Guide to Habitats

The organization of this guide generally follows taxonomic order. However, bacteria, especially those with macroscopic field marks, are often closely identified with particular ecological communities. One way to use this guide is to go into the field seeking not just a particular taxonomic group but a whole assemblage of bacteria from different groups, all living and interacting together in a specific habitat. This guide to habitats provides suggestions for organizing field trips to places such as the seashore, a temperate forest, a farm, or a gourmet food shop. Some field trips, such as a visit to Yellowstone National Park, are incorporated into specific chapters. Others may be planned by using the index. Field trips can also be organized around adding to an insect, shell, or other collection. An advanced theme for a field trip is to seek out parts of a particular biogeochemical cycle. Finally, you can "plan" imaginary trips, such as a search for bacteria-like extraterrestrials on other planets.

Field Trips Incorporated into Specific Chapters

HOT SPRINGS

Chapters 1, 3, and 17 are devoted entirely to bacteria of hot springs. Some cyanobacteria can also live in hot water; therefore, read chapter 13 for characteristics by which cyanobacteria are identified. Keep in mind that the runoff from hot springs cools and then reaches ambient temperature. Therefore, hot springs may provide good views of temperate bacteria. Furthermore, hot springs may be sulfur-rich or iron-rich. Therefore, check chapter 9 on sulfureta and chapter 7 on iron-oxidizing bacteria. Note too that chapter 3 is specifically about boiling, acidic, sulfurous springs.

SALT FLATS AND OTHER HYPERSALINE ENVIRONMENTS

Chapter 4 is focused on the salt-loving bacteria. See also descriptions of cyanobacteria in chapter 13, as some of these are salt tolerant. Salt flats are often rich in sulfur compounds. Therefore, plan to read chapter 9 on sulfureta for a more complete picture.

SULFUR-RICH ENVIRONMENTS

The full panoply of sulfur-based bacterial activities is highly accessible and often quite colorful and interesting. If you can smell sulfur with or without stirring up the water or sediment, it's probably a sulfur-rich environment (see chapters 5 and 9). Such environments include marine waters, such as intertidal flats and estuaries, and fresh waters, especially in areas with sulfur-rich sediments, as well as sulfur springs. Polluted (or overfertilized) soils and waters may also smell sulfury. If you visit boiling sulfur springs, consult chapter 3. Keep in mind too that some salinas (high salt) areas are sulfury. As with many of these field trips, it is worthwhile to familiarize yourself with cyanobacteria (chapter 13), because these often thrive in sulfury environments.

Sulfur caves are not very accessible, nor are deep sea sulfur springs and seeps. If you do happen to have an opportunity to view either (perhaps through connections with a professional researcher), the information in chapters 5 and 9 should be helpful.

GROCERY STORES, RESTAURANTS, AND KITCHENS

Be inspired by chapter 10 and then seek out grocery stores and restaurants where savory foods are being prepared. At the very least, eat interesting cheeses! Enjoy the many beverages enhanced by bacteria! Try making some foods and beverages yourself. Get specialized cookbooks or make contacts with people who are brewing, baking, or pickling and learn from them. In addition to all of the comestibles described in chapter 10, there are some foods and drinks enhanced by vinegar, courtesy of the alpha proteobacteria described in chapter 6. Also, some cuisines use cyanobacteria as food (chapter 14). If a food or sauce seems quite salty, consider the participation of salt-loving bacteria (chapter 4).

By avoiding bland or highly processed or chilled fresh foods, you may already be venturing into the realm of microbially enhanced cuisine. Suggestion: Have a dinner party based entirely on foods and drinks embellished by bacteria. Even if you are somewhat cautious, you can put together a nice meal (or appetizer) of aromatic cheeses, olives, sourdough bread, and lambic beer (or certain wines).

A supplement to understanding and appreciating bacterial foods is to understand what happens to the food after we eat it. Consider reading about intestinal gases (in chapters 2 and 9) as well as about the bacteria of our digestive system (chapters 12 and 15). Many of our symbiotic bacteria are the same as or closely related to the bacteria that ferment foods—which is probably how they were first introduced to our food.

ANIMALS

In this guide to bacteria, other organisms (e.g., animals) are mentioned mostly as hosts for bacterial symbionts. Chapters 12 and 14 are devoted almost entirely to such symbioses. It is suggested that you work backward in planning a field trip to look at animal hosts; use other guide books to familiarize yourself with the animals that you expect to see, and also review these two chapters. In general, if an animal is eating plants (or algae), it has bacterial symbionts helping it to digest cellulose. The digestive systems of animals are wonderful bacterial habitats. To learn which bacteria are producing various intestinal gases (of carnivores, herbivores, or omnivores), see chapters 2 and 9. Also, nearly every moist or transiently moist surface of every animal is a habitat for bacteria. Therefore, although parts of chapter 12 seem to be specifically about humans, you could substitute nearly any other animal. For additional information on other symbionts, see chapters 15 and 16. Keep in mind also the gamma proteobacteria that are symbionts of shipworms and the bioluminescent gammas that are symbionts of many deep-sea organisms (chapter 8). Sulfureta abound in symbiotic associations as well (chapter 9), some of which may be depicted in museums in dioramas, for example of deep-sea vents.

Zoos and aquaria provide opportunities to observe the challenges of maintaining wild animals in captivity. Often, these challenges include keeping the bacteria happy. In zoos, some fastidious herbivores (e.g., three-toed sloths) are difficult or impossible to maintain because they and their symbionts are accustomed to specific diets and habitats. Most aquaria maintain a biological filter of nitrate-

using bacteria (chapter 6) to keep the tanks clean and do regular battle against films of cyanobacteria. Also, herbivorous (actually algivorous) fish (and their symbiotic bacteria) present some challenges in feeding, often requiring supplements to their diets.

PLANTS AND FUNGI

To view bacteria–plant or bacteria–fungi (lichen) symbioses, you need to be fairly confident about your ability to identify plants and lichens. Plan to work backward—using guides to the plants and lichens of the habitat you are in, and looking for specific ones that are known to have symbionts (based on your reading of this field guide). Many plants contain nitrogen-fixing bacterial symbionts; see chapters 6 (on *Rhizobium*), 11 (actinomycetes), and 14 (cyanobacteria). Plant galls are a somewhat difficult subject for amateurs because it can be difficult to determine whether they were caused by bacteria, viruses, or fungi. Nevertheless, galls on herbaceous plants and trees are fascinating and worth seeking out. Also, look for cyanolichens and for plants growing at the edges of bogs that show the effects of metal toxicities due to bog bacteria (chapter 7). In the bog itself, you might find insectivorous plants, some of which are assisted in digestion by bacteria, or which may be digesting the bacteria themselves.

Field Trips to Specific Habitats

FARMS (INCLUDING COTTAGE INDUSTRIES)

Look for bacterial participation in pest control, fertilization (as in legumes), and the husbandry of domestic herbivores. Cud chewing and gaseous belching by ruminants, as well as the odors of chicken houses, compost heaps, and freshly turned soil, are all bacterial field marks. The making of silage and the careful avoidance of green hay in lofts both require a consideration (even if unconscious) of bacteria. Frost damage to plants may have bacterial aspects, along with some precipitation, such as snow! Farm work may include cottage-industry activities such as using traditional (bacterial) methods of preserving food and drink and traditional cloth-dying and linen-making techniques. In contrast, farming on an industrial scale might involve smelly waste lagoons (remediated by bacteria), eutrophication of water bodies (encouraging a diversity of bacteria), and soils that have become salty (encouraging halophiles) due to excess fertilizer. Special feedlot diets (and doses of antibiotics) may be detrimental to the bacterial symbionts of ruminants.

URBAN SETTINGS

Look for mosses, enhanced by the presence of cyanobacteria, on sidewalks and roofs. Any damp, shadowy wall or fountain is likely to have cyanobacteria. Look for bacterial "decay" of some stone monuments, including those in cemeteries. Ornamental plants in parks or in florist shops may be keyed out, and some (e.g., legumes and cycads) may be found to be symbiotic with bacteria. Sewers and Dumpsters may be sources of methanogens. Grocery stores, especially ethnic or gourmet ones, may have interesting cheeses and other fermented foods and drinks.

INDUSTRIAL AREAS

Watch for signs of methanogens, the producers of landfill methane and "sewer gas." Also, note any corrosion of concrete, stone work, and metal—a complex phenomenon that often has a bacterial component. Some industries are attempting bacterial remediation of wastes that go beyond the usual sewage treatment. These include clean-up of oil spills and reclamation of metals in mine waters. Some bacterial processes have been modified for the purpose of making beers, cheeses, and dyes on a commercial scale. Strict control of microbes or appropriation of microbial-type chemical reactions may often be seen in such processes. Furthermore, any genetic engineering of organisms using bacterial genes may be viewed as a direct appropriation of bacterial activities.

AQUATIC COMMUNITIES

All microbial ecology is essentially aquatic ecology. A field trip to any watery habitat is likely to involve the use of many chapters of this field guide. Take the following list of destinations, and use it along with the index to plan specific field trips to sources and bodies of water:

1. Fresh waters (lakes, ponds, streams, rivers)
2. Karstic bodies of water, with or without the presence of sulfides
3. Iron-rich waters (these are likely to show signs of manganese activity as well)

4. Marine waters (coral reefs, intertidal flats, estuaries, rocky and sandy shores)
5. Alkaline (soda) waters

Note that hot springs and hypersaline waters are mentioned in the first section of this chapter because they are the subject of entire chapters. Also, wetlands may be flooded to various degrees, some making the transition to "body of water" on a seasonal basis. Even the driest of habitats listed here, including deserts and dunes, may be viewed as microbial communities waiting in dormancy for moisture via rain or flood.

DUCKWEED

It happens that duckweed (a floating aquatic plant) is mentioned in three different places in this field guide, and it might be considered a very specific focus for a field trip as long as one has access to a microscope. Chapter 7 recommends the waters and sediments beneath duckweed as a source of magnetotactic bacteria. Chapter 16 suggests looking for tiny freshwater clams among duckweed and breaking them open to look for spirochetes. And chapter 18 describes communities of microbes attached to plants (including duckweed), rocks, logs, and the surface films of water. Although they are challenging to see even under a good microscope, some community members are likely to be stalked bacteria of the planctomycetes and other stalked microbes.

A bit of duckweed under the scope is likely to be a rewarding experience in general, and is good practice for microscopy even if you cannot see any bacteria. Often an abundance of ciliates and rotifers or other eukaryotic microbes may be observed. Also rewarding—even if it yields mostly eukaryotes—is some of the surface film of a still pond or lake.

WETLANDS

Wetlands of all kinds (such as bogs and swamps) are highly recommended as field trip destinations. Keep in mind the wide range of habitats to explore: iron-rich waters and sediments, aerobic and anaerobic habitats, and many interesting symbiotic associations, such as those of carnivorous bog plants.

CAVES, CLIFFS, AND DAMP ROCK LEDGES

Look for cyanobacteria on the rocks and just under the surfaces of rocks. For more exotic bacteria, use the index to locate information on troglodytic archaea and sulfur bacteria of unusual caves.

DESERTS AND DUNES

In either deserts or dunes, look for the cyanobacteria (and other microbes) of "desert crust." Whatever plants are surviving in the relatively poor soils are often highly dependent on nitrogen-fixing bacteria. Also, depending on which rocks and sediments are present, you might see endolithic cyanobacteria, halophilic bacteria, and desert varnish. Keep in mind that any body of water, including temporary ones such as the damp swales between sand dunes, is likely to have an active and complex microbial community.

TEMPERATE FORESTS

Forests, by definition, are dominated by trees and may be among the more difficult of habitats for microbial field trips. Try focusing on symbioses, such as those between nitrogen fixers and plants or between bacteria and herbivores. Forests are good places to view the effects of microbial decomposition (e.g., leaf litter, leaf mold). However, much of this decomposition may be dominated by the activities of fungi.

TROPICAL FORESTS

From a temperate point of view, everything in the tropics is more so—more niches, more competition, more biomass, and more species diversity. You are, therefore, forgiven if you are looking everywhere but at the bacteria, instead focusing on the dense tropical forests with layers and layers of large complex organisms. If you are investigating the ground, though, keep in mind that cycles of decomposition are quicker, resulting in thinner soils. Fungi rather than bacteria seem to be the major decomposers and major displayers of their activities. As with temperate forests, you might focus on symbioses between bacteria and plants (e.g., bromeliads) and between bacteria and animals (especially herbivores).

Field Trips That Focus on Biogeochemical Cycles

A biogeochemical cycle is the sequence of chemical reactions by which a particular element is converted from one form to another

as it passes through organisms, bodies of water, the atmosphere, and various geological features. The usual representation of these cycles is a complicated set of loops showing many different possibilities. Some of the more important cycles are those of carbon, nitrogen, sulfur, phosphorus, and iron.

A complete plan for a field trip should include the use of an ecology textbook and its diagrams of specific cycles. Be assured that most parts of the major cycles are mediated in whole or in part by bacteria. Strategic use of an ecology text along with the index of this book can help you plan a far-flung and perhaps lengthy field trip to view as many parts as possible of one of the cycles. Many ecology books do not mention bacteria as extensively as they might, given their focus on biogeochemical cycles. Often bacteria and fungi are discussed together as "saprophytes" or "decomposers." However, even parts of cycles attributed (by some ecology texts) to plants and animals may be readily extrapolated to bacteria, including cyanobacteria and other autotrophs and the myriad fermenters that make herbivorous life possible.

Field Trips Organized around Collections

INSECT COLLECTIONS

Focus on insects with bacterial symbionts, looking in particular at the chapters on proteobacteria as well as in the index. Gall makers are an interesting focus for an insect collection, along with the galls themselves. Some are formed via bacterial interactions, although many others involve fungi or viruses.

FOSSIL COLLECTIONS

The index of this guide may help you arrange a fossil collection with a bacterial theme. Key words include microfossil, stromatolite, death mask, trilobite, slate, and limestone. Keep in mind that most of the history of life (4 billion years) has involved bacteria.

SHELL COLLECTIONS

Use the index to focus on those organisms with bacterial symbionts or with strategies for coping with sulfidic environments. These include *Mya*, *Ensis*, plumed worm cases made up of mollusc shells, lucinids, thyasids, and solemyids.

PLANT OR LICHEN COLLECTIONS

Focus on those organisms with agrobacterial or nitrogen-fixing symbionts. It may be possible to make dried, pressed, or boxed herbarium mounts of some bacterial structures of plants. A lichen collection might focus on those with cyanobacteria.

Unconventional or Imaginary Field Trips

Expeditions to the North or South Poles, voyages in deep-sea research submarines, treks to remote places accessible only with guides, visits to deep mines and caves not open to the public, and other such adventures are not described here, even though such areas are full of bacteria. Obviously if you or I have an exceptional opportunity for an exotic field trip, as passionate amateur naturalists we will take full advantage of the opportunity by scouting guide books of all sorts. Should the opportunity arise, selective use of this guide would serve as a useful introduction. If remote parts of the planet are difficult to reach, however, anyone can explore other planets or fantasy landscapes—even if just in the imagination.

OTHER PLANETS

In seeking life on other planets, it is wise to consider bacteria rather than animal-like organisms that somehow resemble or behave like us. Most life is bacterial, and only bacteria have colonized the Earth with such diversity and versatility. Animals are an anomaly on our own planet; they are far outnumbered by microbes and are relative latecomers in the history of life on Earth. We humans have occupied the planet for a mere 50,000 generations (20 years per generation for about a million years) and, despite our growing population, we are still rather scarce in most environments. For example, we have an almost complete lack of presence in and on the ocean, which occupies three quarters of our planet.

Some Earthly bacteria are reasonable prototypes for the sorts of organisms that we might look or test for on other planets. Indeed, when planetary geologists consider which planets and moons might be capable of supporting life, they are often thinking of life below the surface of the planet, most likely on a microscopic scale. The Earth is unusual in its abundance of water and moderate

temperature, a result of its distance from the sun. Most planets (and moons) are too cold (or hot) at the surface to have liquid water, but some may have molten interiors near which life might dwell. Subsurface conditions could exist in which heat-loving bacteria (some of them chemoautotrophs) might support a community of microbes (and possibly larger creatures) similar to those of deep-sea hot springs. Also, cold, even subfreezing, brines beneath some planet surfaces could potentially harbor slow-growing halophiles. Try reading chapters 1–4, 7, 9, and 17, keeping in mind that extraordinary conditions on Earth—boiling, acidic springs, for example—may have counterparts on other planets.

BACTERIA IN FAIRY TALES AND FANTASY LITERATURE

Wildly sprouting agrobacterial swellings of trees are often depicted in haunted woods, such as in the illustrations of Arthur Rackham. Odd smells and exudates (miasmas) of swamps and bogs are often bacterial, and marsh gas that sometimes bursts into mysterious flames is a product of methanogens. The very nature of bogs (with their eponymous bogeymen) lends itself well to fairy-tale settings. Surely the source of iron tools used by dwarves, for example, would have been bacterial bog iron. Some gigantic bacterial colonies such as those of *Nostoc* have fascinated humans, as evidenced by the numerous colloquial names for the colonies and the prevalence of slime in fantasy settings. Furthermore, the gigantic animals of both past and present are almost always herbivores, in debt to their digestive bacteria. Authors inventing gigantic animals might keep in mind that not all animals should be made ferocious and predatory! The circumstances of bacteria are so weird and otherworldly that this entire field guide could be read with fantasy or fairy-tale literature in mind.