Ecology and industrial microbiology
Microbial diversity – sustaining the Earth and industry
Editorial overview
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The Handelsman lab dissects the structure and function of microbial communities by describing their molecular diversity and by decoding the language by which the members communicate with each other and with plant and animal hosts.

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Industrial microbiology exploits the ecological adaptations that microorganisms have developed to communicate with and survive in their environments. This issue of *Current Opinion in Microbiology* explores the intersection of industrial microbiology with ecological microbiology, which is the study of these adaptations. The reviews in this issue focus on the structure and function of microbial communities and the transformation of organic and inorganic substrates by bacteria. These topics unite industrial applications with ecological innovation, using bacterial transformation of chemical environments and their virtually limitless adaptive strategies to cultivate industrial applications. Several themes emerge that illustrate how the complexity and vitality of microbial communities and their interactions with the chemical and physical environment produce their myriad industrial uses: microbial ecology requires innovative methods to illuminate the lives of microorganisms in their natural habitats; communities and the behavior of individuals in them are shaped by communication networks mediated by diffusible signals; microorganisms transform the environments in which they live, and the biochemical drivers of the transformations are the instruments of medicinal, agricultural and industrial applications.

The opportunity for discovery of new industrial applications from microorganisms is as large as the variety of environments they confront. Much of the environmental variation experienced by microorganisms is produced by the chemical complexity of the world around them. The local diversity is staggering. Max Blumer estimated that a single sediment may contain as many as 100 000 distinct organic chemical structures [1]. Where does this chemical diversity come from? Firstly, chemical diversity is generated by the non-biological process diagenesis, the spontaneous, heat-driven transformation of organic molecules that form petroleum and kerogen. Secondly, over 100 000 different compounds have been identified from biological sources. The chemical diversity of the environment is further complicated by the 65 000 chemical compounds currently entered into commerce by the chemical industry [2].

Both natural and synthetic chemicals select for microorganisms that respond to them or transform them. Complex organic compounds are recycled back to CO_2 by microbial oxidation reactions. These reactions are as diverse as the chemical compounds that are their targets, so that a total compilation of the global recycling of all organic compounds by all individual bacterial species is clearly beyond our current capacity to fully document. However, as in all fields of complex knowledge, it is possible to discern patterns and commonalities on which generalizations can be based. These generalizations, used wisely, will reveal the fundamental principles of microbial ecology. Industrial applications based on this knowledge will inevitably follow, and early indicators predict that an exciting expansion of technology will be possible.

In the first review, Torsvik and Øvreås (pp 240–245) introduce the complexity of the soil microbial community. The soil contains vast diversity, and most of the microorganisms that contribute to that diversity are unculturable by standard methods. A gram of undisturbed soil may contain 10 billion microorganisms representing 6000–10 000 different genomes. The review explores emerging approaches to dissecting and understanding the soil community that involve methods that circumvent culturing its members, including PCR analysis, fluorescent *in situ* hybridization, microautoradiography, oligonucleotide arrays and metagenomics. Abraham *et al.* (pp 246–253) delve deeper into microbial communities, exploring both individual and cooperative abilities to degrade polychlorinated biphenyl (PCB) compounds in soils and sediments. This rapidly evolving field is driven by the industrial need to manage the impact of the annual production of 1.5 million tons of PCBs, but the research contributes to our fundamental knowledge of bacterial biochemistry and community function as well as to bioremediation applications. Studying PCB degradation highlights the need to study consortia of microbes rather than individuals. Abraham *et al.* teach us that "mosaic pathways", segmented into more than one species, are often responsible for transformation of PCB compounds, so that studying one taxon in pure culture will reveal only a partial image of the complex biochemistry occurring among partners in the interactive environment of the soil microbial community. It is likely that many other functions are accomplished by cooperative efforts among microorganisms, and cooperative biochemical pathways will emerge as one of the key principles of microbial ecology.

Biofilms provide the physical organization and proximity necessary to facilitate cooperative functions among species. The formation and maintenance of biofilms is an area of intense interest in fields of medicinal, agricultural, industrial and environmental microbiology. Microbial communication is believed to be a critical feature of biofilm function. Kjelleberg and Molin (pp 254–258) offer a critical look at the role of quorum sensing in the function of microbial biofilms, but caution against concluding that quorum sensing is either a central or unique means of communication in biofilms because of the difficulties in isolating variables and seeing a biofilm from the perspective of its members. Leveau and Lindow (pp 259–265) address the problem of seeing the world from the perspective of a microorganism. To meet this challenge, they introduce the powerful technology of biosensors, which are reporter gene systems that quantitatively sense concentrations of metals, nutrients, or ions and degrees of physical parameters as a bacterium senses them. A bioreporter transduces the signal that the bacterium would receive, making it perceptible to the human observer without requiring the signal itself to be amplified and therefore skewed from the signal perceived in the natural system. Few tools of microbiology provide such precise snapshots of the conditions in a community because few can take measurements with as little disturbance of the community.

Bacteria sense many chemical signals in their environments and respond to them in various ways. One way that they respond is by swimming toward compounds that provide food or a signal of a protective environment. Parales and Harwood (pp 266–273) review bacterial chemotaxis to aromatic molecules. Some of these compounds play a key ecological role as plant-derived signals that initiate intimate relationships, including tumor formation by *Agrobacterium tumefaciens* and nodulation by *Rhizobium*. Bacteria are also attracted to diverse aromatic pollutants, such as benzene, naphthalene and chlorinated herbicides, as a precedent to degradation of these compounds. It is likely that the response to aromatic compounds and the associated chemotactic signal transduction pathways evolved to mediate response to plant-derived compounds, but may now be exploited for human ends to deal with environmental pollutants of related chemical structures. Similarly, many bacteria can degrade or transform plant-derived alkaloid compounds, such as opiates from the poppy plant, and these degradation abilities can be harnessed for drug discovery or modeling transformation of drugs in the human body. Rathbone and Bruce (pp 274–281) provide us with an insight into the pathways used by bacteria to confront the alkaloids they encounter in nature and survey the exploitation of these pathways to manipulate and create synthetic alkaloids for medicinal application and to construct biosensors for drug detection.

The study of microbial biotransformation reactions has focused largely on chemical substances of particular interest to humans. The terms 'biotransformation', 'biocatalysis' and 'biodegradation' have been used almost interchangeably, depending on the interest of the people studying the reactions. In this issue, there are excellent descriptions of biodegradation reactions for the biotransformation of potentially toxic compounds. Examples include the nitroaromatic explosives, such as 2,4,6-trinitrotoluene (TNT), the PCBs, and the phosphotriester pesticides and nerve agents. In the case of PCBs, Abraham *et al.* point out that these materials have apparently been co-opted as final electron acceptors in anaerobic sediments where electron acceptors are probably deficient. This represents a specific adaption to the chemical environment. With TNT, Heiss and Knackmuss (pp 282–287) tell a somewhat different story of apparently non-specific reduction of nitroaromatic explosives to generate intermediates that react to oligomerize and condense with soil organic material. Whatever the intent of the soil microbes, these reactions have potential utility by rendering the compounds less leachable and bioavailable and, thus, can be construed as environmental detoxification. In the case of synthetic phosphotriester compounds, microbial hydrolysis offers a dramatic reduction in toxicity and, thus, has broad applications. Phosphotriester pesticides such as paraoxon have been shown to be excellent substrates for the phosphotriesterase from *Pseudomonas diminuta*, which has been extensively studied by Raushel (pp 288–295) and is the subject of the review on this topic in this issue. The review points out that the most toxic of the synthetic organophosphate compounds are military nerve agents such as soman and VX.

The naturally occurring enzyme has very little activity directed against the most toxic isomers of soman and VX. However, a detailed study of the enzyme structure and function has yielded high-resolution information about the active-site determinants that allow rational design of the enzyme to change its stereoselectivity. These studies are important for better understanding enzyme chiral recognition, but are also vital for design of better systems for detoxification of organophosphate triesters.

Microbial transformations can take us out of this world, literally and figuratively. In the review by Nealson and Cox (pp 296–300), we learn about a broad range of metabolism that has been discovered recently and holds great importance for bioremediation in the modern world, even though it is probably ancient in origin. The microbial reduction of metals may be some of the most fundamental electron transfer reactions of single-celled organisms, and evolved early after the inception of life on Planet Earth. In this context, Nealson points out that these may be among our best signature reactions for discerning whether biotransformations are occurring, or have occurred, on other planetary bodies in our solar system. The search for life on other planets has also provided impetus for further study of psychrophilic, or cold-loving, bacteria on earth. The review by Deming (pp 301–309) describes recent progress in understanding the physiology of bacteria that inhabit such environments as Antarctic frozen lakes. These studies also have earthly interest. Industries are finding increasing applications for enzymes that are active at cold temperatures, and psychrophiles are an obvious source of these biocatalysts. Thus, microbial ecology continues to expand its boundaries, into the inner depths of soil particles on Earth and beyond our planet in the quest for life outside Earth's boundaries.

As we explore the microbial world more fully, we must keep in mind that microbes evolve more quickly than we can study them, providing an ever-increasing diversity of function for industrial application. The metabolism of PCBs and organophosphate nerve agents discussed in this issue are but two examples of the efficient microbial metabolism of compounds that have been in the environment for several decades only. The enzymes that bacteria use to metabolize the herbicide atrazine appear to be evolved recently from housekeeping enzymes that catalyze such reactions as pyrimidine deamination [3]. These rapid evolution events are predicated on the great diversity and apparent plasticity of bacterial enzymes. This, in turn, has made for a burgeoning industry based on directed evolution, using such techniques as DNA shuffling. And the ability to obtain genomic libraries of uncultured microorganisms will further increase our access to nature's diversity, again providing both a window into nature and new raw materials for the future's more bio-based industries [4,5]. And so, the linkages between microbial ecology, evolution and industrial applications become even stronger.

References

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