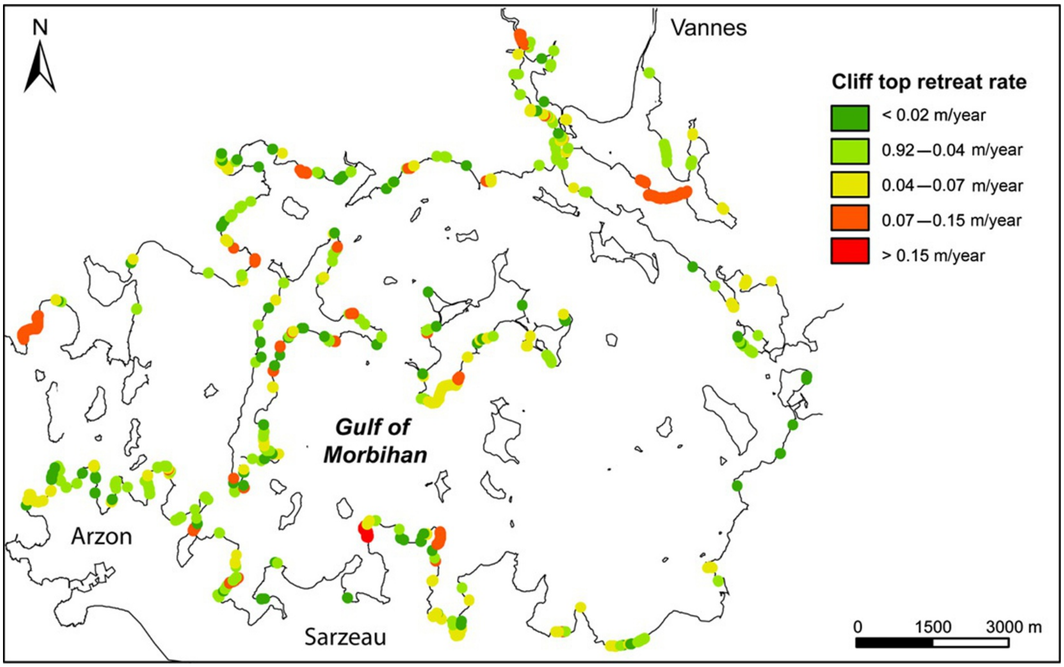

Fig. 6
Clifftop retreat along the Gulf of Morbihan coastline (1952–2004).

The clifftop retreat values along the Quiberon Peninsula display a similar homogeneous spatial distribution (Fig. 7). Cliff retreat rates ranging from less than 0.02 to 0.07 m/year are more frequent, and are observed all along the coastline. The maximum retreats, faster than 0.15 m/year, are located on the central part of the Quiberon Peninsula windward coast. They are associated with weathered material capping the cliff face.

4.2 Spatial Associations Inferred From the Nearest-Neighbor Analysis

Fig. 8 displays the spatial distribution of tree and scrub vegetation cover, as well as the distribution of clifftop retreat values along the Gulf of Morbihan coastline. Both the types of vegetation cover are homogeneously distributed along the Gulf coastline, except for tree cover, which is less dense toward the southeast. Higher clifftop retreat values are located in sectors with a denser tree cover. On the contrary, lower clifftop retreat values are located where scrub vegetation cover is denser. These results suggest a spatial relationship between the distributions of cliff vegetation cover and clifftop retreat values, which can be interpreted in terms of the spatial correlation. Previous authors have proposed that vegetation plays a role in controlling subaerial weathering (French, 2001). Based on this, the increased densities of specific classes of clifftop retreat located close to higher concentrations of certain types of vegetation cover can be assumed to suggest the catalytic role of vegetation on cliff retreat processes in the Gulf of Morbihan.

On the Quiberon Peninsula, most of the hard rock cliffs are capped either by an eroded soil layer where vegetation cover is lacking (category 4) or by grass vegetation (Fig. 9). Higher values of clifftop retreat are measured in sectors showing higher densities of category 4. In addition, these sectors broadly correspond to those associated with an enhanced development of anthropogenic features, especially footpaths. These observations are suggestive of positive relationships between the distribution of clifftop retreat values and the state of vegetation cover, as well as the intensity of human pressure.

4.3 Analysis of Statistical Relationships Between Clifftop Retreat Values and the Studied Factors

In the Gulf of Morbihan, MCA reveals two main axes that account for 57.66% of the total variance (Fig. 10). The first axis explains 40.92% of the total variance. It is mainly defined by variables referring to natural factors such as cliff and vegetation cover categories, or higher classes of clifftop retreat. Microcliffs are associated with grass vegetation cover, as well as both higher and lower values of cliff retreats. Weathered cliffs are associated with shrub vegetation and medium classes of cliff retreat. The second axis explains 16.47% of the total variance. It is defined by variables that refer to natural factors, such as vegetation cover, as well as anthropogenic pressures such as the addition of footpaths or increase of artificial areas. This latter axis allows us to link the high weathered cliffs (type 3) covered by shrub vegetation with

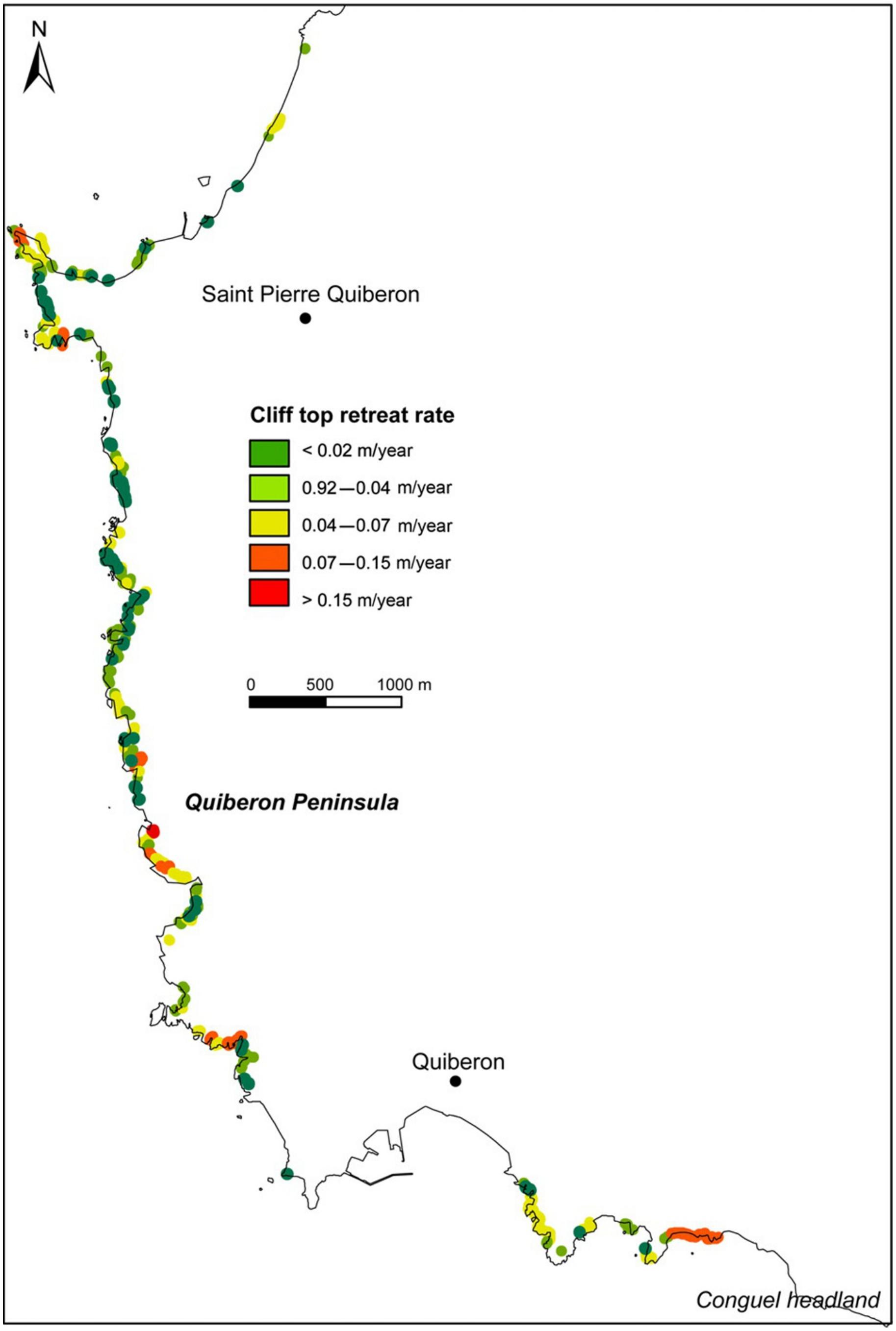

Fig. 7
Clifftop retreat along the Quiberon Peninsula coastline (1952–2004).

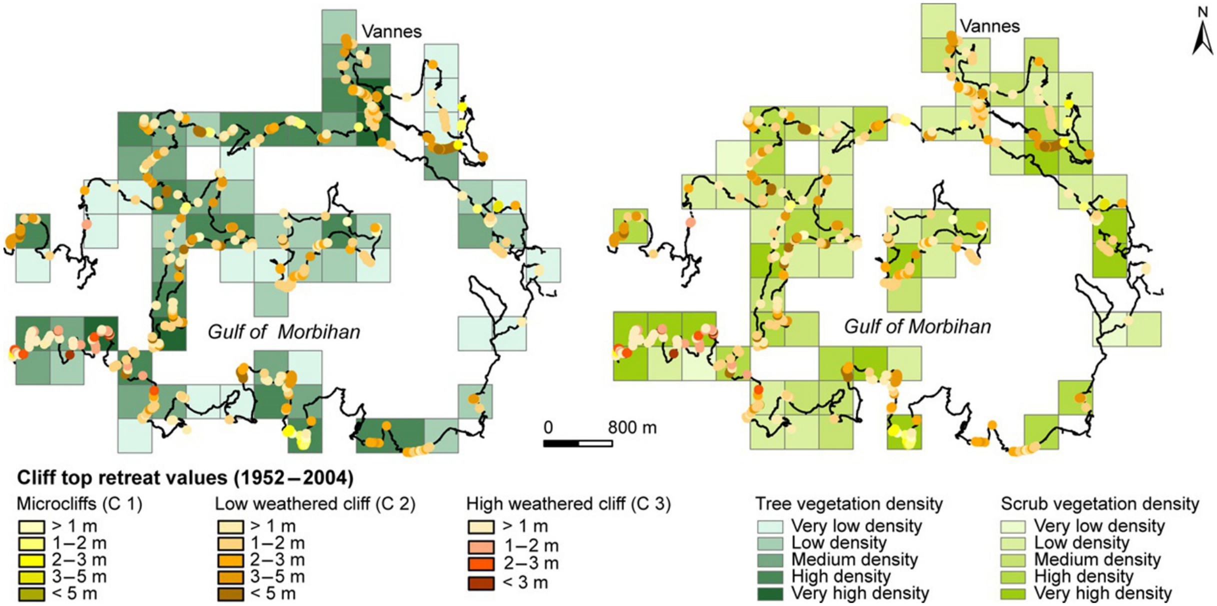

Fig. 8

Spatial distribution of clifftop retreat values and vegetation cover in the Gulf of Morbihan.

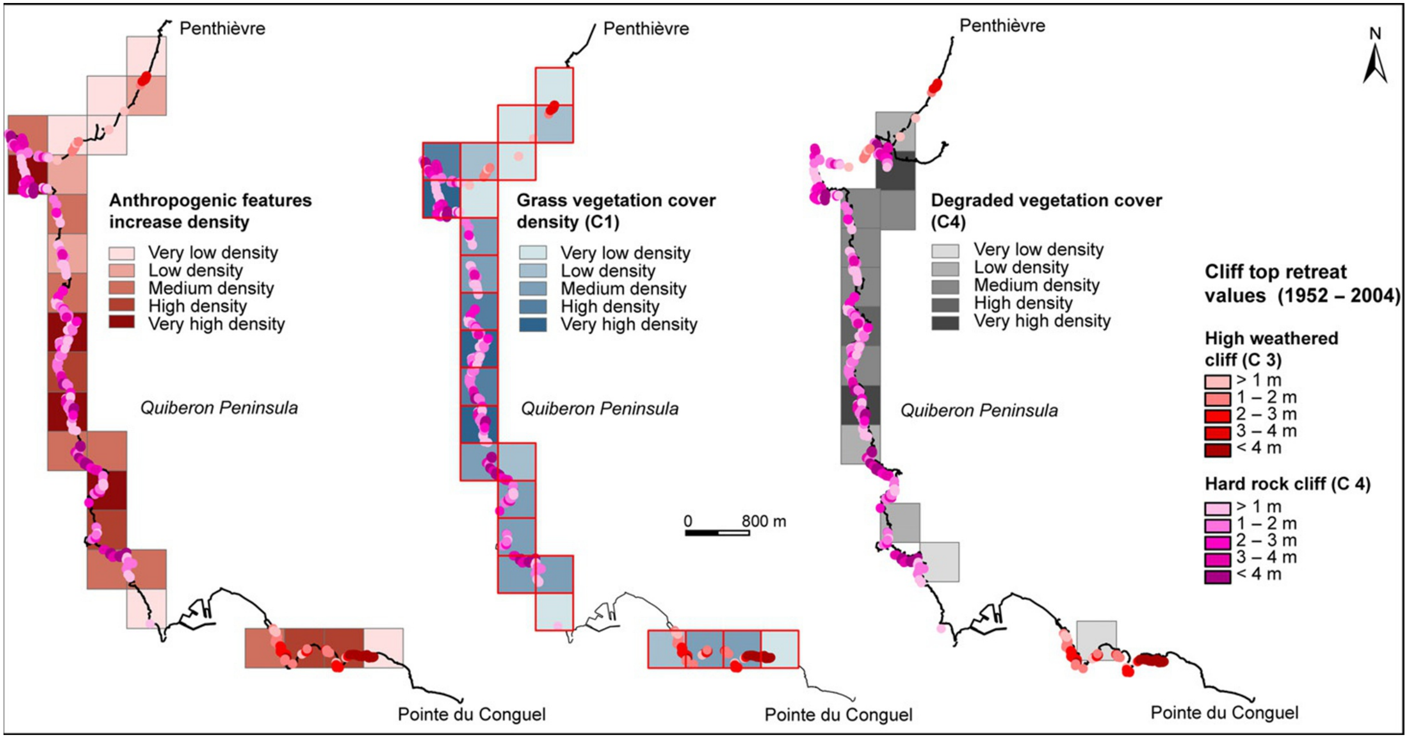

Fig. 9

Spatial distribution of clifftop retreat values, vegetation cover, and anthropogenic features on Quiberon Peninsula.

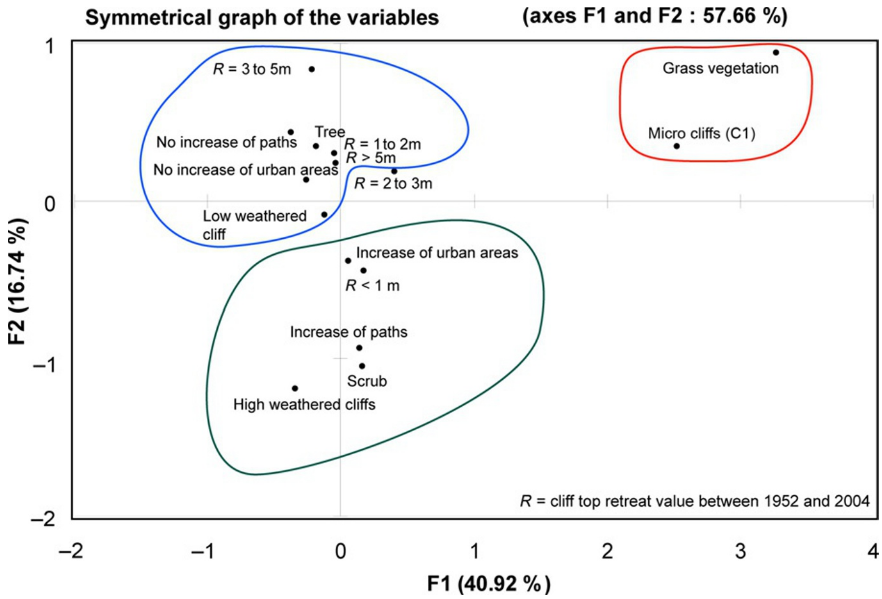

Fig. 10

Projection of modalities onto the first two axes obtained from MCA (Gulf of Morbihan—1952/2004).

an increase of anthropogenic pressures and lower values of clifftop retreat. On the contrary, higher values of clifftop retreat are associated with small weathered cliffs (type 4) and tree vegetation cover. According to the results displayed by these axes, clifftop retreat appears controlled by the type of vegetation cover, combined with the morphology of the cliffs (height, depth of weathered layer, and soil layer). Indeed, MCA leads to associate different values of clifftop retreat with each cliff category, in relation with their vegetation cover: microcliffs are likely to record both high and low values of cliff retreat. Weathered cliffs are associated with low to medium classes of clifftop retreat, except when the vegetation cover is composed of trees. The combination of tree vegetation cover with a deep weathered layer leads to higher cliff retreat values.

HCA highlights these results and emphasizes the role of vegetation cover. It allows identification of three clusters. Cluster 1 is composed of low retreat sites associated with a scrub or grass vegetation. These sites are also often characterized by an increase of anthropogenic pressure. Cluster 2 refers to high retreat sites recorded on cliffs belonging to category 2 and covered by tree vegetation. They are located in sectors with higher densities of tree vegetation (Fig. 11). Cluster 3 groups high and low values of clifftop retreat recorded on category-3 cliffs covered by grass vegetation.

For the cliffs of the Quiberon Peninsula, MCA results identify two axes that explain 52.77% of the total variance (Fig. 12). The first axis explains 40.73% of the total variance and is mainly defined from variables related to natural controlling factors such as cliff category, vegetation

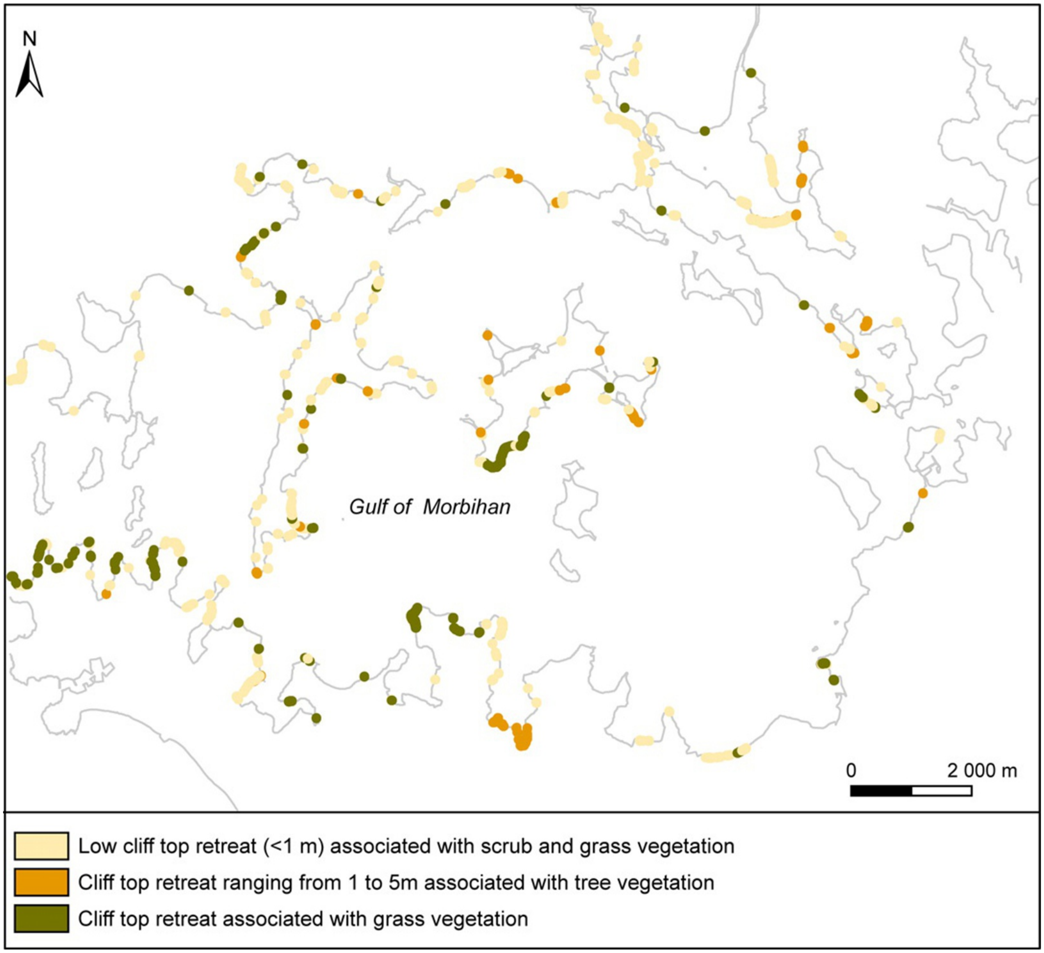

Fig. 11
Spatial distribution of clusters obtained from HCA (Gulf of Morbihan—1952/2004).

cover, and cliff orientation, and, to a lesser extent, the addition of footpaths on clifftops. Along this axis, higher classes of retreat are associated with the south and northwest oriented weathered cliffs covered by shrub and tree vegetation, as well as with the addition of footpaths. Rocky cliffs with no soil layer or vegetation cover are associated with lower classes of cliff retreat. The second axis explains 12.40% of the total variance, and is defined by variables related to the vegetation cover, the increase in anthropogenic pressure on clifftops, and the orientation of the coastline. It reveals a contrast between two groups of variables: on the one hand, the north, northeast, or east oriented weathered cliffs covered by grass vegetation associated with the addition of footpaths on clifftops, and on the other hand, the southeast oriented cliffs characterized either by grass vegetation cover or no soil layer or vegetation cover. Thus, it is safe to conclude that the evolution of the Quiberon Peninsula cliffs is likely to

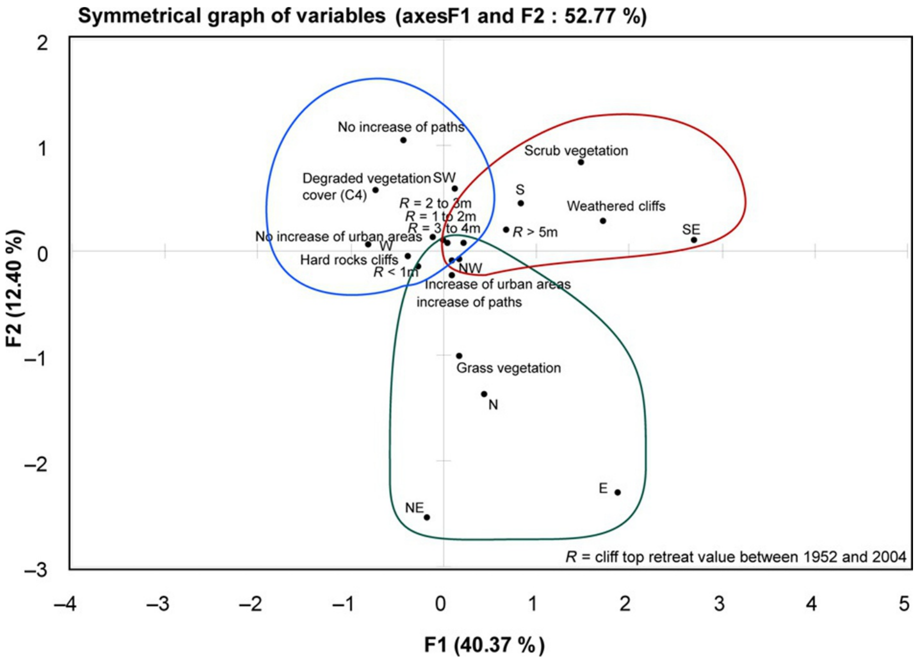

Fig. 12
Projection of modalities on the two first axes obtained from MCA (Quiberon Peninsula—1952/2004).

be controlled by their morphology, their exposure to prevailing winds and waves, and the vegetation cover, as well as the intensity of anthropogenic pressure, and especially footpaths running along the coastline: higher classes of clifftop retreat are associated with the location of footpaths on the clifftop.

Results obtained from HCA attribute the sites to three clusters (Fig. 13). Cluster 1 groups together high-retreat sites located on hard rocky cliffs associated with an increase of anthropogenic features established on clifftops. Cluster 2 refers to low-retreat sites located on hard rock cliffs. These two clusters reinforce the inferences drawn from MCA and spatial analysis. The third cluster is composed of high-retreat sites located on soft rock clifftops.

5 Discussion

The results presented in the previous section highlight the dominant role of vegetation cover in controlling clifftop retreat in the Gulf of Morbihan. Both spatial and statistical analysis show that higher classes of clifftop retreat are observed on low soft rock cliffs characterized by shallow soil, a thick weathered layer in relation to the cliff height, and the presence of tree vegetation cover. The higher the density of tree cover, the higher the values recorded for clifftop retreat. On the contrary, higher concentrations of shrub vegetation are associated with lower clifftop retreat values. Anthropogenic features established on clifftops do not lead to an increase

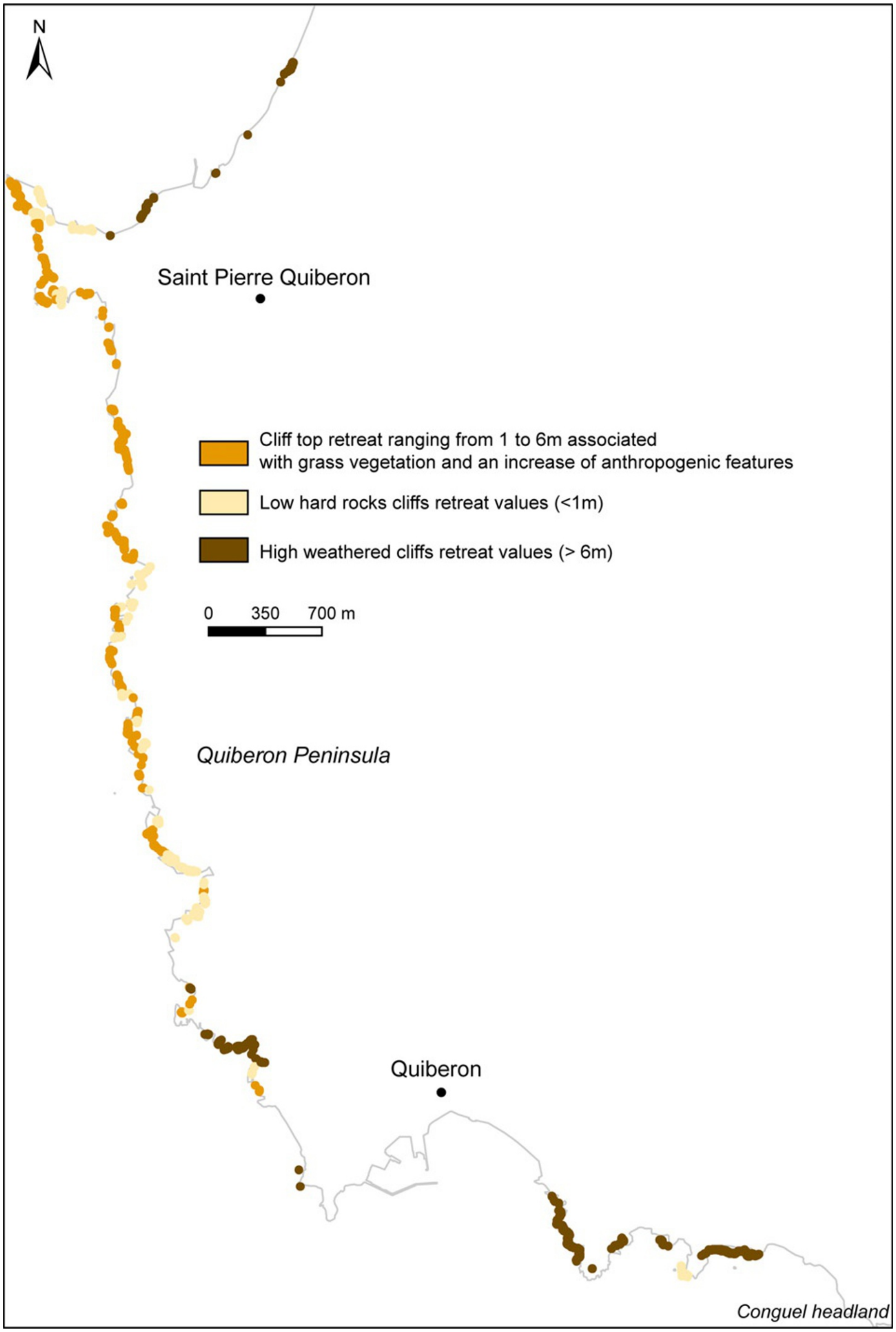

Fig. 13
Spatial distribution of clusters obtained from HCA (Quiberon Peninsula—1952/2004).

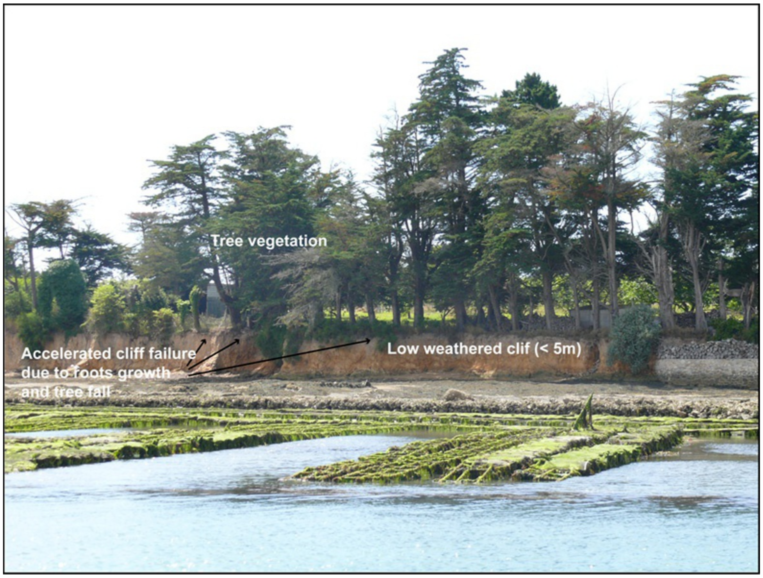

Fig. 14
Example of accelerated clifftop retreat due to growth of trees.

of clifftop retreat values. The retreat of cliffs covered by tree vegetation is accelerated by wind breakage, which is directly linked to the presence of tree vegetation on clifftops (Fig. 14). The growth of roots from trees on the clifftop contributes to destabilizing the thin soil layer and the weathered layer. Percolation is enhanced along the roots which, in turn, increases the local fracture networks and intensifies weathering. As a consequence of this destabilization and erosion of the weathered and soil layers, trees tend to be blown down while tearing up large areas of soil and weathered layers. In addition, within the Gulf, most of the coastline is occupied by private properties associated with residential use and hidden from view by numerous trees planted by the owners. In such a context, most of the trees established on the Gulf clifftop are present owing to human choice related to subjective landscape preferences and private property management practices (Roger, 1997; Salomé, 2000). Thus, the increase of clifftop retreat associated with the location of tree vegetation can be interpreted as a special form of morphological change on the coast brought about by human activities.

Along the Quiberon Peninsula coastline, spatial and statistical analyses point to the role of interactions between cliff morphology, vegetation cover, cliff exposure to wind and wave action, as well as human pressure on clifftops to account for the distribution of clifftop retreat values. Higher values of cliff retreat are associated with a high concentration of anthropogenic pressures, and especially the presence of footpaths running along clifftops. Sectors of the coastline with hard rock cliffs capped by a weathered layer are also characterized by a high density of eroded soil layers where vegetation cover is absent or composed of short vegetation cover. The exposure of the Quiberon cliffs to strong westerly winds contributes to limiting the development of vegetation and favors the establishment of short vegetation cover, providing little protection from weathering processes, and being easily disturbed by trampling. Interactions between the establishment of footpaths, trampling, and weathering have been previously discussed (Gallet and Roze, 2001). The establishment of footpaths facilitates the access to the clifftops, and thus increases trampling, which, in turn, contributes to disturbing the vegetation cover. The vegetation cover disturbance increases weathering by increasing runoff processes and favoring the formation of gullies. At the same time, trampling processes contribute to compacting the footpath soil, thus limiting infiltration while increasing runoff. It also hinders the development of the vegetation cover and, ultimately, reduces the water infiltration capacity of the clifftop (French, 2001). Water infiltration processes are thus concentrated at the borders of the footpaths, where weathering processes due to rain water action are thus focused (Van Waerbeke, 1999). In the case of the Quiberon cliffs, weathering processes are likely to be favored by natural factors, including geological and meteorological constraints. At the same time, natural clifftop weathering is likely to be enhanced by increased visiting of clifftops, especially in areas with denser footpath networks.

According to these observations, interactions between vegetation cover, the intensity of anthropogenic pressures, and cliff morphology can produce some specific combinations leading to a major local increase of weathering processes and clifftop retreat along the cliff coastline of South Brittany. Along the Gulf coastline, human-induced clifftop retreat is mainly related to the type of vegetation established on the clifftop. Where trees are planted on highly weathered low cliffs characterized by a thin soil layer, *wind breakage* leads to high values of clifftop retreat. Along the Quiberon Peninsula coastline, the evolution of the cliffs is likely to be strongly controlled by cliff morphology and exposure. Moreover, higher concentrations of footpaths and degradation of clifftop vegetation tend to favor an acceleration of clifftop retreat.

6 Conclusion

Spatial and statistical analyses allowed an overall analysis of clifftop retreat factors on a sub-regional scale. For each coastal cliff system, spatial and statistical analyses yield the same trend. Because these analyses are carried out using independent methods, the observations contribute to validating each of these approaches. The main results discussed here suggest that cliff retreat results from a combination of natural and anthropogenic factors. Human activities lead to an acceleration of clifftop retreat processes. However, such an increase could occur in at least two different ways in South Brittany: In the Gulf of Morbihan, the human impact on cliff evolution is characterized by a time lag due to the time required for tree growth. Human pressures can be related to the introduction of non-natural vegetation cover, which, in turn, lead to an intensification of subaerial processes. On the Quiberon Peninsula, human impacts due to trampling processes are associated with an acceleration of natural subaerial weathering. The approach adopted here, based on spatial data analysis, allowed us to map areas likely to be concerned by these changes, hence providing an efficient tool for coastal managers.

Acknowledgments

We thank Professor Hervé Regnauld for his valuable comments for improvement of the manuscript, Dr. M.S.N. Carpenter for linguistic corrections, and the Conseil Général of Morbihan for supporting this study.

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