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Biological reef survey using spot satellite data classification by cellular automata method - Bay of Mont Saint-Michel (France)

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Abstract

A reef called “Les Hermelles” occurs in the intertidal zone of the Bay of Mont Saint-Michel (Normandy, France). The reef is composed of the sea-worm *Sabellaria alveolata* and thus, is one of the northernmost biological reefs in the world. To map Les Hermelles in the field is difficult because of its great distance from the coastline and its brief exposure to the air. Consequently, the last map dates back to 1980. In 1984, mussel farms were developed around the reef. Since then, they are often regarded as the factor responsible for the perceived decline of the reef. The main goal of the study was to assess the possibility of mapping Les Hermelles using satellite imagery and if so, to give a rough idea about its recent evolution since the 1980 map. A multi-spectral SPOT image satellite was used for the tests. Areas of reef, sand, silt, mud and sea-water show similar spectral signatures. Moreover, these environments are often mixed within a single pixel. Consequently visual interpretation and the usual classification approaches failed, showing inter-class confusion. A new classification based on cellular automata appears to be promising. Applied to the example of Les Hermelles, this method was successful and showed a certain stability of the reef dynamic tendencies since 1980. Although the preliminary results have to be securely based on field data acquired close to the satellite-image date, they already confirm the key role that sandbars play in the reef dynamics whereas the role of the mussel farms remains unclear if not null. The classification by cellular automata presents the advantage that no supervision is required, and that spectral and geographical information are both used together.

Keywords: Cellular automata; Remote sensing; Mapping; Intertidal zone; Biological reef

1. Introduction

The epicontinental shelves such as the English Channel show exceptional tidal amplitudes, often exceeding 10 m. The presence of the Cotentin peninsula (Normandy, France) increases the tidal amplitude within the Bay of Mont Saint-Michel, where the tidal range is particularly high, up to 15 m (Fig. 1). A reef of the sea worm *Sabellaria alveolata*, known as “Les Hermelles”, occurs in the central part of the bay within the mediotidal zone (i.e. it does not emerges at every low tide.) Les Hermelles reef emerges at low tide only if the tide coefficient is greater than 70. The reef is one of the northernmost biological reefs in the world. To map it in the field is difficult because the period of exposure to air is short and it is far from the coastline (from 3 km to its closest part up to 5.5 km.) Consequently the last map that was made in the field dates back to 1980 (Legendre, 1980). In 1984, mussel farms were developed around the reef. Since the reef is highly sensitive to the sea current and the sedimentary conditions, mussel farms are often

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suspected to be the factor responsible for the perceived decline of the reef. Considering the difficulty and high-cost of field mapping, the main objective of this study was to assess the feasibility of mapping Les Hermelles using satellite imagery, and to give a general idea about its recent evolution. This paper presents the application of an original classification method using SPOT satellite data and the first results for the general reef evolution since the 1980 map.

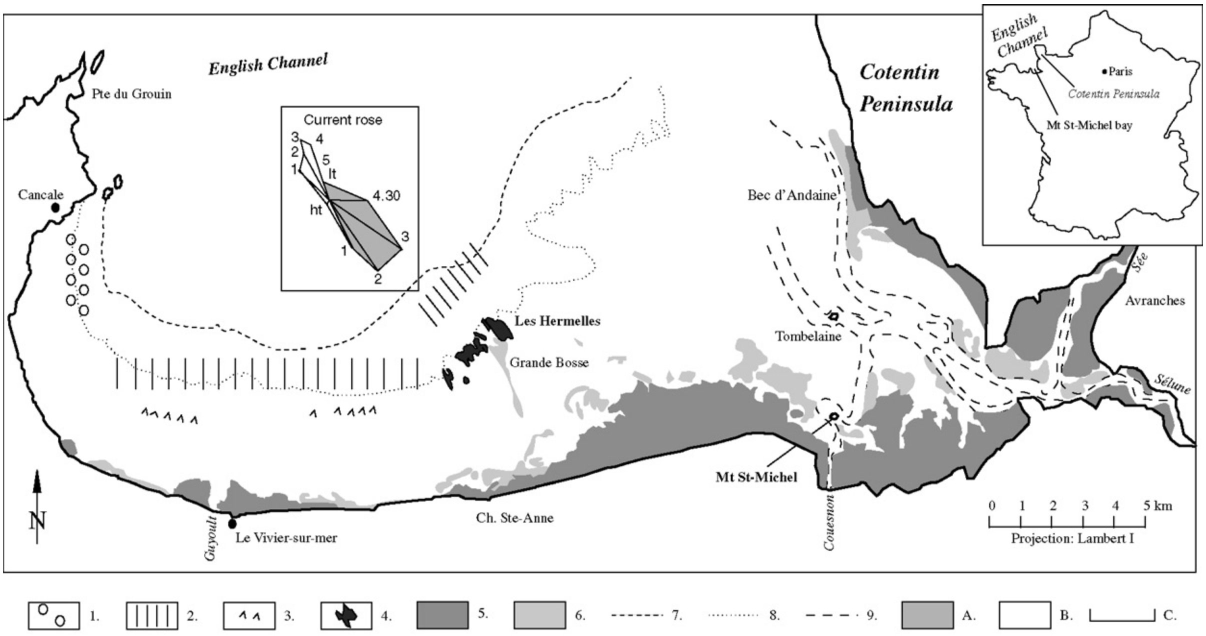
Les Hermelles

Sabellaria alveolata is a polychaete annelid which is 2–5 cm long, sedentary (living in a cemented tube) and gregarious (from 15,000 to 60,000 worms/m^2). This, worm species catches food and mineral microparticules in the turbid sea-water using filaments in its mouth. Thus, its mouth plays a sorting role, rejecting some particles, conveying others whether as food or as material to build the living tube. The constructor organ cements the received sand grains with a phosphorous, calcium, magnesium and manganese compound, and places this material on the top of the living tube that increases in height (Gruet, 1982; Wilson, 1971).

The *Sabellaria alveolata* lives for 4–5 years and its sexual reproduction occurs from the end of its first year until its death. The development of the planktonic larvae lasts for 1.5–3 months before turning into worms. Many of them die during this period, or shortly after, if they do not find a suitable location to inhabit. The larvae loss is balanced by reproduction throughout the year and the large number of oocytes generated by each worm, around 350,000 per year. The new population needs a rigid substratum in which to settle, for example, rocks, pebbles, shells or ideally, an already established *Sabellaria alveolata* settlement.

Therefore, a *Sabellaria alveolata* reef may increase in mass, or decrease if recruitment to the worm population is reduced for a few years. Reef development is vertical as well as horizontal by concretion. The latter situation can also occur when a block of the reef falls apart and moves away where it becomes a new reef unit on which the new worm generation can settle. The tidal stream primarily controls a *Sabellaria alveolata* reef orientation. The more bi-directional the water mass flows, the more likely the reef is to be elongated in a mass flow perpendicular orientation. In the same way, the less bi-directional the water mass flow, the more round is the shape of the reef.

Les Hermelles on the low central tidal flat of the Bay of Mont Saint-Michel is a *Sabellaria alveolata* reef that appeared during the 18th century on an oyster shell accumulation in the ancient river bed of the Couesnon



1. Oysters farms - 2. Mussel beds - 3. Fisheries - 4. Hermelles reef - 5. Salt marshes - 6. High flat sands - 7. 0m isobath (French Marine Map) - 8. Limit of the sea on the SPOT HRV-XS image used (acquisition: 15th January 1995, 37 min before low tide, tide coefficient 70) - 9. Channels on this satellite data
Current rose: coefficient of tide: 72, at 2.5m from the sea bed, the figures show the time left before and after the high tide (ht) (measurments in 1953 by EDF -SEDM)
A. Floodtide - B. Ebb tide - C. Scale: 1 knot

Fig. 1. Bay of Mont Saint-Michel as seen 15th January 1995.

Fig. 2. Hermelles reef.

that changed its route around 1780 (Larsonneur, 1989). Nowadays, the reef is not continuous but it spreads in 1 m high "shrubs" orientated NNE-SSW perpendicular to the currents, over 90 ha (Figs. 1 and 2). The zones free of this worm within the reef boundary are inhabited by many animal species including the barnacle *Balanus crenatus*, the mussel *Mytilus edulis*, and crabs *Macropipus puber*, *Carcinus maenas* and *Porcellana platycheles*. On French marine maps, the reef bottom lies from about 2.50 m at the northeastern part to 4.50 m towards the southwest. Thus, as the *Sabellaria alveolata* shrubs are 1 m tall, the reef top lies at 3.50–5.50 m.

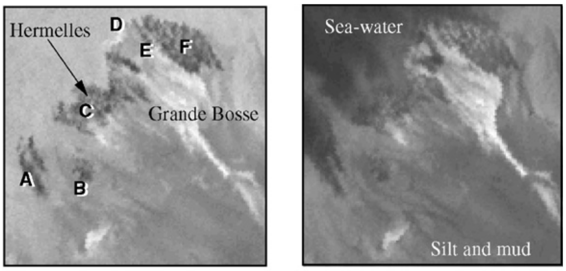
The turbidity of the Bay of Mont Saint-Michel is high, from 10 to 50 mg/l at high tide, and the reef acts as a huge water filter and breakwater (Caline et al., 1988). It is associated with a bank of shell sand called "La Grande Bosse" which grows in sheltered positions behind the reef. La Grande Bosse has its own dynamics it appears on the western part of the reef, increases and moves eastward and coastward. Finally, it splits from the reef and moves coastward, while another shell bar appears on the western part of the reef.

The evolution of "Les Hermelles" has been studied from 1947 to 1980 by aerial photography and by topographic fieldwork (Legendre, 1980; Le Rhun, 1982; Caline et al., 1988). From 1947 to 1980, the eastern units were the most stable while the western ones were unstable. This was probably due to wandering channels responsible for general instability. Meanwhile, the central parts had extended to become contiguous and formed two units. Important mussel farms were developed around the reef over this period but especially later, in 1984, when huge mussel beds appeared on the reef's north side. Mussels are also filter feeders and so could compete against *Salbellaria alveolata.* Moreover, those installations slow down the currents and are often considered as the cause of mud deposition.

Since 1980 the reef has not been mapped and thus, its evolution has not been assessed since that time. However, the local population perceives a decline of the reef and looks at mussel farms as the factor responsible for this decline. The study brings into focus the hypothesis that the tendencies described for 1947–1980 are still going on, or the alternative hypothesis that the tendencies have changed since 1980 especially considering the presence of mussel beds.

2. Methods

Satellite scenes cover several thousands of square kilometres and their geometric distortions can be easily corrected. The HRV-XS sensor of the SPOT-3 satellite operates in three different spectral bands: Green (XS1 [0.50; 0.59] μm), Red (X*S*2 [0.61; 0.68] μm) and near-infrared (XS3 [0.79; 0.89] μm). The spatial resolution of this sensor is 20 m × 20 m and so, it is adequate for a general cartographic approach. Although, the same satellite in panchromatic mode (HRV-P) provides better spatial resolution (10 m × 10 m) with just one single band ([0.51; 0.73] μm), such an image was not available. We used here a SPOT HRV-XS image recorded on 15 January 1995, 37 min before low tide while the tide coefficient was 70. Thus, the sea limit occurred at about 4 m deep (Fig. 1). Fig. 3 shows Les Hermelles extracted from the whole raw satellite data in visible (XS1) and



HRV-XS1 band *HRV-XS3 band*

Scale of each subpicture: 140 x 140 pixels eq. 2800 x 2800 m
The features A-F are the reef unit names and are discussed in the text

Fig. 3. Hermelles reef from SPOT raw data.

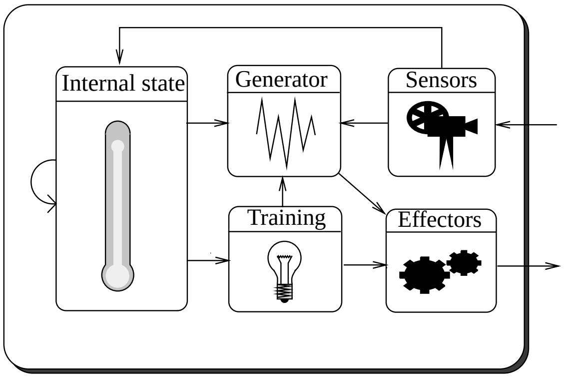


Fig. 4. Agent internal structure.

near-infrared (XS3). Unfortunately, on the picture the sea still hides the deepest parts of the reef. For instance, unit D remains completely immersed. However, the shell sand "La Grande Bosse" and most of the reef units are readily visible. This handicap reveals the first great difficulty in Normandy that is to get altogether at the same time, high tide coefficient, low tide, cloud-free sky and satellite pass time. This satellite image was still the best we could use and therefore was selected to test the new mapping approach.

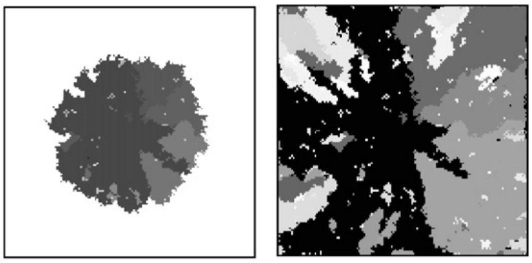
The choice of visual interpretation was rejected because although the emerged reef is readily visible on the SPOT picture, its boundaries are not obvious to delimit and this approach is subjective. Some popular classification methods, either unsupervised ones such as clustering algorithms, or supervised ones such as the maximum likelihood algorithm, were applied. These methods that are based on spectral signatures, led to significant confusion between the biological reef, sand, silt, mud and turbid water classes. Confusion occurs because the spectral signatures of these landscape elements are similar to one another, and because the classes are never pure: some silt always covers the reef, sea-water has a high sediment content and, mud and silt on the tidal flat remain soaked. In addition, considering the pixel size ($20\,\text{m} \times 20\,\text{m}$), a pixel may include the turbid sea-water, the wet sediment and patches of reef, and so be a mixed pixel (Marchand, 1997; Lhomer and Minoux, 1987). Thus, in this application spectral signatures are not enough for satisfactory classification.

Instead, we used a genetic algorithm, based on Artificial Life concepts for this purpose (Cazoulat and Victorri, 1994a; Cazoulat, 1996; Goldberg, 1989). This approach allows the SPOT data to be analysed in both spectral and topological terms. The consideration of a spatial neighbourhood conceptually maintains continuity of structure in the form of edge and contiguity (Walsworth and King, 1999). The main advantage of the method is that neither spectral nor spatial supervision nor the number of the final categories, are required. The method is based on cellular automata, agents that will progressively spread over their "land", which is the satellite image itself. They classify the SPOT HRV-XS image, as they will create their own social system with different agent groups having their own integrity. Each agent group composes a final class, or region, on the classification result.

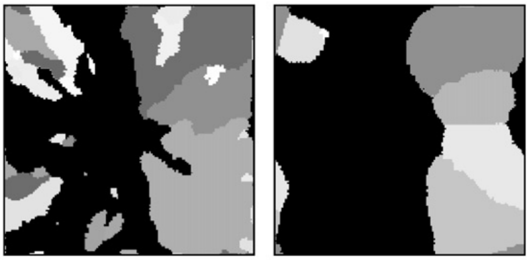
An agent is an autonomous entity that possesses a certain perception of its environment via an internal structure. The agent structure includes an internal state, sensors, effectors and an adaptation mechanism (Fig. 4). The sensors inform the agent about the environment. Meanwhile, the effectors act by reproduction, death, or moving. The adaptation mechanism links the perception from the first ones and the possible actions of the latter in a sensory motor loop. The agent organisation binds its structure and its environment by rules that lead to the emergence of the dynamics and social system (Axerold and Hamilton, 1981; Cazoulat and Victorri, 1994b).

The algorithm presents three phases: initialisation, expansion and erosion. For initialisation, the user puts the first agent (germ) anywhere on the land. All the agents will be descended from this germ and will receive the same internal structure including a region number and a reference value. The region number identifies the agent group. At this first step, the germ's region number is initialised with the number 1. The reference value is a digital number (DN) of the SPOT-XS pixel and its possible range is from 0 to 255. The germ's reference value is initialised with the current value of the pixel where it is put.

During the expansion phase, each agent, starting from the germ, regularly chooses at random one of its eight neighbour pixels. If this pixel is not yet inhabited, the agent duplicates itself on it. The new agent is either a clone or a mutant. A clone inherits its region number and reference value from its parent. A mutant is initialised as a germ for a new group. Therefore, it receives a new region number and its reference value is initialised with the DN of its current pixel on which it



(A) From the first mutant agents to the spread over the space



(B) From small population agent extinctions to uniformity

Fig. 5. Result of expansion phase (A) and erosion phase (B).

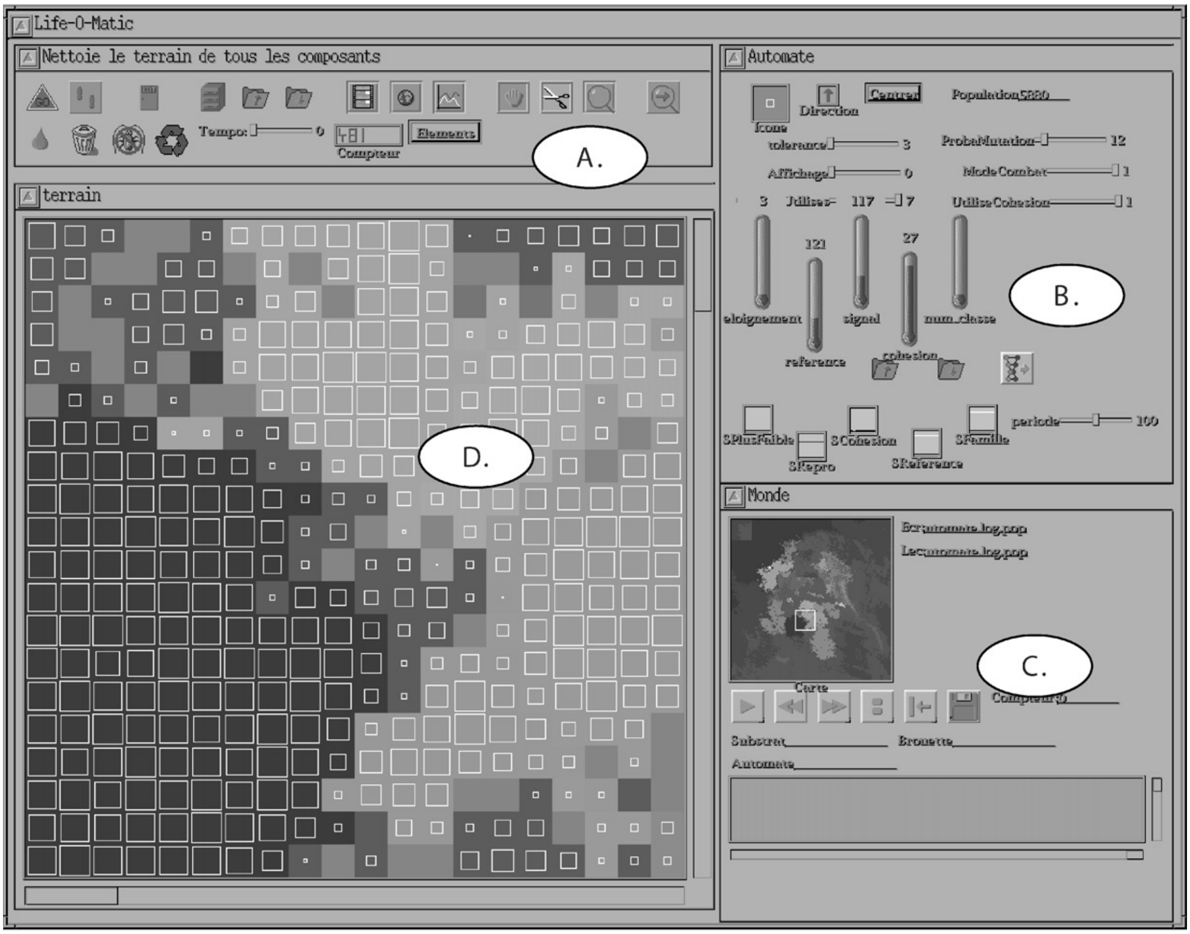
occurs within the SPOT image. At the end of this expansion step, the landscape is filled up with agents (Fig. 5a).

When just alive, the first action of the new agent is to calculate an Euclidean distance between its reference value and the DN of its current pixel on which it appears. Of course, this distance would be drawn for a mutant considering its initialisation. The distance is then compared to a threshold that is a tolerance. Unless the distance is smaller than this threshold, the new agent will die. Thus, this threshold defines the living domain of the agent. The user sets it through the graphic interface at the beginning of the process, but it can be changed during processing.

At the outset each agent region is a class that is geographically and spectrally constrained, like it would be if the conventional region-growing method were used. The region-growing method is offered as a tool in some software (e.g. Erdas Imagine): from one pixel selected by the user, the region grows incorporating those neighbouring pixels that are spectrally similar. Both methods present the great advantage of considering the geographical and spectral aspects within the classification process, in contrast to other supervised and unsupervised classification methods that are based only on spectral dimension (e.g. clustering, maximum likelihood methods). A major argument in support of the agent classification approach compared with the region-growing one is that it is able to build more than one region from the starting point. The other regions appear through the mutation process. The mutation rate as the threshold defining the agents' domain of life, is given at the beginning of the process but can be changed during processing. The mutation process introduces diversity without knowing a prior the number of classes or the class distributions over the SPOT image. This is probably the main argument in support of the method. The disadvantage of the method is, however, that some useless regions may be created, even when the picture is uniform (Fig. 5a).

The erosion phase arises at the last step, when agents have filled the SPOT image. It aims to erase small and useless regions. It should also be noted that the agent's internal structure includes a group cohesion variable. This component of the agent considers the size of the group and the fraction of the eight neighbours that belong to the same group. The bigger the region, the greater is the agent's group cohesion. Also, the more neighbours belong to the same group, the better is the agent's group cohesion. Thus, considering a group of agents occupying a region cohesion is highest at the centre of the region and lowest at the boundaries.

Iteratively, each agent repeatedly chooses at random one of its eight neighbour pixels and tries to duplicate itself, this continues until no pixel is free anymore. If an agent of the same group already occupies the chosen pixel then, the attempt to duplicate is over. Otherwise, a fight starts between the agent that tries to duplicate itself, (the attacker) and the agent of a different group that occupies the chosen pixel. Thus, the regions' boundaries are not only where the group cohesion values are the lowest, but they are also the conflict zones. An Euclidean distance is calculated for both agents, between their reference value and the chosen pixel DN. However, the inverse of each agent's group cohesion value weights this distance. Thus, high values of group cohesion reduce the effective distance, and the smaller it is the better. If the attacker does not have the smallest distance, it dies. Otherwise, the attacked agent dies and the attacker duplicates itself putting on the pixel either a clone or mutant. An important aspect of creating a clone is to increase the cohesion value of every single agent of the group and thus, the cohesion of the whole group. This weighting implies a social benefit of being in a group. The individual entities of the group get more powerful as the group cohesion increases and vice versa. Thus, the erosion phase tends to eliminate small regions unless they have a well-identified spectral signature (Fig. 5b). Meanwhile, the biggest regions increase in size up to the point at which this is no longer possible, considering the difference between their spectral signature and the DN of the surrounding pixels. Then, the number and the spatial distribution of the regions become stable improving the stability of the whole system during this erosion phase (Dawkins, 1980; Lindgren and Nordahl, 1991; Nowak, 1993). Finally, the classification is complete when the classification is stable, and less than 5% of pixels change from one agent



Clockwise quadrant from top left: A. Global control panel for the process (run, stop, break, save...) - B. Control panel for the selected agent and its environment (region, reference and current values...) - C. Global land display panel in real time - D. Zoom to select an agent

Fig. 6. User interface simulation platform.

group to another in one iteration. Those changing pixels are located at the region boundaries where the group cohesion values are the poorest and the fights continue.

The classification is displayed in real time on a user interface termed the platform (Fig. 6). This platform was created first to visualise experimentations and simulations that were conducted about population evolution (Bura et al., 1994; Cazoulat, 1996). This user interface is a control panel used for general purposes such as running or stopping the process, saving the result and changing some global parameters (number of channels used, tolerance threshold, mutation rate), and also for monitoring the internal structure of an agent. Only band XS1 was used although a multispectral classification is possible. Bands XS1 and XS2 show an important correlation ($r > 0.75$) and the high water absorption in the near infrared spectra induces no improvement by using band XS3 (Fig. 3). The classification of XS1 was conducted through the user interface in three steps. First, the mutation probability and the tolerance threshold were set respectively at $0^0/_{00}$ and $100^0/_{00}$. This step led to only one agent group covering the whole-image and resulted in its average spectral value. Second, the mutation probability was set at $1^0/_{00}$ while the tolerance was brought down to 3. During this step, many agents of the first and unique group died because their reference value was too far from the DN of their current pixel. Simultaneously, new agent groups had emerged. Third, the mutation probability remained at $1^0/_{00}$ while the tolerance was raised to 10. This step was the shortest and had no other goal than to fill the conflict zones prior to saving the result in a file.

The interpretation of the different regions in the result is similar to that of an unsupervised classification (e.g.

Scale of each subpicture: 140 x 140 pixels eq. 2800 x 2800 m. A. SPOT HRV-XS1 raw band - B. Sabellaria alveolata patches (in black) and sand bars (in grey), two types of agent regions after the agent segmentation and its interpretation - C. Limits of the Hermelles reef (in white) and sand bars (in black) that correspond to the minimum cohesion lines of the agent regions, superimposed to XS1 raw band.
The reef units (A-F) are discussed in "Initial results concerning the reef dynamic"

Fig. 7. Result of agent population classification.

clustering). The user bases his interpretation of the newly classified SPOT HRV-XS image, on his field knowledge, the spectral signature of the agent groups and their spatial distribution. As sand influences reef development, the two groups "*Sabellaria alveolata*" and "Sand" were both retained for the final representation (Fig. 7).

3. Initial results concerning the reef dynamic

A qualitative comparison between the 1980 map and the cellular automata classification of SPOT-XS1 image of 1995 leads to some comments about the reef dynamics (Fig. 8). At this stage, the differences between the two superimposed maps are assumed to be related to mostly either the sea-water mask on the deeper parts of the reef, or the evolution of the reef that is closely connected with the sand bars. However, the results are preliminary, giving only general tendencies for the different units of the reef. Unit A was described in 1980 as previously exposed to some anthropogenic degradation as it was a fishing zone (Legendre, 1980). Between 1980 and 1995, unit A showed recovery and even expansion mainly along its north side. Meanwhile, the attached sand bars along its south side had moved towards the coastline. Unit B is the oldest part of the reef and occurs at the highest position on the tidal flat (+4.50 m). The sedimentation process has consequently filled-up the bay of Mont Saint-Michel, so this present high position implies a long daily exposed period for the worm *Sabellaria alveolata*. The shape of this map unit was described in 1980 as having deteriorated, with scattered and damaged *Sabellaria alveolata* shrubs. The initial results of the SPOT classification show firstly that the whole unit B continued to decline. Secondly, parcel B_3 that had likely fallen off, continued to be carried along by the currents towards the upper flat. This patch may disappear in future because of a long exposure to air. Unit C was not in good conditions in 1980: C_1 was sanded up in its central part and C_2 was just recovering from a mussel invasion. During the 1980–1995 period, the shell sand bar La Grande Bosse progressed from west to east, towards unit F and its extremity split and moved south, towards the coastline. Meanwhile a new shell sand bar was growing behind the southwestern part of unit C_1. This evolution of La Grande Bosse is well known and has often been described (Larsonneur, 1989; Legendre, 1980). Consequently, the unit expanded where it became free of sand and regressed where the new shell sand accumulation occurred (Fig. 8). Unit C balance seems positive taking into account that an assessment would be underestimated due to the fact that the sea covered at least the northern part of unit C_2. Unit E decreased considerably due to complete sinking into the sand of unit E_2 although, the area of E_1 is likely underestimated due to the presence of the sea. Unit D as well as the more distant units G and H, could not be mapped as they were in the sea-water column at the time when the SPOT satellite recorded the data. Therefore, the corresponding pixels of the satellite image were associated with a sea region in the agent classification results. Unit F is a remarkably perfect and large tabular piece of *Sabellaria alveolata*, which is seldom observed. It was described in 1980 as the most stable part of the reef since 1947. Unfortunately, its northern fringe was immersed during the the SPOT-image acquisition in 1995. The map of the emerged part reveals again its good stability in 1995, and even an increase at its SW extremity.

4. Method discussion and conclusion

With respect to classification accuracy, Mumby et al. (1997) questioned "…whether an accuracy of (say) 40%

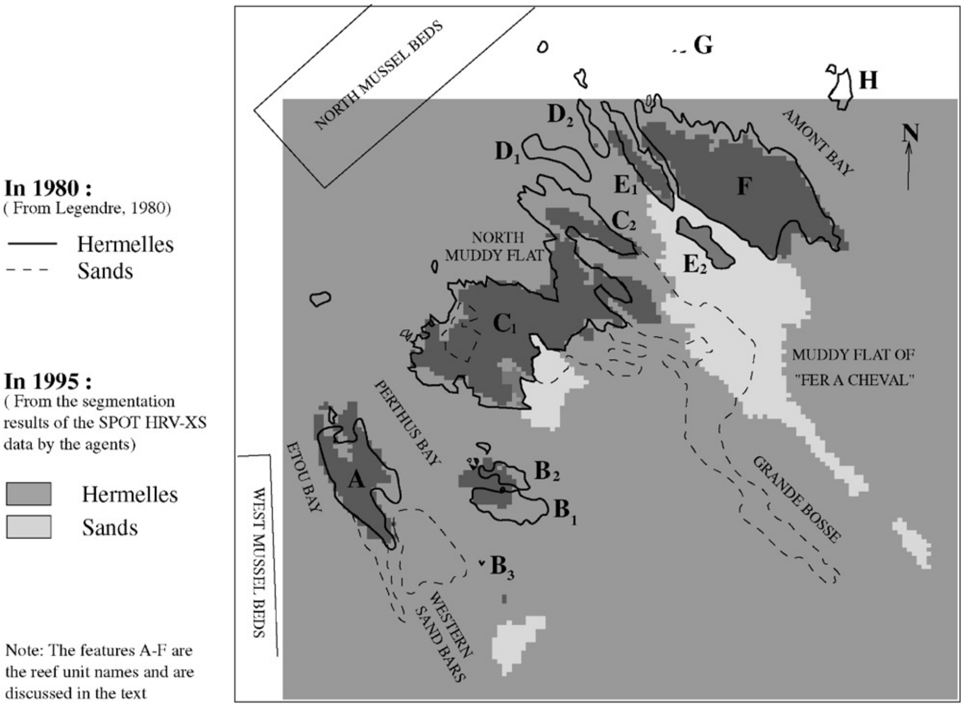


Fig. 8. Evolution of reef between 1980 and 1995.

is worthwhile when the alternative is no mapped information at all?" The key issue of method assessment arises from this remark. Overall accuracy corresponds to "the sum of correctly labelled test sites divided by the total number of test sites" (Green et al., 1998). Thus, in order to assess the accuracy of a Satellite image method, field data collected as close as possible to the satellite-acquisition day are needed.

In our study, the accuracy could not be assessed because of the lack of field data close to the date of SPOT image-acquisition, and thus it is more a qualitative evaluation of the results based on field knowledge, the 1980 map and old air photographs. There is no significant difference in spectral signatures between reef and sediment or sea as there often is between vegetation and water within mangrove, for example. Visual interpretation was tried by the author and it interpretation failed at the first attempt. The spectral-based classifications show such great confusion between the different expected classes in our study that no qualitative comparison with the 1980 map was possible. The cellular automata method has shown some promise and may outperform spectral-based clustering; at least it allowed a qualitative comparison. An advantage of the cellular automata method is that no spectral or geographic supervision is required.

Finally, the aim of this study was to assess the feasibility of mapping Les Hermelles using SPOT satellite data and to evaluate, its recent evolution since the 1980 map. At this stage, the cellular automata method was successful and appears to be a promising exploration. Unfortunately, some parts of the reef were under water at the image-acquisition time and therefore could not be mapped. However, the cellular automata method showed a stability of the reef dynamic tendencies since 1980, especially that its evolution remains linked with La Grande Bosse sand bar dynamics. The mussel farms developed on the north side of the reef in 1984 seemed not to modify the reef horizontal dynamics.

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