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Temporal changes in community structure of tide pools following the "*Erika*" oil spill

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Abstract – The impact of the "*Erika*" oil spill on the tidal rock pool community, and particularly on two species of sea urchin (*Paracentrotus lividus* and *Psammechinus miliaris)*, was investigated over a 3-year period, at Piriac-sur-Mer (Department of Loire-Atlantique, France, 47°21.6′ N; 2°31.7′ W). A dramatic increase in the abundance of two macroalgae *Ulva* sp. and *Grateloupia doryphora* occurred following a 100% mortality of sea urchins observed three weeks after the oil spill. The density of sea urchins and of other main herbivores, the periwinkle *Littorina littorea* and the trochid mollusks *Gibbula umbilicalis* and *Gibbula pennantii,* were monitored between January 2000 and March 2003. There was significant inverse relationship between the overall density of herbivores (sea urchins, periwinkles and trochid mollusks) and the percent cover of algae in the tidal pools. The first urchins in the tidal pools were observed two years after the oil spill and it took three years to reach sea urchin densities comparable to the reference value of 63 ind.m^{-2} obtained before the oil spill.

Key words: Oil spill / Seaweed / *Grateloupia doryphora* / Echinoderm / *Paracentrotus lividus* / *Psammechinus miliaris*

Résumé – Changements temporels de structure de la communauté de mares intertidales, suite à la marée noire de « *Erika* ». L'impact de la marée noire de l'« *Erika* » sur la communauté de mares rocheuses intertidales, et particulièrement sur deux espèces d'oursins (*Paracentrotus lividus* et *Psammechinus miliaris)*, a été étudié sur une période de 3 ans, à Piriac-sur-Mer (Département de Loire-Atlantique, France, 47°21.6′ N ; 2°31.7′ O). Une prolifération de macrophytes, la chlorophycée *Ulva* sp. et la rhodophycée *Grateloupia doryphora*, s'est produite au printemps 2000, à la suite de la mortalité de la totalité des oursins, survenue 3 semaines après la marée noire. L'évolution de la densité des oursins a été suivie de janvier 2000 à mars 2003, ainsi que celle des autres principaux herbivores, la littorine *Littorina littorea* et les gibbules *Gibbula umbilicalis* et *Gibbula pennantii*. L'interaction entre les herbivores et les macrophytes présents dans les mares a été étudiée à l'aide d'un suivi simultané du pourcentage de recouvrement des deux macrophytes. Ce pourcentage a significativement diminué au cours des trois années du suivi, passant de 92 % lors de l'été 2000 à 60 % pour l'été 2001 pour atteindre 30 % lors de l'été 2002. Cette évolution est inversement corrélée avec celle de la densité totale des herbivores (oursins, littorines et gibbules) qui a augmenté régulièrement au cours du suivi. Les oursins ont mis deux ans avant de recoloniser les mares médiolittorales et trois années ont été nécessaires avant d'atteindre des densités moyennes comparables à celle mesurée dans ces mares (63 ind.m^{-2}), avant l'accident pétrolier.

1 Introduction

Over the last three decades, eastern North Atlantic coast has experienced many oil spills (Lacaze 1980; Dauvin 1997) such as "*Torrey Canyon*" (1967), "*Bohlen*" (1976), "*Amoco Cadiz*" (1978) and "*Tanio*" (1980). Although each of these events caused severe ecological disturbance, resulting in death of organisms, decrease in larval recruitment and alteration of biological cycles for some taxons (e.g. Crustaceans and Gastropods), some opportunistic species benefited by establishing and proliferating (Chassé 1978; Cabioch et al. 1980; Dauvin 1981; Raffin et al. 1991a). On December 12th 1999, the oil tanker *Erika* ran aground south of Penmarc'h Point (south Finistère), releasing 20 000 t of heavy oil, which drifted for several days with the currents. A violent storm occurred on December 25th which resulted in the deposit of oil slicks along 400 km of coastline in the departments of Finistère, Morbihan, Loire-Atlantique and Vendée (Fig. 1). Composed of 25% resins and asphaltenes, 25% polycyclic saturated hydrocarbons and 50% aromatic hydrocarbons, this oil of low biodegradability (Oudot 2000) cast ashore at high tide with a strong tidal coefficient. The oil impacted the

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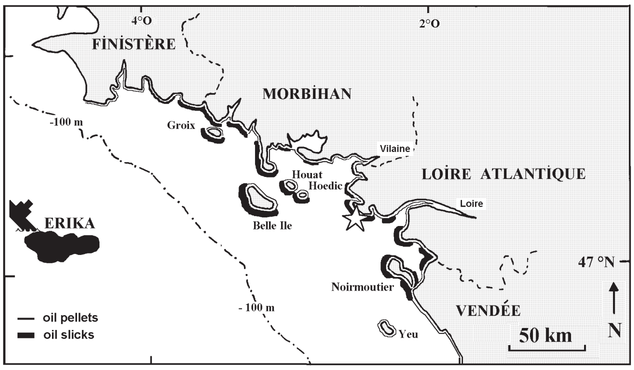

Fig. 1. Schematic representation of the *Erika* oil spill pollution of the French Atlantic coast. Location of the study site (star).

intertidal rock pools located near the town of Piriac-sur-Mer (47°21.6′ N; 2°31.7′ W) on the French Atlantic coast.

Two species of sea urchins, *Paracentrotus lividus* and *Psammechinus miliaris*, usually inhabit these pools, using the burrows made by *P. lividus*, to protect from the water forces and predators (crabs, starfish and fish) (Boudouresque and Verlaque 2001). In November 1999, there was a density of 63 urchins m^{-2} both species confounded. In January 2000, all the urchins were found dead within their burrows. By the following spring, these pools had been invaded by two erect algae, *Ulva* sp. and *Grateloupia doryphora*, while in previous years they were colonized mainly by crustose coralline algae (Gruet, pers. comm.).

Sea urchins play a key role in shallow marine communities as causal agents of primary producers structure (Verlaque and Nédélec 1983; Verlaque 1984; Bulleri et al. 1999; Ruitton et al. 2000; Guillou et al. 2002). They can regulate the abundance and distribution of macroalgae in many habitats (Palacin et al. 1998; Boudouresque and Verlaque 2001), by a process of top-down community control (Hairston et al. 1960). Although it has long been recognized that urchin grazing affect algal vegetation, their role in structuring algal assemblages in littoral rock pools has been little studied (Benedetti-Cecchi and Cinelli 1995).

In this study, we investigate the temporal changes in the abundance of herbivores and macroalgae in intertidal rock pools following the *Erika* oil spill. The specific objectives are to 1) monitor the densities of sea urchins *Paracentrotus lividus* and *Psammechinus miliaris* and of other main herbivores in the pools: the trochid mollusks of the genus *Gibbula* and the periwinkle *Littorina littorea*, 2) investigate the process of recolonization of the rock pools by sea urchins from tidal channels and 3) analyse the interaction between the herbivore community and the macrophytes found in the pools by simultaneously measuring the algal percent cover of the two main macrophytes, *Ulva* sp. and *Grateloupia doryphora*. The latter is an invasive rhodophyte never previously observed in the pools.

2 Materials and methods

Study site

The study site is located near the town of Piriac-sur-Mer (47°21.6′ N; 2°31.7′ W) on the French Atlantic coast, between the estuaries of the Vilaine to the north and the Loire to the south (Fig. 1). It consists of a weatherbeaten coast facing north-west/south-east, with a flat 200 m long rocky area, (from the beach to the sea), scattered with pools and crossed by tidal channels (Fig. 2). The intertidal pools are located at the level of mid-tide mark (between + 2 m and + 4 m above zero on sea charts), and surrounded by mussel beds.

Density of herbivores

The densities of sea urchins *Paracentrotus lividus* (Lamarck) and *Psammechinus miliaris* (Gmelin), of periwinkle *Littorina littorea* (Linnaeus) and of trochid mollusks *Gibbula umbilicalis* (Da Costa) and *Gibbula pennantii* (Philippi) were estimated by counting their numbers in 10 quadrats (50 × 50 cm), placed in 5 randomly selected intertidal rock pools (2 quadrats/pools).

Size structure of *P. miliaris* populations in tidal channels and pools

The sea urchins were collected from the tidal channels crossing the flat rocky area (Fig. 2). In these channels, there are not many *P. lividus* so only *P. miliaris* was measured. The test diameter of *P. miliaris* individuals was measured with a precision of 0.5 mm using a vernier caliper. These data were recorded during the fall of 2000 and of 2001, then every two months from 2002 until the end of the study. The identification of the different cohorts was made using the method of Bhattacharya (1967). With regard to the pools, it is very difficult to remove the individuals embedded in the holes, and measurement of the size of the sea urchins in the pools was thus carried out only once or twice a year.

Macrophyte cover

Only the chlorophyte *Ulva* sp. and the rhodophyte *Grateloupia doryphora* (Montagne) Howe, were included in this study as they represented more than 95% of the cover by erect algae in the rock pools. The percent cover of these species was estimated from 2000 to 2003 using three fixed quadrats of 50 × 50 cm, placed in three different pools (1 quadrat/pool). Each quadrat, subdivided into squares of 100 cm^2, was drawn, numbered and analyzed using the Geographic Information System software MapInfo©, in order to determine the area of each subdivision of the quadrat.

Fig. 2. General view of the rock pools (star) with a tidal channel crossing the intertidal zone (Piriac-sur-Mer, department of Loire-Atlantique, France).

Statistical analysis

The change in the percent cover of macrophytes was analyzed for each quadrat by the Friedman repeated measures analysis of variance on ranks (Conover 1999). A comparison of the densities of sea urchins was carried out using the non-parametric test of Kruskal-Wallis. The means were systematically compared to the initial density measurement, recorded in November 1999 before the shipwreck of the *Erika*. Finally, in the absence of initial data prior to the oil spill of the *Erika*, the densities of trochid mollusks and of periwinkle were dealt with by a simple mean comparison between seasons using a Student test. The means are shown with their 95% confidence intervals ($CI_{95\%}$).

3 Results

Change in the density of sea urchins in the pools

Before the oil spill, in November 1999, the measurements indicated an average density of 63 ± 24 sea urchins m^{-2} ($CI_{95\%}$) in all the pools of the flat rocky area. In January 2000, 100% of sea urchins were found dead inside their burrows. The sea urchins were absent from the pools from January 2000 to September 2001 (Fig. 3). From the winter of 2001/2002, an increase in the density of sea urchins was observed, reaching 23.3 ± 4.6 sea urchins m^{-2} ($CI_{95\%}$) in the summer of 2002. This density was significantly less than the number measured before the oil spill (Kruskal-Wallis; $p < 0.001$). It was only from the fall of 2002 that the sea urchins regained a density comparable to that observed before the oil spill (Kruskal-Wallis; $p > 0.05$).

Size structure of *P. miliaris* in the tidal channels and the pools

The first sea urchins observed on the site were found in September 2000 under the rocks, on the bottom of the tidal

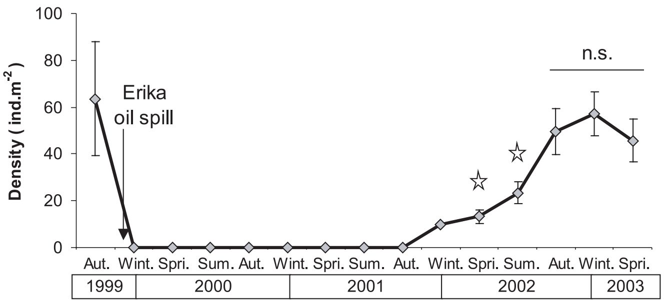

Fig. 3. Sea urchin density (sum of both species *Paracentrotus lividus* and *Psammechinus miliaris)* in intertidal rock pools at Piriac-sur-Mer from fall 1999 to spring 2003. Means are shown with their 95% confidence interval ($n = 5$). N.S. = difference not significant compared to the reference value before the oil spill, $p > 0.05$, $* = p < 0.05$.

channels. This was a single cohort with an average diameter of 7.5 mm. In September 2001, two cohorts, with an average diameter between 11 and 17 mm, were living together in these channels. The first *P. miliaris* that reappeared in the pools in December 2001 measured 23.1 ± 1.4 mm ($CI_{95\%}$) whereas there was only a single cohort in the channels measuring 15 mm on average. During the following two years, only the adult sea urchins with a test diameter greater than 20 mm occupied the intertidal pools while two cohorts of smaller sea urchins, whose average size varied between 7 and 17 mm, were regularly identified in the channels.

Changes in the trophic competitors of sea urchins in the pools

In these pools, the principal trophic competitors of sea urchins are the periwinkle *Littorina littorea* and the trochid mollusks *Gibbula umbilicalis* and *Gibbula pennantii.* Their densities before the oil spill are not known. The change in the density of periwinkles indicates an increase from

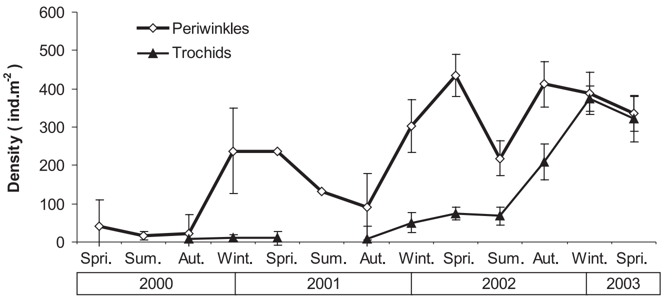

Fig. 4. Periwinkle (*Littorina littorea*) and trochid mollusk (*Gibbula umbilicalis* and *Gibbula pennantii)* density in intertidal rock pools at Piriac-sur-Mer from spring 2000 to spring 2003. Means are shown with their 95% confidence interval (n = 5).

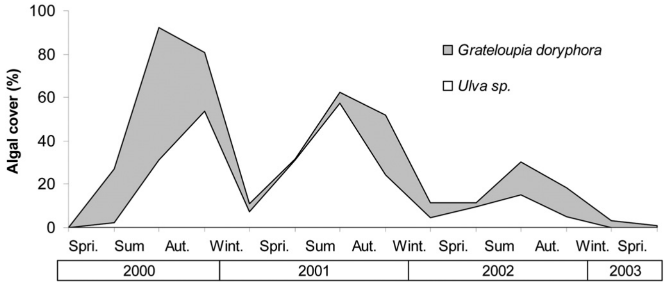

Fig. 5. Mean algal percent cover of the macroalgae *Ulva* sp. and *Grateloupia doryphora*, in intertidal rock pools at Piriac-sur-Mer from spring 2000 to spring 2003.

40 ± 69 ind.m^{-2} (CI$_{95\%}$) to 336 ± 46 (CI$_{95\%}$) ind.m^{-2} (CI$_{95\%}$) between spring 2000 and spring 2003 (Fig. 4). There were seasonal fluctuations with marked decreases in the summer period. The density of trochid mollusks varied between 8 and 10 ind.m^{-2} in 2000 and 2001 (Fig. 4). Between the winter of 2001/2002 and 2002/2003, their density increased from 50 ind.m^{-2} to >300 ind.m^{-2}. The difference between the average densities in spring 2000 and spring 2003 is highly significant (t- test; $p < 0.001$).

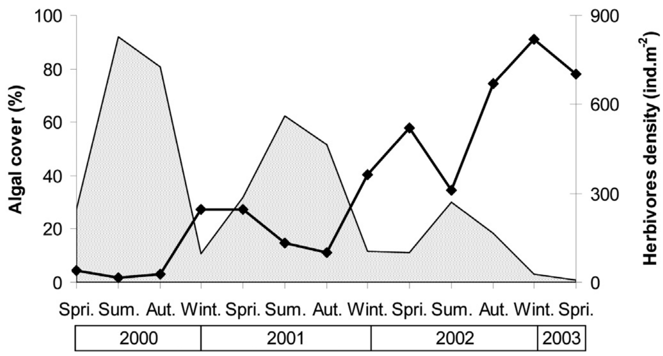

Fig. 6. Total herbivores density (sea urchins, periwinkles and trochid mollusks). vs. algal cover (*Ulva* sp. and *Grateloupia doryphora)*, in intertidal rock pools at Piriac-sur-Mer from spring 2000 to spring 2003.

Change in the percent cover of macrophytes

The abundance of *Ulva* sp. and *Grateloupia doryphora* varied similarly in the quadrats studied between spring 2000 and spring 2003, with a clear seasonal trend characterized by peaks in summer (Fig. 5). The average percent cover of algae in the pools was 92% during summer 2000, close to 60% in 2001 and less than 30% in 2002. The differences in summer percent cover are significant for each quadrat (Friedman test, $p < 0.05$).

The change in percent cover of algae in the pools was inversely correlated with the change in the total density of herbivores (sea urchins, periwinkles and trochid mollusks) (Fig. 6, Spearman correlation coefficient = −0.94; $p < 0.05$).

4 Discussion

In the intertidal pools of Piriac-sur-Mer, two species of sea urchin, *Paracentrotus lividus* and *Psammechinus miliaris*, live together at the bottom of burrows hollowed out by *P. lividus*. Three weeks after the arrival of oil slicks from the *Erika*, all of the sea urchins were found dead in their burrows. If this mortality was due to the wave action of the storm that caused the wreck of the *Erika*, it would likely have resulted in a dispersal of the sea urchins outside of these pools. The speed and the extent of the echinoderm mortality strongly suggests a causal link involving the oil of the *Erika*, whether it be a direct effect (toxicity of hydrocarbons) or an indirect one (such as the anoxia of sea urchins covered in oil). Observations carried out in January 2000 on many other sites on the Loire-Atlantique coast revealed accumulations of sea urchins and starfish *Asterias rubens*, in a state of putrefaction, at the high-water mark (Gruet et al. 2001; Désaunay Y., pers. comm.). Despite the absence of reference data from before the *Erika* oil spill, the increase in the densities of trochid mollusks and periwinkles observed in this study, suggests that these gastropods were affected by the oil. However, *Littorina littorea,* with a mean density of 238 ind.m^{-2} at the end of 2000, resisted the pollution better than the trochid mollusks which were almost absent from the pools during two years. Similar observations were made at the time of previous pollution due to oil spills (Raffin et al. 1991b). With the return of the sea urchins to the pools, the density of periwinkles seemed to stabilize between 300 and 400 ind.m^{-2}.

The recolonization of the pools by the sea urchins began in December 2001, almost two years after the oil spill. It took three years to reach the same densities as those before the *Erika* oil spill. This recolonization took place in two steps: 1) recolonization of the tidal channels by juveniles, 2) recolonization of the pools by adults. The first sea urchins were observed in the tidal channels from September 2000. They formed a single cohort with an average diameter of 7.5 mm. As *P. miliaris* lays only once a year (Kelly 2000) and there were no adults in the pools, these juveniles must be the offspring of parents from elsewhere. Throughout this study, the individuals of *P. miliaris* collected in the tidal channels were mostly juveniles with a diameter of less than 20 mm. In contrast, only those sea urchins larger than 20 mm in diameter colonized the burrows in the intertidal pools. These results suggest that the juveniles resulting from a spring recruitment first settle in the tidal channels before reaching the pools. The factors determining this transfer remain to be established, but the hypothesis of migration may be proposed. In fact, a change occurs in the feeding of sea urchins during their growth (Verlaque 1984) and the search for new food sources is a significant factor triggering the process of migration (Alves et al. 2001; Fernandez et al. 2001; Kelly and Cook 2001). The macrophytes that grow in the intertidal pools represent a food source and the pools offer a protection for sea urchins against their predators in the channels, such as *Asterias rubens, Portunus puber* and *Cancer pagurus* (Boudouresque and Verlaque 2001).

Many experiments have demonstrated the grazing impact of sea urchin populations on algal communities. In the Mediterranean, the withdrawal of sea urchins from some zones led to a 25% rise in cover by macrophytes, while their reintroduction was followed by a return to the previous values (Palacin et al. 1997). In subtidal Mediterranean zones, a high density of *P. lividus* resulted in areas devoid of erect algae (Palacin et al. 1998; Bulleri et al. 1999). However, Benedetti-Cecchi et al. (1998) suggest that the behavior of sea urchins scattered in intertidal pools is different, as these authors did not observe the formation of bare zones in this habitat. At Piriac-sur-Mer, in the absence of sea urchins, there was a dramatic growth of algae in the pools during the summer of 2000, with a percentage cover of more than 95%, *Ulva* sp. and *Grateloupia doryphora* taken together. In contrast, these same pools contained few erect thalloid algae before the oil spill (Gruet 1989). The proliferation of macrophytes, caused by the death of the herbivores after an oil spill, is a recurrent event in studies of oil tanker accidents (Southward and Southward 1967; Lacaze 1980; Conan et al. 1981; Newey and Seed 1995; Crump et al. 1999). Although *Ulva* sp. are common in the region, *G. doryphora* had never been observed previously on this site. Simon et al. (2001), however, noted the presence of some clumps of *G. doryphora* at Croisic (situated north of the Loire) in October 1999. This is an invasive and opportunist alga, which took advantage of the absence of sea urchins to settle in the pools and the channels of Piriac-sur-Mer. Native to Peru, this rhodophyte was first described in France in the Thau lagoon in 1982 (Riouall et al. 1985). It can be found, fixed on a solid substrate, in both sheltered (Cabioch et al. 1997) and exposed (Villalard-Bohnsack and Harlin 2001) surroundings. *G. doryphora* is the biggest rhodophyte ever observed (Simon et al. 2001) and can grow to a length of 3 m for a width of 30 cm. Studies carried out on those sites where *G. doryphora* has been accidentally introduced, show that there is always a proliferation to the detriment of the endemic algae, whatever the type of habitat (Simon et al. 2001; Villalard-Bohnsack and Harlin 2001).

The changes in the percent cover of the two species of macrophytes, *Ulva* sp. and *Grateloupia doryphora*, showed a marked seasonal cycle, with a maximum in summer followed by the disappearance of Ulva in winter while some clumps of *G. doryphora* survived (cover < 10%). However, the percent cover of these two algae fell significantly between the summers of 2000 and 2002 although the climatic parameters (temperature, sunshine, rainfall) did not vary significantly during these three years (Harin 2003). The significant correlation between the decrease in algal cover and the rise in herbivore density illustrates the pressure of grazing exerted by the return of the herbivores to these pools.

At the end of these three years of study, it is still too soon to establish the new structure of the community in intertidal pools. However, it can be noted that, for the two species of sea urchin, the time-scale needed to return to densities of the same order as observed before the pollution, is shorter than the ten years indicated by Dauvin (1991) for amphipod populations. The establishment of a permanent surveillance network of the French Atlantic coast benthos would enable both an understanding of the new ecosystem gradually developing in these intertidal pools and a careful monitoring of the distribution of the invasive rhodophyte *Grateloupia doryphora*.

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