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PRELIMINARY QUANTIFICATION OF THE EROSION OF SANDY-GRAVELLY CLIFFS ON THE ISLAND OF PORQUEROLLES (PROVENCE, FRANCE) THROUGH DENDROGEOMORPHOLOGY, USING EXPOSED ROOTS OF ALEPPO PINE (*PINUS HALEPENSIS* MILL.)

ABSTRACT: ROVÉRA G., LOPEZ-SAEZ J., CORONA C., STOFFEL M. & BERGER F., *Preliminary quantification of the erosion of sandy-gravelly cliffs on the island of Porquerolles (Provence, France) through dendrogeomorphology, using exposed roots of Aleppo pine (Pinus halepensis* Mill.*).* (IT ISSN 0391-9838, 2013).

This study is a first attempt to specify the geodynamic processes leading to the erosion of detrital quaternary cliffs on the island of Porquerolles, and to quantify the rate of erosion by means of dendrogeomorphology. The island is located in the Mediterranean Sea, off the coast of Provence (France). This method identifies the roots of Aleppo pine (*Pinus halepensis* Mill.) that have been unearthed by cliff retreat. The year of denudation is revealed by the net change in tracheid anatomy in tree rings, so that the retreating rates of cliffs can be established and the ratio between the distance of loosening and the number of years since denudation can be assessed. 13 root samples were used to determine that the cliff retreat is due to small rockfalls, at an average rate of 2.5 cm/a. This value is compared to other rates of erosion quantified on rocky or sandy shores. A review of the method and a comparison with methods based on photogrammetry and micrometrics are proposed.

KEY WORDS: Littoral geodynamics, Erosion rate, Mediterranean Sea, Quaternary cliff, Dendrogeomorphology, Tracheid root, Aleppo pine.

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INTRODUCTION

Coastal erosion is a phenomenon that has been studied for a long time, especially in France (*e.g.* Guilcher, 1954; Paskoff, 1993, 2004; Salomon, 2008). Although the Mediterranean coasts are little affected by rising tides, storms and associated large swells, they are significantly affected locally by erosion. The rate of coastal retreat has increased in recent decades so that expensive technical solutions are constantly being deployed to reduce this degradation. Four main factors have been identified: a reduced sediment supply from the mainland, a progressive rise in sea level, the effect of human development on the coastline, and the increasing number of tourists (Rigoni, 2003; SDAGE Rhône Méditerranée Corse, 2005; Lambert & *alii*, 2007; Tsimplis & *alii*, 2008; Brunel & Sabatier, 2009; Letetrel & *alii*, 2010; Brunel, 2012). Coastal retreat can be assessed diachronically using archive documents (*e.g.* «cadastre»), and photogrammetric or LIDAR surveys (Catalao & *alii*, 2002; Hénaff & *alii*, 2002; Costa & *alii*, 2004; Pierre & Lahousse, 2004; Pierre, 2006; Young & *alii*, 2009). For an accurate estimation of ablation at fine scales on areas of distinct lithologies, the practice of micrometrics can be applied (Stephenson & Finlayson, 2009).

In this study, we aim to assess the rates of erosion of small cliffs made of sand and gravel on the island of Porquerolles (Provence, France) by means of a dendrogeomorphological approach. This is based on the use of Aleppo pine roots located on the coastline, which have been unearthed by the progressive retreat of the cliffs. Another objective of this paper is to provide a methodological discussion as dendrogeomorphology has never been applied to quantify coastal erosion. The first results and a first assessment of the methodology are thus presented, so that a comparison can be made with the methods usually applied in this field.

LOCATION AND GEOMORPHOLOGY OF THE STUDY AREA

A few miles off the coast of Provence, the island of Porquerolles partially closes the southern part of Hyères harbour where erosion rates have already been recorded on beach sites of the Giens peninsula (Capanni, 2011; fig. 1A). The island is 7.5-km long, 1.7-km wide, and rises 135 m asl. It is a touristic island, which is partly cultivated (vineyards); afforestation affected the vegetation cover during the 20th c. (Aleppo pine, oak, cistus scrub, etc.). The Mediterranean Botanical Conservatory and the National Park of Port Cros are particularly involved in the management of the island. The description of landforms shows a contrast between the northern and southern parts of the coastline; for example, the south and southwest coasts are made up of cliffs while both the north and northwest coasts have alternating small headlands (peaks of Lequin, Prime, and Bon-Renaud) and beaches, the latter being located at the mouth of rivers draining small catchments (Notre-Dame, La Courtade). Some parts of the coastline display small cliffs made of sand and gravel, situated behind the beaches and next to the headlands. This study focused on these types of cliff, in the area of La Courtade (fig. 1B, 1C).

The geological structure of the island is very similar to that of the Maures massif (Bordet & *alii*, 1976) and is dominated by phyllite rocks (phyllite of Camaures and Sauvettes). These alternate with quartzite veins (quartzites of the Temple), the largest of which forms a ridge with a north-south aspect, extending from Cape Les Medes to Mont-Sarranier (126 m). The cliffs studied are dark ochre in colour and consist of a matrix of sand and gravel of palaeo-alluvial origin, deposited during the Würm period. These sediments were provided by the erosion of soils and rubificated regosols located in the upstream parts of watersheds (Bordet & *alii*, 1976). Sequences of erosion and accumulation occurred while the marine base level was lower than the present one by several tens of metres (Bronner, 1985). Locally, these detrital formations are adjacent to sandstone dunes (also of a Würmian age). Since the end of the glacial period, these deposits have been affected by sea erosion to form the current receding cliffs located just behind small beaches (fig. 1C); the sea-level rise is a major factor driving this trend.

The morphogenesis of the La Courtade cliffs is controlled by both the mechanical erosion of the sea (swell in particular) and subaerial processes. According to our observations, the more dramatic sequences of morphogenesis are due to the «Mistral noir» blowing from north to northwest or when the «Mistral blanc» blows abruptly (from the northwest) after many rainy days due to low pressure in the Gênes gulf area and the associated easterly winds (fig. 1B). In such cases, three factors lead to erosion and

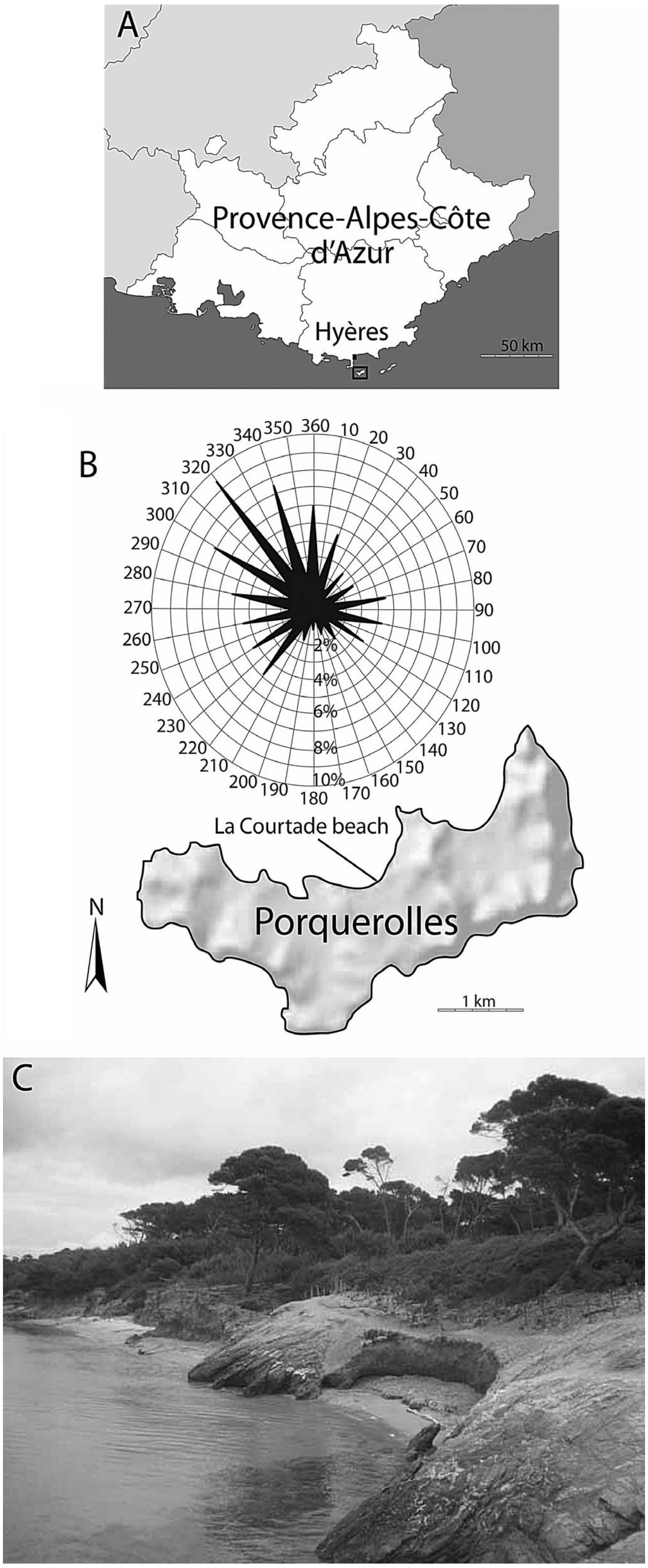

FIG. 1 - Location of the study site. A: Location of Porquerolles Island. B: Location of La Courtade beach, and wind rose frequencies (after Paquier & Meulé, 2010). C: Northern part of the beach of La Courtade. Alternation of rocky headlands (phyllite) and small beaches dominated by sandy-gravelly cliffs affected by erosion.

may act together: strong winds, storm surge, and cliff hydration. The short length of the foreshore (5-10 m) and the small height difference between the average level of the water and the bottom of the cliffs (0.5 to 1 m) allow waves and swells to impact the foot of the cliffs directly. Some notches are thus carved, characterised by a height of about 1 m and a depth of tens of decimetres (fig. 2). These sporadic episodes are complemented by rill surficial erosion throughout the year. This process is generated by the seasonal meteorological contrasts and the rhythmicity of moderately windy types of weather. For instance, small mechanical raindrop impacts (splash), alternating desiccation-hydration (hydration provided by moisture spray or wetness during rainy weather), and salt weathering in sandy layers may occur. In addition, localised hydration in the middle and lower horizons is provided by rainwater infiltration and runoff from the inland part of the cliff. Very locally, when surface runoff is concentrated enough, small gullies can grow and cut the back and front of the cliff. Trampling due to tourist traffic, especially on the back and at the base of the cliffs, may also make the cliff unstable.

FIG. 2 - Segment of a sandy-gravelly cliff. The base of the landform corresponds to a compact sandy horizon (I) recovered by torrential debris revealing angular phyllite and quartzite, centimetric to decimetric (II). The upper third is made of sand and gravel horizons, sometimes individual, sometimes overlapping (III). The retreat of the cliff is revealed by the denudation of an Aleppo pine root.

METHODS

In the past, the dendrogeomorphological approach (Alestalo, 1971; Shroder, 1980; Schweingruber, 1988, 1996) has been applied to determine the effects of the process or to quantify erosion rates on the mainland (LaMarche, 1968; Stoffel & Bollschweiller, 2008; Stoffel & *alii*, 2010). Other applications have also been developed to estimate the retreat of some estuarine shores (Bégin, 1990; Bégin & *alii*, 1991) or banks of lakes (Maleval & Astrade, 2003; Fantucci, 2007). The tree ring characteristics or the morphology of aerial tissues of trees can be studied but, during the last ten years, some authors have also examined tree roots and cellular characteristics in order to measure the ablation rate of the substratum. This method has been successfully applied to torrential erosion in mountainous areas (Gärtner & *alii*, 2001; Gärtner, 2007; Hitz & *alii*, 2008; Corona & *alii*, 2011a) and the incision of small gullies under mid-latitude temperate forests (Malik, 2008).

On Porquerolles Island, we collected the roots of five Aleppo pine trees (*Pinus halepensis* Mill.), ranging in age from 30 to 50 years, and spread over a distance of 400 m along La Courtade beach (fig. 1). A total of 17 fragments of loose roots, with a diameter of 40 to 110 mm, were sampled and provided 55 slices. Each slice constituted a reference point to measure the erosion rate. The samples were acquired in March 2012. The protocol used came largely from our experience in Haute-Provence in the measurement of erosion in marly catchments from roots of Scots pines (*Pinus sylvestris* Mill.) (Corona & *alii*, 2011b; Lopez-Saez & *alii*, 2011). However, the use of successive rings, separated by only 20 cm on root sections of different aspects, is original. Firstly, our aim was to provide more reference points and to be more precise in assessing the rate of erosion in the immediate vicinity of the root studied. Secondly, we wanted to estimate erosion rates not only at one point but, by using pairs of roots, at several points in both vertical and horizontal directions that determine some facets. In this case, we obtain an average depth lost to an accurate surface area and thus a lost volume. For this first test of the method, we used only 13 samples from two different root sections (R3 and R4), belonging to the same tree (tab. 1). Three reasons explain this strategy: (i) the se-

TABLE 1 - Characterisation of samples acquired from R3 and R4 and erosion rates assessed from the observed anatomical changes

	A	B	C	D
1				
2		**Root number**	**Distance between root and cliff (in cm)**	**Exposure year**
3		R3.1	45	1996
4		R3.2	50	1994
5		R3.3	62	1994
6		R3.4	60	1994
7		R3.5	60	1994
8		R3.6	55	1991
9		R3.7	34	1996
10		R3.8	18	1998

lected tree is set in an area mostly affected by cliff erosion; (ii) it is necessary to test the method at a very fine scale (a few square metres of cliff) before performing a spatial approach on a large coastline with many more trees; (iii) our investigation focused on the relevance of the information provided by the aspect of the root relative to the plane that the eroded surface forms. Concerning the third reason, the root sections R3 and R4 correspond to two fragments characterised by a large radius of curvature whose chord is in the same plane as the cliff. In relation to this plane, R3 is oriented vertically (1.6 m-long), while R4 has a sub-horizontal aspect (1.2 m-long), and is laterally shifted (offset by 1 m) in the upper half of the cliff. Finally, the combination of both vertical and sub-horizontal planes enables the survey of a rectangular facet of 6 m^2.

The erosion rate of the substratum in a specific area is the ratio of the distance, between the root and the ground, with the number of years since the root became unearthed (Corona & *alii*, 2011a). This distance is measured by a micrometric gauge (accuracy ±1 mm) or a metal ruler (accuracy ±5 mm) for distances greater than 25 cm. In the case of a cliff, the distance is measured perpendicular to the face and includes the root diameter. The thickness of wood grown since the denudation event is also included (for methodological details, see Corona & *alii*, 2011b). The year of denudation is determined by a change in the cellular structure inside the tree root ring (Gärtner & *alii*, 2001; Gärtner, 2007). After the denudation event, the surface area of wood cells decreases by an order of magnitude of 60% (fig. 3A; Corona & *alii*, 2011b). This trend is accompanied by lignification of the cell membrane. To ascertain the year of anatomical change, the average area of 10 early wood cells was measured in each of the rings of the sample, using the software Wincell Pro 2009 (fig. 3B).

RESULTS AND DISCUSSION

Reconstitution of stages and rates of cliff retreat

On Porquerolles Island, the anatomical change corresponds exactly to the year in which the root section appeared in an aerial environment. A denudation chronology of root sections and the rate of cliff recession can thus be established. The anatomical change in cells was checked several times by comparing, in the same root, the anatomical structure of the bare portion immediately next to the cliff with a portion buried a few millimetres into the cliff. The hypogeal (underground) part remains characterised by a structure with large cells (tracheids) while the epigeal (aboveground) part displays reduced-surface tracheids, with thick and lignified membranes. This anatomical change appears abruptly as soon as the portion emerges into an aerial environment; it is more sudden than what we observed in the Southern Alps (Draix). In the latter area, the reduction in the surface of the tracheid begins while the roots are still located a few centimetres under the ground surface (Corona & *alii*, 2011b). This early decrease can be explained by the different climatic conditions between Porquerolles Island and Draix (located at 800 m asl), including the absence of frost in the ground on the Mediterranean coast. In fact, frost could be a stimulating factor impacting the root structure a few years before it emerges into an aerial environment. Furthermore, on Porquerolles Island, cellular metamorphosis reveals that the sporadic processes of erosion are causing most of the impacts, while in the marly badlands of the Draix area, continuous and regular erosion processes such as rill-wash are having an effect (with a rate from 5 mm to 1 cm/a; Rovera & Robert, 2005).

In the present study, erosion rates from the dendrogeomorphological analysis are given in tab. 1. For the root section R3, the first exposure event occurred 21 years ago (1991), at R3.6. For root R4, the section is younger than R3 and loosening began in 2003, at R4.3. These results can provide a chronological framework of the evolution of the cliff with an accuracy of 1 year. Since 1991, the evolution at root R3 has occurred in three stages. The first step corresponds to the event when the root started to become bare, in 1991. A top notch, initiated at R3.6, is evidenced by the anatomical change observed in this section, set in fine sand strata. The rest of the root remained buried because no significant variation in the cell surface is observed in other sections (fig. 3B). The second stage occurred in 1994 and corresponds to a marked retreat; the anatomical changes are observed in sections R 3.2 to R 3.5. This pattern is interpreted as the impact of a small landslide, which was favoured by the notch (see above) in the weak sandy strata. The third stage has occurred since 1995 and corresponds to a slow evolution of the upper part of the profile (in agreement with the presence of a resistant gravel horizon) and also of the lower part of the profile, at R3.7 and R3.8 sections. At the foot of the cliff, ablation and accumulation alternates; debris accumulation provided by the cliff constitutes a thin protective embankment whose excavation occurs periodically due to natural geomorphic processes or pedestrians. For the R4 root, at the top of the cliff, several steps can be distinguished. A first loosening occurred in 2003 in the centre of the root (R4.3). Then loosening increased laterally from 2004 to 2006, recording the highest values towards the area where root R3 is positioned. This shows that the changing profile of the cliff, initiated during the 90s at R3, impacted the R4 area (in a more lateral position) 10 years later.

Although erosion remains sporadic, we decided to assess the average annual ablation rates in order to compare our results with the values provided by other authors. Nevertheless, the rate of retreat of the cliff at R3 excludes the situation in 1991 (R3.6) described above and we consider here that the root was in an aerial environment (bare section almost 1-m high) in 1994 (R3.2 to R3.5). We thus obtain a value of 59 cm over 23 years, indicating a rate of 2.6 cm/a (maximum speed of 3.4 cm/a and a minimum of 2.1 cm/a). Concerning the cliff at root R4, during the period 2003-2012, the denudation was about 19 cm, so that a rate of 2.2 cm/a can be assessed, a value that remains close to that estimated from R3.

A comparison with the rates established for similar cliffs and physical settings (coastal parameters, materials,

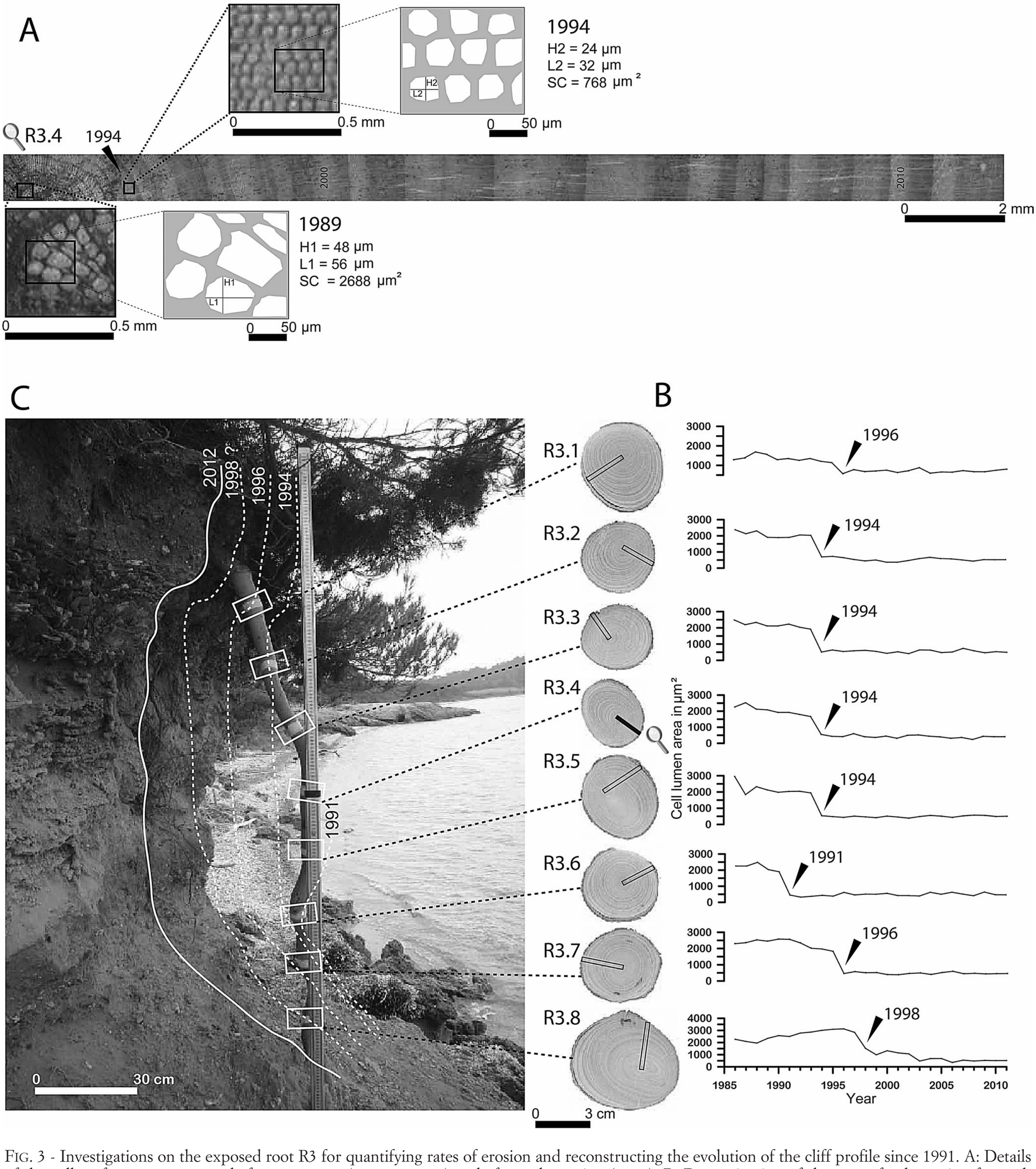

FIG. 3 - Investigations on the exposed root R3 for quantifying rates of erosion and reconstructing the evolution of the cliff profile since 1991. A: Details of the cell surface measurement before exposure (1989 to 1993) and after exhumation (1994). B: Determination of the year of exhumation for each section. C: Evolution of the cliff profile in relation to the position of the investigated root section.

etc.) is not easy and, except for one value recorded on Hyères harbour beaches, we only propose for this preliminary study a few rates depending on the morphoclimatic context, lithology and type of coastline (ocean or lake), different enough from those of the Mediterranean Sea. The estimated value on Porquerolles is much lower than those for high chalk or limestone cliffs, like those of the Algarve region where a rate of 17 cm/a was assessed (Catalao & *alii*, 2002) or the Pays-de-Caux area, where a rate of 14 cm/a was assessed (Hénaff & *alii*, 2002). Our estimations are close to the lowest rates measured for some sedimentary cliffs in California (7 cm/a; Moore & Griggs, 2002), or in Boulogne with 4 cm/a in Fond-du-Guet, in the northern part of cape Blanc-Nez (Lahousse & Pierre, 2002). They are also close to the rates measured in detrital formations (moraine) on the border of Ontario Lake (1 to 3.5 cm/a, according to Davidson-Arnott, quoted by Stephenson & Finlayson, 2009). Finally, in Hyères harbour, average erosion rates of 60 cm/a (1990-2003) were recorded on the sandy segments of the Giens peninsula (La Capte), affected by significant port facilities and development (Capanni, 2011). These are 25 times higher than our estimations acquired on the small sandy-gravelly cliffs of Porquerolles Island (over an equivalent period).

A first assessment of the method

Applied to coastal dynamics, dendrogeomorphology exhibits both strengths and limitations. In this study, an initial assessment of the methodology is proposed.

The limitations are easily identifiable as the method needs a sufficient number of loosened trees and roots (2 or 3 roots per tree, 5 to 10 trees). Here, the study was carried out at a very fine scale and the calculation of erosion rates was evaluated for only two or three decades. We can also highlight that the sampling protocol is difficult to apply in the field and that data processing requires a specific laboratory and the destruction of samples.

The benefits of this method are, however, undeniable. In the case of border trees affected by loosened roots, and about thirty years of age (or more), we can measure annual erosion rates with an accuracy of about 1 cm. The initial conditions can be found in several segments of the Provence coast, affected by sub-spontaneous afforestation since the second half of the 20th c., so that our investigations could be applied over a wider area. As the root system of a single tree enables the study of 5 to 10 m^2 of a cliff, a dozen well distributed trees will enable the estimation of erosion along a coastline segment of *ca*. 1 km. From our observations, it is possible to reconstruct the evolution of not only detrital cliffs, whose height can reach about 10 m, but also sandy or swampy coasts if woodlands are present.

This preliminary study may refine future sampling protocols. Reconstructions will be more accurate if the samples are acquired carefully: a slice acquired every 10 cm on the same root should provide annual sequences. The study also reveals that for a cliff, sub-horizontal root (R4) or oblique sections (R3.1 to R3.2 stretch) are the most interesting to establish an annual sequence. Furthermore, the vertical sections (R3.3 to R3.8) can complement the data, if the root appeared in a sub-aerial environment during a single year, or to identify two years (or more) of denudation if cliff erosion is triggered by a basal notch that gradually enlarges. Such detailed patterns reconstructing the yearly evolution of cliff profiles will enable the comparison of the rate of geomorphic processes with some hydrodynamic and climatic events that have affected the major study area.

Compared to photogrammetry and micrometrics, the dendrogeomorphological approach appears to be an intermediate method that can complement the others. Its accuracy is about one centimetre, while that of photogrammetry is many decimetres. On the contrary, photogrammetry can cover a wider coastline and a sequence of many decades. Conversely, micrometrics can provide sub-millimetric accuracy but only over a very short timescale, perhaps for a few years only. Furthermore, micrometrics involves the installation of an instrumental device in the field. In the future, it would be interesting to couple dendrogeomorphology with at least one of the other two methods to ensure the significance of the recession rates obtained, and to perform a calibration.

CONCLUSION

By means of exposed roots, simple indicators investigated *in situ*, we can characterise the evolution of small sandy to pebbly cliffs: their morphogenesis is sporadic, and occurs through the action of small landslides at an average rate of erosion of a few centimetres per year. Although the «dendrological potential» of a coastline has been achieved on Porquerolles Island, the erosion rate can be mapped and surveyed along the entire perimeter of Hyères bay, based on several measurement points investigated at regular intervals (every 5 to 10 years). By practicing an optimal sampling that preserves the life of trees (2-3 bare roots per individual), this approach could survey erosion for many decades in the future, as the stock of trees and bare roots will probably increase in the near future and will be renewed (unless, of course, there is an accident or a modification of management policies of the coastal landscape).

It should also be noted that coastal erosion is of great concern; it involves planning and policy-makers because it threatens many homes and infrastructures locally, as well as the natural heritage and touristic activities of many municipalities.

Thus, in the context of a possible worsening of coastal erosion along the Mediterranean shoreline, many small beaches and cliffs carved into Quaternary deposits could become control sites and be integrated into a survey network. The *Conservatoire du Littoral*, some natural parks, universities and many environmental services could be involved in such a network.

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