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Microbial ecology of hydrocarbon-polluted coastal sediments

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Coastal shorelines suffer a variety of pollution injuries from both sides, from the sea, predominantly by crude oil from shipping and offshore mining, and from the land, principally through agricultural practices, urban wastewaters, and industrial activities. As a result, multi-pollution hot spots are found along shorelines, especially in estuaries and harbors. Microbial communities have evolved to adapt their metabolism to the presence of multi-contaminants (Duran et al. 2008; Gillan et al. 2005; Iannelli et al. 2012; Kaci et al. 2014; Sabadini-Santos et al. 2014; Wang and Tam 2012). However, hydrocarbon compounds and crude oil-derived products are the most abundant pollutants, the more spectacular source being oil spill as illustrated by the recent catastrophe of Deepwater Horizon in 2010, the largest oil spill so far observed (Atlas and Hazen 2011). Although they are frequently found at unacceptably high concentrations, hydrocarbons are natural compounds, and thus, most of them can be biodegraded by the collective catabolic diversity of microorganisms (Duran and Goñi Urriza 2010; Head et al. 2006; Leahy and Colwell 1990; Miralles et al. 2007; Paisse et al. 2011; Paisse et al. 2010), particularly demonstrated in coastal marine ecosystems such as salt marshes with microbial mat structures (Bordenave et al. 2004a;

Bordenave et al. 2008; Bordenave et al. 2007; Bordenave et al. 2004b), mangroves (Brito et al. 2009; Brito et al. 2006) and estuaries (Chronopoulou et al. 2013; Coulon et al. 2012). However, coastal marine sediments constitute particular ecosystems submitted to fluctuating oxygenation and redox conditions from the tidal cycles and burrowing activities of the macrofauna that in turn drive microbial degradation processes (Cravo-Laureau and Duran 2014). The biodegradation of hydrocarbon compounds in such oxic/anoxic oscillating environments still remains poorly understood (Cravo-Laureau et al. 2011; Cuny et al. 2011; Vitte et al. 2013; Vitte et al. 2011). The understanding of the particular microbes involved, their ecology, their genetic and enzymatic capacities, their interactions, as well as their functioning in the changing redox conditions, is crucial for the implementation of efficient bioremediation strategies (Goñi-Urriza et al. 2013; McGenity 2014). The DECAPAGE project (ANR CESA-2011-006 01; <http://iprem-eem.univ-pau.fr/live/DECAPAGE>), funded by the French National Agency for Research (ANR), was precisely devoted to understand the adaptation mechanisms driving the reorganization of bacterial communities in response to petroleum in coastal sediments. In this special issue, the scientists involved in the DECAPAGE project present their contribution for understanding the microbial ecology in hydrocarbon-polluted mudflat sediments. The special issue also includes articles from scientists involved in other projects and programs in order to enlarge the topic to diverse ecosystems, to different biological organization levels from microbial and macrobenthic communities to bacterial populations, and addressing remediation strategies as well. Thus, the 15 articles compiled in this special issue explore diverse facets of the microbial ecology of hydrocarbon-polluted coastal sediments. The article of Acosta-González et al. (2015) reviews the impact of the Prestige oil spill, an accident that occurred in 2002 at the

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Spanish Atlantic coast, on coastal environments with special emphasis on the microbial community aspects, responding to one of the primary questions arising when an oil spill catastrophe occurs: what we learn from the past (Goñi Urriza and Duran 2010) to combat oil pollution.

The description and characterization of bacterial communities in coastal environments also provide crucial information on the behavior of microbial communities in front of a contamination. The powerful resolution of high-throughput sequencing approaches allows the characterization of structural and metabolic changes of microbial communities in contaminated marine ecosystems. The comparison of microbial communities from marine sites with contrasted contamination levels described in Duran et al. (2015a) showed specific bacterial assemblages according to the type of contaminant. The study, focusing on Actinobacteria assemblage, revealed the ecological importance of Actinobacteria for maintaining both general biogeochemical functions through a “core” Actinobacteria community and specific roles associated with the presence of contaminants. Such information is pivotal for the implementation of efficient bioremediation processes in marine ecosystems.

Experimental ecology, based on mesocosm approaches, provides essential knowledge on microbial ecology and hydrocarbon biodegradation, essential transition from laboratory to field studies (Cravo-Laureau and Duran 2014; Kostka et al. 2014). In this issue, four papers use sophisticated mesocosm approaches mimicking as close as possible the environmental conditions to dissect the microbial assemblages involved in hydrocarbon degradation. Sanni et al. (2015) reveals the importance to combine culture-dependent and culture-independent approaches to estimate the potential for natural attenuation in tidal mudflats. The study also reveals the importance of *Oleibacter*, *Alcanivorax*, *Cycloclasticus*, and *Thalassolituus* related species in hydrocarbon degradation. The organization of a hydrocarbon-degrading microbial assemblage is strongly influenced by environmental conditions as illustrated in this issue by mechanical reworking of sediments (Duran et al. 2015b) and oxygenation regimes (Milton et al. 2015), studies that demonstrated the complexity of bacterial interactions and revealed potential new hydrocarbon-degrading candidates. The study focusing on sulfate-reducing microorganisms (SRM) by Stauffert et al. (2014a) confirms the influence of environmental parameters, particularly the bioturbation activity of burrowing macrofauna such as *Hediste diversicolor*.

Although the influence of burrowing macrofauna on the structuration of microbial communities in oil-polluted sediments has been demonstrated (Cuny et al. 2007; Pischedda et al. 2011; Stauffert et al. 2015; Stauffert et al. 2013; Stauffert et al. 2014b), little is known on the effect of hydrocarbons on macrofaunal communities (Louati et al. 2014a; Louati et al. 2013). Four papers in this issue evaluated the impact of crude

oil and polyaromatic hydrocarbons (PAHs) on macrofauna. Gilbert et al. (2014) showed that the macrofaunal community structure was not affected by an oil contamination in a historically hydrocarbon-contaminated sediment but the sediment-reworking activity was characterized by a deeper particle burial. In contrast, Ferrando et al. (2015) demonstrated the deleterious effect of crude oil on macrofaunal community structure and reworking activity in a pristine sediment without pollution history suggesting that macrofaunal species could serve as bioindicators of pollution. The paper by Louati et al. (2014b) confirms the negative impact of PAHs on macrofaunal communities and further demonstrates the capacity of bioremediation strategies (biostimulation and/or bioaugmentation) to mitigate the effects of PAHs on macrofauna diversity. Such observation suggests strong links between microorganisms and macrofauna. The relationships between macrofaunal and microbial communities are discussed by Ben Said et al. (2015).

The isolation and characterization of new hydrocarbonoclastic bacteria are always useful for a better understanding of the bacterial hydrocarbon degradation mechanisms; particularly bacteria showing the capacity to degrade both *n*-alkanes and PAHs are of special interest as described by Guermouche M'rassi et al. (2015). Among hydrocarbon-degrading bacteria, *Marinobacter* related species, as true marine hydrocarbon bacteria, are efficient degraders of aliphatic and polycyclic aromatic hydrocarbons as well as acyclic isoprenoid compounds (Duran 2010). Bonin et al. (2015) showed the substrate specialization in lipid compounds and hydrocarbons of *Marinobacter* genus through analyzing the physiological capacities of 34 *Marinobacter* strains and the genomic analysis of 16 *Marinobacter* genomes. The horizontal gene transfer allows bacteria to acquire adaptive genes, particularly catabolic gene clusters for hydrocarbon degradation (De la Cruz and Davies 2000; Huang et al. 2009). In this issue, Abella et al. (2015) review the current knowledge on integrons in marine environments and demonstrate their implication in bacterial adaptive responses, especially in hydrocarbon and toxic metal contamination contexts.

Finally, two papers in this issue evaluate remediation strategies that use either dispersants (Cuny et al. 2015) for increasing hydrocarbon bioavailability or electron acceptors as substitute to oxygen (Brundrett et al. 2015). Cuny et al. (2015) demonstrated that the use of the dispersant accelerated hydrocarbon removal but had negative effect on the sediment-reworking activity by macrofauna, which was observed with no obvious effect on macrofauna diversity. Brundrett et al. (2015) showed that chlorate was efficient as oxygen to mineralize Macondo crude oil from the Deepwater Horizon oil spill in salt marshes, which is a promising remediation strategy preventing unwanted secondary impacts of nitrate amendments.

The microbial ecology in sediments' coastal areas is extremely complex. Many questions remain to be elucidated such as the structure/function relationships and microbial interactions and networks (Cravo-Laureau and Duran 2014). The next-generation sequencing technologies combined with systems biology approaches are promising holistic approaches to elucidate the burning microbial ecology questions in order to open the black box of microbial processes involved in hydrocarbon degradation.

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bial ecology and diversity, with an emphasis on extreme, polluted, and estuarine and coastal ecosystems. Relevant recent discoveries include the characterization of the taxonomic and functional microbial diversity in extreme and contaminated ecosystems: behavior of sulfate-reducing bacteria populations in acid mine drainage and microbial mats according to the fluctuation of environmental parameters, the diversity of ring hydroxylating dioxygenases in polluted microbial mats, and the organization of hydrocarbon-degrading prokaryotic communities in mudflat sediments. He is PI of the ANR DECAPAGE project (<http://iprem-eem.univ-pau.fr/live/DECAPAGE>) aiming to understand the microbial ecology of hydrocarbon-polluted coastal sediments.



Philippe Cuny is Professor in Marine Microbial Ecology at the Mediterranean Institute of Oceanography (MIO, Aix-Marseille University). His current research interest is focused on the study of the microbial community dynamics and hydrocarbon biodegradation activity in marine sediments and hypersaline environments submitted to chronic or massive oil inputs. Special attention is paid to the interactions between micro- and macroorganisms that strongly influence the fate of hydrocarbons

in bioturbated marine sediments. In particular, the effects of bioturbation-induced redox oscillations on the functioning of the hydrocarbonoclastic communities are studied. The conclusions of the recent works highlight the need of a more holistic and integrative ecological approach in order to understand and predict the fate of oil in marine ecosystems.



Patricia Bonin is CNRS senior scientist at Mediterranean Institute of Oceanography in CNRS-Aix-Marseille University joined Unit. She is head leader of a research team (Equipe Microbiologie Environnementale et Biotechnologie). She has 25 years research experience in microbial ecology of hydrocarbon-polluted coastal sediments with particular expertise on nitrogen cycling and microbial ecology associated bacterial processes at the aerobic-anaerobic interfaces: sediments or

microbial mats. Her multidisciplinary approaches, at the interface of biogeochemistry and microbial ecology, drove significant advances in the knowledge of the ecology of this cycle including the coupling between aerobic and anaerobic processes and the behavior of organic matter at aerobic-anaerobic interfaces or interactions between nitrogen and metallic cycling.



Cristiana Cravo-Laureau is Associate Professor in Environmental Microbiology at Pau University. She has special interest in investigating the involvement of the microorganisms in the biogeochemical cycles and their role in pollutant degradation (natural environments and pure strains). She focuses on the role of microorganisms in hydrocarbon degradation in anoxic polluted environments. She has isolated and characterized hydrocarbonoclastic sulfate-reducing strains. Her research also

deals with aerobic and anaerobic communities involved in biodegradation of different oil-polluted ecosystems. She also expanded her research interests to the impact of oxic/anoxic oscillations on microbial communities and hydrocarbon degradation, and the influence of oscillations on anaerobic metabolisms.