Figure 5.23 Volumes of water and air associated with a 100 g slice of soil solids in a well-granulated silt loam at different moisture levels. The top bar shows the situation when a representative soil is completely saturated with water. This situation will usually occur for short periods of time during a rain or when the soil is being irrigated. Water will soon drain out of the larger pores (macropores). The soil is then said to be at the field capacity. Plants will remove water from the soil quite rapidly until they begin to wilt. When permanent wilting of the plants occurs, the soil water content is said to be at the wilting coefficient. There is still considerable water in the soil, but it is held too tightly to permit its absorption by plant roots. A further reduction in water content to the hygroscopic coefficient is illustrated in the bottom bar. At this point the water is held very tightly, mostly by the soil colloids. (Top drawings modified from Irrigation on Western Farms, published by the U.S. Departments of Agriculture and Interior)
Soil as a Transition Between Aquatic and Aerial System

**First Phase of Soil Water Evaporation**
- **Surrounding Conditions**
  - Air Temperature: 15°C
  - Wet Temperature: 10°C
  - Relative Humidity: 51%
- **Natural Displacement of Mites and Springtails**
- **Free Water**
- **Gravitational Moisture** = Sub-aquatic System
- **pF** > 2.5

**Second Phase of Soil Water Evaporation**
- **Surrounding Conditions**
  - Air Temperature: 15°C
  - Wet Temperature: 10°C
  - Relative Humidity: 51%
- **Natural Displacement of Mites**
- **Migration and Active Fall-out of Springtails**
- **Capillary Moisture** = Edaphic System
- **pF** > 2.5

**Third Phase of Soil Water Evaporation**
- **Surrounding Conditions**
  - Air Temperature: 15°C
  - Wet Temperature: 10°C
  - Relative Humidity: 51%
- **Migration and Active Fall-out of Mites**
- **Adsorptive Moisture** = Aerial System
- **pF** > 4.7
Bacteria in a Drying Environment

## Metabolic Grouping

<table>
<thead>
<tr>
<th>Energy Source</th>
<th>Carbon Source</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Autotrophs (fix CO₂)</td>
</tr>
<tr>
<td>Light (Photo-)</td>
<td>Photoautotrophs</td>
</tr>
<tr>
<td>Chemical (Chemo-)</td>
<td>Chemoautotrophs</td>
</tr>
</tbody>
</table>

- Photo-autotrophs: algae, cyanobacteria, and higher plants:
  - \( \text{CO}_2 + \text{H}_2\text{O} \Rightarrow \text{Organic C} + \text{O}_2 \)
- Chemo-heterotrophs: most bacteria, fungi, protozoa, etc:
  - \( \text{Organic C} + \text{O}_2 \Rightarrow \text{microbial biomass} + \text{CO}_2 + \text{waste} \)
# Classification of Soil Organisms

<table>
<thead>
<tr>
<th>Classification</th>
<th>Body Width</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Microflora</td>
<td>&lt; 10 µm</td>
<td>Bacteria, Fungi</td>
</tr>
<tr>
<td>Microfauna</td>
<td>&lt; 100 µm</td>
<td>Protozoa, Nematodes</td>
</tr>
<tr>
<td>Mesofauna</td>
<td>100 µm to 2 mm</td>
<td>Acari, Collembola</td>
</tr>
<tr>
<td>Macrofauna</td>
<td>2 mm to 20 mm</td>
<td>Earthworms, Snails</td>
</tr>
</tbody>
</table>
Organisms and Scale

Figure 5. Composition of a soil fauna selection, arranged according to feeding type (left phytophages, upper predators and right saprophages), size of the animals indicated, and habitat size expressed as various squares (modified after Van der Drift, 1963)

**Source:** Doelman, P and HJP Eijsackers. 2004. Vital Soil.

**Source:** Nardi, J.B. 2003. The World Beneath Our Feet.
Fig. 3. Soil organisms, their approximate counts and ecologically important activities.
Figure 10.4  Influence of various sizes of soil organisms on the decomposition of corn leaf tissue buried in soil. Small bags made of nylon material with four different-size openings (mesh size) were filled with 558 mg (dry weight) of corn leaf tissue and buried in the soil for 10 weeks. The amount of corn leaf tissue remaining in the bags was considerably greater (less decomposition had taken place) where the meso- and macrofauna were excluded by the smaller mesh sizes. [Data from Weil and Kroontje (1979)]
Scale Relationships

- In biology, scaling relationships among morphological and physiological variables are well-known. For instance:

\[ D = 3W^{-0.98} \]

Prokaryotes in Soils

- The number of bacteria in soil is consistent across ecosystems: $10^7$-$10^9$ cells/g.

Table 2. Number of prokaryotes in soil

<table>
<thead>
<tr>
<th>Ecosystem type*</th>
<th>Area, $\times 10^{12}$ m$^2$</th>
<th>No. of cells, $\times 10^{27}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tropical rain forest</td>
<td>17.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Tropical seasonal forest</td>
<td>7.5</td>
<td>0.5</td>
</tr>
<tr>
<td>Temperate evergreen forest</td>
<td>5.0</td>
<td>0.3</td>
</tr>
<tr>
<td>Temperate deciduous forest</td>
<td>7.0</td>
<td>0.4</td>
</tr>
<tr>
<td>Boreal forest</td>
<td>12.0</td>
<td>0.6</td>
</tr>
<tr>
<td>Woodland and shrubland</td>
<td>8.0</td>
<td>28.1</td>
</tr>
<tr>
<td>Savanna</td>
<td>15.0</td>
<td>52.7</td>
</tr>
<tr>
<td>Temperate grassland</td>
<td>9.0</td>
<td>31.6</td>
</tr>
<tr>
<td>Desert scrub</td>
<td>18.0</td>
<td>63.2</td>
</tr>
<tr>
<td>Cultivated land</td>
<td>14.0</td>
<td>49.1</td>
</tr>
<tr>
<td>Tundra and alpine</td>
<td>8.0</td>
<td>20.8</td>
</tr>
<tr>
<td>Swamps and marsh</td>
<td>2.0</td>
<td>7.3</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>123.0</strong></td>
<td><strong>255.6</strong></td>
</tr>
</tbody>
</table>

*From ref. 73.
†For forest soils, the number of prokaryotes in the top 1 m was $4 \times 10^7$ cells per gram of soil, and in 1–8 m, it was $10^6$ cells per gram of soil (16). For other soils, the number of prokaryotes in the top 1 m was $2 \times 10^9$ cells per gram of soil, and in 1–8 m, it was $10^6$ cells per gram of soil (18). The boreal forest and tundra and alpine soils were only 1 m deep. A cubic meter of soil was taken as $1.3 \times 10^5$ g.

$$D = \frac{2.6 \times 10^{29} \text{ cells}}{1.23 \times 10^{20} \text{ km}^2} = 2 \times 10^9 \text{ cells} / \text{km}^2$$
Bacteria in Soils

• A large number of bacteria colonize the subsurface; BUT how crowded is the soil ecosystem?
  – Assuming a *specific surface area* (see Table 2.7) of 15 m²/g and a bacterium diameter of 10⁻⁶ m, the area covered by a bacterium is 3.14 x 10⁻¹² m². The 10⁹ cells/g will cover 3.14 x 10⁻³ m² or **0.02%** of the specific surface area!
  – Assuming a *specific surface area* of 700 m²/g the percent of covered surface drops to **0.0005%**.
Abundance of Species

How many species of bacteria in soils?
6,000 to 40,000 taxa / g of soil!

Fig. 6. A crude estimate of the distribution of number of species of all terrestrial animals, categorized according to characteristic length $L$. The dashed line indicates the relation $S \sim L^{-2}$, as in Fig. 2 ($S$ is number of species) [after (18)]. The question mark emphasizes the crudity of these estimates and the inadequacy of the data for small size classes.

The Soil Food Web

Soil Organism Relationships

- Mutualistic associations
- Competition
  - Food source
  - Water
  - Antagonistic mechanisms
    - antibiotics
- Parasitism/Pathogenesis
Biological Diversity

- Species diversity
- Functional diversity
- Functional redundancy
  - multiple organisms to perform a function.
  - *stability*: ability to continue to perform. functions under wide variation in conditions or inputs.
  - *resilience*: ability to return to functional health after a disturbance of normal processes.
Where Do Organisms Live?

- *Around roots*: rhizosphere is the narrow region of soil directly around roots.
- *In litter*, particularly fungi.
- *On humus*, only fungi can degrade humus.
- *On the surface of soil aggregates* biological activity is greater than within aggregates.
- *In spaces between soil aggregates.*
Bacteria and the Double Layer

Stenotrophomonas maltophilia 70401

Soil Ecology

• Soil conditions limit the habitat of microorganisms
  – Temperature (optimal 15-25 °C)
  – Soil water content and potential (optimal: -10 to -70 kPa).
  – Soil porosity (mainly pore size: habitable vs. non-habitable pore space).
Compaction

- Accessible pores should have a neck diameter p of at least:
  - p > 30 μm: nematodes
  - p > 5 μm: protozoa
  - p > 0.2 μm: bacteria

The Role of Soil Biota in the Decomposition of SOM
Seasonal Microbial Activity

Bacterial and Fungal Activity in a temperate grassland or cropland.

- January
- Month
- December
- Early summer
- Late summer
- First frost
- Last frost
Field Measurements: CO$_2$ and Temperature
Concentration of CO$_2$ in the Soil Atmosphere

• Related to respiration by bacteria, fungi, protozoa and other chemo-heterotrophs.

• Several experiments found that temperature is between 2-5 times more important than water content in determining concentrations of CO$_2$ in soils.

• An empirical equation relates log (PCO$_2$) and Actual Evapotranspiration (AET)—see lecture 8.
Distribution of Microorganisms

Fungi

- Mushrooms, mildews, molds, yeast
- Some form *hyphae* and *mycelia*
- $10^5 - 10^6$/g soil
- Tolerant of acid conditions, aerobic
- Decomposers
  - able to decompose resistant compounds: lignin, cellulose,
- Symbiotic associations
- Pathogens - opportunistic
- Antibiotic production (e.g. penicillin)
Fungal Symbiosis

- *Mycorrhizae* ("fungus-root") associate with plant roots
  - Ecto-mycorrhizae: hyphae grow between root cells and mantle the roots of many trees
  - Endo-mycorrhizae: hyphae grow into root cells
    - Vesicular-arbuscular (VAM)
    - trees, agronomic crops, vegetable & fruit crops
- Mycelium growing into soil increases surface area of absorbing tissue
- Improve P and water uptake
Actinomycetes

- Heterotrophic, aerobic
- Branched hyphae
- $10^7$/g soil
- Tolerates low soil moisture, high temperature
- Intolerant of low pH
- Slow growing
- Decompose cellulose and other resistant compounds
- Symbiotic with many plants
- **Antibiotics** (e.g. streptomycin)
Bacteria

- Very diverse metabolism
  - Autotrophs and heterotrophs
  - Aerobes, anaerobes, and facultative
- Unicellular ~1μm
- Most numerous in soil
  - $10^8 - 10^9$/g soil
- Rapid growth
- *Rhizobium*–legume symbioses
Rhizobial Symbiosis

• *Rhizobia* or *Bradyrhizobia* associate with legumes
• Specificity of infection
• Root nodules contain bacteria
• N$_2$ is “fixed”, 10 - 20 g N/m$^2$/y
• Nitrogenase enzyme
  \[ \text{N}≡\text{N} \longrightarrow 2\text{NH}_3 \longrightarrow \text{amino acids} \]
• N-compounds available to plant
• *Rhizobia* receive nutrients and organic compounds from plant
Metabolic Classes of Bacteria

• Source of Energy: autotrophic or heterotrophic

• Terminal Electron Acceptor
  – Oxygen: Aerobic
  – Other: Anaerobic
    \[ \text{NO}_3^-, \text{SO}_4^{=}, \text{Mn}^{+4}, \text{Fe}^{3+} \]
    • decomposition products: methane, ethanol, \( \text{H}_2\text{S} \)
  – Either: Facultative Anaerobe
Bacterial-Mediated Transformations

• Nitrifiers
  – oxidation of ammonium: \[ NH_4^+ \rightarrow NO_2^- \rightarrow NO_3^- \]

• Denitrifiers
  – anaerobic reduction of nitrate \[ NO_3^- \rightarrow N_2O, N \]

• N\(_2\) Fixers
  – nitrogen gas reduced into organic forms of nitrogen