MICROBIAL DIVERSITY OF OREGON SOILS: LINKS TO SOIL HEALTH
• To integrate microbial community data with existing soil survey data of soil physical and chemical properties
• To explore the relationship between soil health and microbial communities
Study Design

- Sites stratified by:
  - Common Resource Area (CRA)
  - Acreage
  - Uniqueness
  - Existing pedon data
- 113 sites sampled in Spring 2015
Diversity of Life

• Three Domains
  • Bacteria
  • Archaea
  • Eukarya
Diversity of Life

• Three Domains
  • Bacteria
  • Archaea
  • Eukarya

• Soil microbes in all domains
Diversity of Life

• Three Domains
  • Bacteria
  • Archaea
  • Eukarya

• Soil microbes in all domains

• 1 gram of soil:
  • ~1 billion bacteria and archaea; ~10,000 species
  • ~100 m fungal hyphae, ~500 species
  • Numerous soil animals
Measuring Microbial Diversity

• Potential methods
  • Lipids (PLFA/FAME)
  • DNA amplicon sequencing
  • Shotgun metagenomics
Measuring Microbial Diversity

- Potential methods
  - Lipids (PLFA/FAME)
  - DNA amplicon sequencing
  - Shotgun metagenomics
- DNA amplicon sequencing
  - 16S and ITS rRNA genes
  - 15 million sequences on a single run!
The Microbial Data

- OTUs (operational taxonomic units)
  - Group sequences base on similarity
  - 97% threshold
  - Roughly considered genus level of taxonomy

Taxonomy of Life
- Domain
- Kingdom
- Phylum
- Class
- Order
- Family
- Genus (OTU level)
- Species
The Microbial Data

- **Bacteria and Archaea**
  - 3,049,632 bacteria and archaea
  - 22,984 different OTUs
    - Average of 2,208 different OTUs per sample

- **Fungi**
  - 3,978,809 fungi
  - 9,360 different OTUs
    - Average of 413 different OTUs per sample
Biogeography: Bacteria and Archaea

Soil Order

Alfisols (8)
Andisols (14)
Aridisols (10)
Entisols (2)
Histosols (1)
Inceptisols (11)
Mollisols (54)
Spodosols (2)
Ultisols (3)
Vertisols (1)

Relative Proportion

Bacterial Phylum
- Proteobacteria
- Acidobacteria
- Bacteroidetes
- Verrucomicrobia
- Actinobacteria
- Gemmatimonadetes
- Chloroflexi
- Planctomycetes
- Firmicutes
- Crenarchaeota
- Nitrospirae
- Other
Biogeography: Bacteria and Archaea
Biogeography: Bacteria and Archaea
Biogeography: Bacteria and Archaea

Soil Order
- Alfisols (8)
- Andisols (14)
- Aridisols (10)
- Aridisol (10)
- Entisols (2)
- Histosols (1)
- Inceptisols (11)
- Mollisols (54)
- Spodosols (2)
- Ultisols (3)
- Vertisols (1)
### Biogeography: Bacteria and Archaea

- **PERMANOVA results**

<table>
<thead>
<tr>
<th>Categories</th>
<th>Number of factors</th>
<th>Variance Explained</th>
</tr>
</thead>
<tbody>
<tr>
<td>Suborder</td>
<td>23</td>
<td>33.5%</td>
</tr>
<tr>
<td>Order</td>
<td>10</td>
<td>20.3%</td>
</tr>
<tr>
<td>Land Use</td>
<td>4</td>
<td>17.5%</td>
</tr>
</tbody>
</table>

![Biogeochemistry scatter plot](chart.png)

*Note: The scatter plot shows the distribution of bacterial and archaeal communities across different soil orders.*
Biogeography: Bacteria and Archaea
Biogeography: Bacteria and Archaea
Biogeography: Bacteria and Archaea

![Biogeography: Bacteria and Archaea](image)
Biogeography: Fungi

Soil Order: Alfisols (8), Andisols (14), Aridisols (10), Entisols (2), Histosols (1), Inceptisols (11), Mollisols (54), Spodosols (2), Ultisols (3), Vertisols (1)

Relative Proportion

Fungal Phylum:
- Basidiomycota
- Ascomycota
- Mortierellomycota
- Glomeromycota
- Mucoromycota
- Olpidiomyctota
- Rozellomyctota
- Cercozoa
- Other
### Biogeography: Fungi

- **PERMANOVA results**

<table>
<thead>
<tr>
<th>Categories</th>
<th>Number of factors</th>
<th>Variance Explained</th>
</tr>
</thead>
<tbody>
<tr>
<td>Suborder</td>
<td>23</td>
<td>28.8%</td>
</tr>
<tr>
<td>Order</td>
<td>10</td>
<td>14.9%</td>
</tr>
<tr>
<td>Land Use</td>
<td>4</td>
<td>13.0%</td>
</tr>
</tbody>
</table>
Biogeography: Fungi
Biogeography: Fungi

[Graph showing biogeographical data related to fungi, including variables such as mean annual temperature, mean annual precipitation, soil pH, and land use categories like forest, rangeland, pasture, and cropland.]
Biogeography Insights

• We found that there is evidence for using soil taxonomy as a organizing principle for describing soil bacterial communities

• Bacteria communities seem to be governed by physical and chemical characteristics of the soils

• Our data suggests there is a strong influence of vegetation on fungal communities
## Current Generation Soil Health Assessment

<table>
<thead>
<tr>
<th>Comprehensive Assessment of Soil Health</th>
<th>SHI Tier 1 Measures</th>
<th>SMAF (subset of 81)</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Soil texture</td>
<td>• Soil texture</td>
<td>• Available water capacity</td>
</tr>
<tr>
<td>• Available water capacity</td>
<td>• Available water holding capacity</td>
<td>• Bulk density</td>
</tr>
<tr>
<td>• Surface and subsurface hardness</td>
<td>• Penetration resistance, bulk density</td>
<td>• Water stable aggregates</td>
</tr>
<tr>
<td>• Water stable aggregates</td>
<td>• Water-stable aggregation</td>
<td>• Organic carbon</td>
</tr>
<tr>
<td>• Organic matter</td>
<td>• Organic carbon</td>
<td>• pH, P</td>
</tr>
<tr>
<td>• pH, P, K, Mg, Fe, Mn, Zn</td>
<td>• pH, P, K, CEC</td>
<td>• Soil respiration (qCO$_2$)</td>
</tr>
<tr>
<td>• Soil respiration</td>
<td>• Soil respiration</td>
<td>• Potentially mineralizable N</td>
</tr>
<tr>
<td>• Active carbon</td>
<td>• Crop yield</td>
<td>• Soil depth</td>
</tr>
<tr>
<td>• Soil protein</td>
<td>• Erosion rating</td>
<td>• EC, SAR</td>
</tr>
<tr>
<td></td>
<td>• Infiltration rate</td>
<td>• Microbial biomass C</td>
</tr>
<tr>
<td></td>
<td>• Nitrogen</td>
<td>• Nematode maturity index</td>
</tr>
<tr>
<td></td>
<td>• Base saturation</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Micronutrients</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Electrical conductivity</td>
<td></td>
</tr>
</tbody>
</table>
## Current Generation Soil Health Assessment

### Comprehensive Assessment of Soil Health
- Soil texture
- Available water capacity
- Surface and subsurface hardness
- Water stable aggregates
- Organic matter
- pH, P, K, Mg, Fe, Mn, Zn
- Soil respiration
- Active carbon
- Soil protein

### SHI Tier 1 Measures
- Soil texture
- Available water holding capacity
- Penetration resistance, bulk density
- Water-stable aggregation
- Organic carbon
- pH, P, K, CEC
- Carbon mineralization
- Nitrogen mineralization
- Crop yield
- Erosion rating
- Infiltration rate
- Nitrogen
- Base saturation
- Micronutrients
- Electrical conductivity

### SMAF (subset of 81)
- Available water capacity
- Bulk density
- Water stable aggregates
- Organic carbon
- pH, P
- Soil respiration (qCO₂)
- Potentially mineralizable N
- Soil depth
- EC, SAR
- Microbial biomass C
- Nematode maturity index
## Current Generation Soil Health Assessment

<table>
<thead>
<tr>
<th>Comprehensive Assessment of Soil Health</th>
<th>SHI Tier 1 Measures</th>
<th>SMAF (subset of 81)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil texture</td>
<td>Soil texture</td>
<td>Available water capacity</td>
</tr>
<tr>
<td>Available water capacity</td>
<td>Available water holding capacity</td>
<td>Bulk density</td>
</tr>
<tr>
<td>Surface and subsurface hardness</td>
<td>Penetration resistance, bulk density</td>
<td>Water stable aggregates</td>
</tr>
<tr>
<td>Water stable aggregates</td>
<td>Water-stable aggregation</td>
<td>Organic carbon</td>
</tr>
<tr>
<td>Organic matter</td>
<td>Organic carbon</td>
<td>pH, P, K, CEC</td>
</tr>
<tr>
<td>pH, P, K, Mg, Fe, Mn, Zn</td>
<td>Carbon mineralization</td>
<td>Organic carbon</td>
</tr>
<tr>
<td>Soil respiration</td>
<td>Nitrogen mineralization</td>
<td>pH, P</td>
</tr>
<tr>
<td></td>
<td>Crop yield</td>
<td>Soil respiration (qCO₂)</td>
</tr>
<tr>
<td></td>
<td>Erosion rating</td>
<td>Potentially mineralizable N</td>
</tr>
<tr>
<td></td>
<td>Infiltration rate</td>
<td>Soil depth</td>
</tr>
<tr>
<td></td>
<td>Nitrogen</td>
<td>EC, SAR</td>
</tr>
<tr>
<td></td>
<td>Base saturation</td>
<td>Microbial biomass C</td>
</tr>
<tr>
<td></td>
<td>Micronutrients</td>
<td>Nematode maturity index</td>
</tr>
<tr>
<td></td>
<td>Electrical conductivity</td>
<td></td>
</tr>
</tbody>
</table>
If soil health is centered on the living soil ecosystem, why aren’t there direct measures of the biological component of soil?
Biological Characteristics to Consider

Abundance

Diversity

Composition
Biological Characteristics to Consider

- Abundance
- Diversity
- Function
- Composition
Biological Characteristics to Consider

Abundance—function
• Most studies of specific functions find a positive relationship

Abundance
diversity
function
composition

Biological Characteristics to Consider

Abundance—function
- Most studies of specific functions find a positive relationship

Diversity—function
- More mixed results, e.g., lower diversity resulted in lower soil respiration but had no effect on litter decomposition

Rocca et al. (2015) ISME J 9:1693
De Graaff et al. (2015) Soil 1:5257
Biological Characteristics to Consider

Abundance—function
• Most studies of specific functions find a positive relationship

Diversity—function
• More mixed results, e.g., lower diversity resulted in lower soil respiration but had no effect on litter decomposition

Composition—function
• Most studies find activity varies with composition

De Graaff et al. (2015) *Soil* 1:5257
Bier et al. (2015) *FEMS Microbiol Ecol* 91:113
Soil Health

- Field assessment of soil quality

<table>
<thead>
<tr>
<th>Soil Health on Cropland adapted from the OSU Willamette Valley Soil Quality Card</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rate the following questions on a scale of 1 to 10.</td>
</tr>
<tr>
<td>1. Does the soil have good structure and tilth?</td>
</tr>
<tr>
<td>2. Is the soil free of compacted layers?</td>
</tr>
<tr>
<td>3. Is the soil full of living organisms?</td>
</tr>
<tr>
<td>4. Are earthworms abundant in the soil?</td>
</tr>
<tr>
<td>5. Is plant residue present and decomposing?</td>
</tr>
<tr>
<td>6. Do crops/weeds appear healthy and vigorous?</td>
</tr>
<tr>
<td>7. Do plant roots grow well?</td>
</tr>
</tbody>
</table>

Soil Health on Rangeland adapted from Interpreting Indicators of Rangeland Health

<table>
<thead>
<tr>
<th>Soil Health on Rangeland adapted from Interpreting Indicators of Rangeland Health</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Are there rills (small erosional rills) on the site?</td>
</tr>
<tr>
<td>2. Is there evidence of water flow patterns on the site?</td>
</tr>
<tr>
<td>3. Are there pedestals (rocks or plants appear elevated) or terraces (plains of soil deposition behind obstacles) on the site?</td>
</tr>
<tr>
<td>4. Is there evidence of windscour, blowout, or depositional areas on the site?</td>
</tr>
<tr>
<td>5. Is there evidence of litter at the site? (If it has not all blown/washed away)</td>
</tr>
<tr>
<td>6. Is the soil surface resistant to erosion? (Strong aggregates, biological crusts, or adhesion of decomposing organic matter to the soil surface)</td>
</tr>
<tr>
<td>7. Is the soil surface lost (to erosion) or degraded?</td>
</tr>
<tr>
<td>8. Is the near soil surface compacted?</td>
</tr>
<tr>
<td>9. Is there a mixture of age classes of plants?</td>
</tr>
</tbody>
</table>

Soil Health on Pastureland adapted from PRW Extension’s Pasture and Grazing Management in the Northwest

<table>
<thead>
<tr>
<th>Soil Health on Pastureland adapted from PRW Extension’s Pasture and Grazing Management in the Northwest</th>
</tr>
</thead>
<tbody>
<tr>
<td>Please circle the most appropriate answer for the following questions:</td>
</tr>
<tr>
<td>1. Plant diversity - Diversity of forage species.</td>
</tr>
<tr>
<td>2. Plant vigor of desirable plants.</td>
</tr>
<tr>
<td>3. Severity of Use - (What is the grazing pressure).</td>
</tr>
<tr>
<td>4. The soil compaction level is:</td>
</tr>
<tr>
<td>5. The soil shows signs of erosion.</td>
</tr>
<tr>
<td>6. Is there dead or decaying plant residue?</td>
</tr>
</tbody>
</table>

Soil Health on Forestland adapted from the USFS Forest Health Indicators

<table>
<thead>
<tr>
<th>Soil Health on Forestland adapted from the USFS Forest Health Indicators</th>
</tr>
</thead>
<tbody>
<tr>
<td>Please circle the most appropriate answer for the following questions:</td>
</tr>
<tr>
<td>1. Plant diversity at the site is:</td>
</tr>
<tr>
<td>2. The soil compaction level is:</td>
</tr>
<tr>
<td>3. The soil shows signs of erosion</td>
</tr>
</tbody>
</table>

Please attach any additional information or include it in the notes section on the opposite side of this form.
# Soil Health: Cropland

## Soil Health on Cropland adapted from the OSU Willamette Valley Soil Quality Card

<table>
<thead>
<tr>
<th>Rate the following questions on a scale of 1 to 10.</th>
<th>Rating</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>1. Does the soil have good structure and tilth?</strong></td>
<td>Cloddy, powdery, massy or flaky</td>
<td>Some visible crumb structure</td>
<td>Friable, crumbly</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>2. Is the soil free of compacted layers?</strong></td>
<td>Obvious hardpan, turned roots</td>
<td>Some restrictions to root growth</td>
<td>No restrictions to root growth</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>3. Is the soil full of living organisms?</strong></td>
<td>Little or no observable soil life</td>
<td>Some (moving) soil critters</td>
<td>Soil is full of a variety of soil organisms</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>4. Are earthworms abundant in the soil?</strong></td>
<td>No earthworms</td>
<td>Few earthworm holes or casts</td>
<td>Many earthworms, earthworm holes, and casts</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>5. Is plant residue present and decomposing?</strong></td>
<td>No residue or not decomposing for long periods</td>
<td>Some residue slowly decomposing</td>
<td>Residue in all stages of decomposition, earthy, sweet smell</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>6. Do crops/weeds appear healthy and vigorous?</strong></td>
<td>Stunted growth, discolored, uneven stand</td>
<td>Some uneven stunted growth, slight discoloration</td>
<td>Healthy, vigorously and uniformly growing plants</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>7. Do plant roots grow well?</strong></td>
<td>Poor root growth and structure, brown or mushy roots</td>
<td>Some fine roots, mostly healthy</td>
<td>Vigorous, healthy root system with desirable root color</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

## Soil Health on Rangeland adapted from Interpreting Indicators of Rangeland Health

1. Are there rills (small erosional ruts) on the site?  
2. Is there evidence of water flow patterns on the site?  
3. Are there pedestals (rocks or plants appear elevated) or terraces (berches of soil deposition behind obstacles) on the site?  
4. Is there evidence of windscou, blowout, or depositional areas on the site?  
5. Is there evidence of litter at the site? (It has not all blown away)  
6. Is the soil surface resistant to erosion? (Strong aggregates, biological crusts, or anhesion of decomposition organ matter to the soil surface)  
7. Is the soil surface lumps (or depressed) or degraded?  
8. Is the soil surface compacted?  
9. Is there a mixture of age classes of plants?  

Please circle the most appropriate answer for the following questions.

## Soil Health on Pastureland adapted from the N.D. Estesner’s Pasture and Grazing Management in the Northeast

<table>
<thead>
<tr>
<th>Plant Diversity - Diversity of forage species</th>
<th>&gt; 7 - 10 species</th>
<th>4 - 6 species</th>
<th>&lt; 5 species</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plant vigor of desirable plants, strong</td>
<td>weak</td>
<td>medium</td>
<td>weak</td>
</tr>
<tr>
<td>Severity of Use - (What is the grazing pressure), heavy</td>
<td>appropriate</td>
<td>light</td>
<td>heavy</td>
</tr>
<tr>
<td>The soil compaction level is: severe</td>
<td>slight or none</td>
<td>none</td>
<td>slight or none</td>
</tr>
<tr>
<td>The soil shows signs of erosion: severe</td>
<td>slight or none</td>
<td>none</td>
<td>slight or none</td>
</tr>
</tbody>
</table>

Please circle the most appropriate answer for the following questions.

## Soil Health on Forestland adapted from the USDA Forest Health Indicators

<table>
<thead>
<tr>
<th>Plant diversity at the site is High</th>
<th>Diversity and community structure</th>
<th>Medium</th>
<th>Low</th>
<th>Monoculture tree species</th>
</tr>
</thead>
<tbody>
<tr>
<td>The soil compaction level is</td>
<td>severe</td>
<td>slight</td>
<td>severe</td>
<td>slight or none</td>
</tr>
<tr>
<td>The soil shows signs of erosion:</td>
<td>severe</td>
<td>slight</td>
<td>severe</td>
<td>slight or none</td>
</tr>
</tbody>
</table>

Please attach any additional information or include it in the notes section on the opposite side of this form.
Soil Health

• Field assessment of soil quality
Soil Health: Cropland
Microbial Diversity

• Alpha Diversity
  • The diversity within a sample
  • Richness
  • Evenness
Cropland: Bacteria Diversity vs. Soil Health
Cropland: Bacteria Diversity vs. Soil Health
Cropland: Fungal Diversity vs. Soil Health

![Graph showing fungal alpha diversity vs. soil quality score for observed and Shannon indices.](image)
Cropland: Fungal Community Composition
Cropland: Bacterial Community Composition
Soil Health Insights and Next Steps

• We found relationships between bacterial/fungal diversity/composition and soil quality scores
  • The pattern for diversity seemed stronger for bacteria; that for composition seemed stronger for fungi
Soil Health Insights and Next Steps

• We found relationships between bacterial/fungal diversity/composition and soil quality scores
  • The pattern for diversity seemed stronger for bacteria; that for composition seemed stronger for fungi

• Additional analyses
  • Compile a laboratory based soil health score
  • Complete bacterial and fungal abundance data
  • Look for indicator taxa
Soil Health Insights and Next Steps

• We found relationships between bacterial/fungal diversity/composition and soil quality scores
  • The pattern for diversity seemed stronger for bacteria; that for composition seemed stronger for fungi

• Additional analyses
  • Compile a laboratory based soil health score
  • Complete bacterial and fungal abundance data
  • Look for indicator taxa

• Additional research
  • Greater density of sampling with selected regions
  • Sample from greater range of crop/management systems
Acknowledgments

OSU
- Karl Rhinhart
- Kristin Kasschau
- Brian Hill

Landowners
- Allen Farms, Breda Flynn, Glen Lorenz, Jr.

PNNL
- Sarah Fansler

ANL
- Sarah Owens

NRCS (and collaborators)
- Portland: Thor Thorson, Cory Owens, Ron Raney, Kyle Stephens, Whityn Owen, Carl Evans, Amy Meredith, Jonas Parker, Pat Jones, Rudy Wiedenbeck, Julie Stewart, Joni Brazier, Lynn Evans, Paul Showalter
- John Day: Stan Winther
- Klamath Falls: Chris Gebauer, Katrin Chambers
- Ontario: Jeff Pace, Shanna Bernal-Fields, Meghan Krueger
- Pasco: Kelley Paup-Lefferts, Scott Bare, Keith Harrington
- Redmond: Kurt Moffitt, Gabrielle Coughlin, Jennifer Moffitt, Emily Weidner, Abe Clark, Evelyn Conrad, Damon Brosnan
- Salem: Jason Martin, David Rand, Dave Johnson, Brandi Baird, Sue Reams, Matthew Fillmore, David Thompson
- Tillamook: Rebecca Rudd