SOIL QUALITY: functional capacity of soil to meet defined human needs by supporting optimal biological activity and diversity for economic production of crops and livestock, regulation of water flow and storage, and provision of environmental buffers.

SOIL HEALTH: continued capacity of soil as a vital living system whereby plant and animal growth and environmental quality is sustained; a holistic approach in which plant, animal, and human health is promoted.
Environmental Conditions

- SOIL
  - Physical properties
  - Chemical properties
- COVER CROPS
- ROOTS (Rhizosphere)
- MICROBIAL COMMUNITY

SOIL ORGANIC MATTER (SOM)

SOIL QUALITY OR SOIL HEALTH

SOIL BIOLOGY
Soil Microbial Diversity (Soil Biodiversity)
[biodiversity = most valuable property of any ecosystem; E.O Wilson, 1999]

Biodiversity
• Provides a range of pathways for primary production and ecological processes (i.e., nutrient cycling)
  • Many processes require multiple different organisms (“Consortia”) to be carried out completely
• Alternative pathways available if one is disturbed
• Ecosystem stability and resistance to stress
• Microbial biomass may withstand stress; diversity may be reduced

Example of Structural Diversity:
Biodiversity in a hypothetical block of field soil --

HEALTHY SOIL, essential to agriculture, is a complex, living medium. The loose but coherent structure of good soil holds moisture and invites airflow. Ants (a) and earthworms (b) mix the soil naturally. *Rhizobium* bacteria (c) living in the root nodules of legumes (such as soybeans) create fixed nitrogen, an essential plant nutrient. Other soil microorganisms, including fungi (d), actinomycetes (e) and bacteria (f), decompose organic matter, thereby releasing more nutrients. Microorganisms also produce substances that help soil particles adhere to one another. To remain healthy, soil must be fed organic materials such as various manures and crop residues.

*Source*: Reganold et al. 1990.
Ideal “functional diversity” in healthy soil provided the diverse microbes necessary for efficient nutrient cycling.

Note: Example for only one of the numerous functions microbes mediate in soils.
Important biological attributes of ‘healthy soils’ are influenced by vigorously growing plants

• Soil Microbial Diversity (Biodiversity)

• Soil Carbon Content & Quality -- Plant root contributions
  • (SOM ≈ 58% C)

Rhizobacteria on plant root surface metabolize plant-derived C and interact with plant.
Soil Microbial Structure and Biological Functions (“Functional Diversity”) Influenced by Plant Roots

Rhizodeposition - 20-60% photosynthate released into rhizosphere (depending on plant)

Fig. 1. Influencing factors of rhizosphere microbial communities and model how microbial communities were selected from soil: by root exudates and their rhizosphere competence. *Factors that are analysed in the review.

Berg & Smalla, 2009
Various common plant-microbe associations

Relative strengths of forces shaping microbial communities

axes depict relative forces exerted by plant, soil, and microbial type. Management and abiotic conditions on plant-soil-microbe interactions further define the microbial community in an agroecosystem. Time that a cropping system is used determines long-term microbial changes.

Management Factor
Do current transgenic cropping systems affect soil microbial function and soil health?

Example: Transgenic Glyphosate-resistant crops and Herbicide Glyphosate

Enters soil – Burndown (Knockdown) applications, direct contact (spray misses foliage), spray drift, released through roots of both susceptible and resistant (including transgenic crops) plants, which allows for efficient, non-selective weed control

Glyphosate is simple molecule but difficult to dissipate
Highly diverse microbial community (consortia) needed to completely degrade glyphosate in the soil environment - well-managed soils is key to success -

Pathway 1:
Enzyme 1 (GOX)
(Phosphonate bond)

Aminomethyl phosphonic acid (AMPA) + Glyoxalate

Pathway 2:

Glyoxalate + CO₂

Pathway 3:
Enzyme 2
+ Acetyl CoA

Sarcosine + CO₂

Enzyme 3 (Gdc)

Glycine

Complete biodegradation requires specific enzymes from many microbes, thus glyphosate may persist in active state in soil longer than generally assumed

Enzymes: 1, Glyphosate oxidoreductase; 2, C-P Lyase; 3, Glyphosate decarboxylase complex; 4, Glyphosate acetyl transferase
Some factors affecting persistence, availability, degradation of glyphosate in soils:

1. Soil pH
2. Soil mineralogy (texture)
3. Soil organic matter content
4. Soil P content, sorption
5. Soil nutrient status (cationic nutrient content)
6. Herbicide formulation and components (i.e., surfactants)
7. Soil surface vegetative residue cover
8. Type of crop management system in place (crop sequence, cover crops)
9. Composition of soil microbial community
Primary mechanism of action of glyphosate is inhibition of aromatic amino acid synthesis; non-selective

5-enolpyruvylshikimate-3-phosphate (EPSP) synthase

Glyphosate is a competitive inhibitor of EPSPS, needed for aromatic amino acid synthesis and proteins; without them, ALL PLANTS DIE.

Modified from Dr. Gina Malczewski
Also an apparent “secondary mode of action” -- soil microbes attack and infect plant roots -- plant-defense compounds derived from aromatic amino acids are not synthesized.

Glyphosate-treated plants do not die if grown in a sterile medium, and tend to resume growth over time as the herbicide leaches out or is metabolized.  
What happens to glyphosate-resistant (GR) crops when treated with glyphosate?

GR soybean showing chlorosis post-glyphosate application – 2009

Glyphosate also binds to cation nutrients

Insufficient nutrient availability and poor herbicide management often confounds overall effects of glyphosate use

Soybean – 2010
Other properties of Glyphosate

*Systemic* – transported throughout the plant.

In RR soybean, glyphosate has been found *localized* in meristematic tissues of growing points, leaves and roots; pod and seed; nodules.

Also glyphosate is *actively released through roots* into rhizosphere soil (root zone) likely with high amounts of carbohydrates & N-compounds in RR soybean - influence microbial community in rhizosphere


Cation chelator - may immobilize critical plant and microorganism nutrients


Glyphosate may also be transferred from treated plants to nontarget living plants via root release

(Neumann et al. 2008)
2010 Soybean (Asgrow RR2Y) – Osage County, MO

Fescue burndown

Fescue – no burndown

Scenarios - Substrates & glyphosate release from grass roots; soil fungi proliferate on grass AND soybean seedling roots; effects of soil residual glyphosate?
Representative GR soybean root colonization assay results observed consistently, 1997-2007

Fusarium colonization – 2007 study

+ Glyphosate  
Check

Glyphosate applied at 0.84 kg a.e./ha (0.75 lb/A) on Pioneer ‘94B01’ at growth stage V4, June 1998 in Pemiscott County, MO

Presence of *Fusarium* is indicator of microbial imbalance in rhizosphere and only potential for pathogenicity.

Fusarium root colonization on GR corn (‘DeKalb DKC60’) Boone County field trial, 2003

Kremer & Means 2009
Glyphosate is released through Glyphosate-resistant and non-transgenic soybean; soluble carbohydrates and amino acids increased in exudates by use of glyphosate and GR soybean.

GR = Glyphosate-resistant soybean
W82 = Non-transgenic soybean (Williams 82)
Gly = Glyphosate

Potential impact of glyphosate on beneficial microorganisms

• Soybean-Bradyrhizobium relationship:

• Reduced fluorescent pseudomonad bacteria:
  Responsible for suppressing fungal growth in root zone, mobilizing nutrients for plant uptake, and producing plant-growth promoting substances

Potential Mn-oxidizing (black) & Mn-reducing bacteria (white, clear) and fungi on roots, in rhizosphere soils

Mn transformations primarily microbially-mediated, thus have major impact on plant nutrient availability. Is glyphosate released into soil involved in Mn availability?

Microbial growth on Gerritsen’s medium (Huber & Graham 1992)
Ratio of potential Mn-reducing and Mn-oxidizing bacteria in rhizosphere of soybean-herbicide treatments - Stage R2, 2006

Higher ratio of Mn-reducers:Mn oxidizers implies higher plant availability of Mn (Rengel. Plant Soil 196:255, 1997)

W82= ‘Williams 82’; RR 2006=DK-838-52; TM= Conventional herbicide tankmix; RU= Roundup

Kremer & Means 2009
Importance of maintaining adequate soil fertility/plant nutrition in GR crop production:
Understanding plant-soil-microbial relationship with GR crops -
Possibilities for nutrient deficiency in plant when soil test indicates sufficient levels

Microbial DNA fingerprints of corn and soybean rhizospheres reveal differences in **DIVERSITY** among varieties and treatments – Higher diversity reflects greater and balanced functional activities beneficial for crop growth/health and soil quality; indicates glyphosate may affect diversity; more study on a greater selection of varieties and soils is needed. **NOTE: Evaluate rhizosphere soil rather than ‘bulk soils’**

Potential impact of *glyphosate introduced into rhizosphere* on mycorrhizal spore germination and root colonization


Demonstrated in grassland ecosystems

Low soil water content affects density of *Fusarium* colonization of soybean root (Means & Kremer 2007)
Saturated soil affects glyphosate effect on soybean root nodulation by rhizobia (Kremer et al. 2010)

What is impact of altered plant-microorganism interactions on **YIELD**?

* Often little impact on yield *

However ----

Possible effect on **potential** for higher yields?

(Better nodulation with no glyphosate likely contributed to slight yield increase in 2010 under wet soil conditions)

Cultivars:
2006 – Pioneer 93M90; Williams 82
2007 – Pioneer 93M92
2008 – DeKalb DK3852; Maverick
2010 – Asgrow AG3539; Maverick

Data shown from field trials in Boone County, MO.

The problem of glyphosate-resistant weeds in glyphosate-resistant crops

Soybean - Missouri, 2010
Post herbicide - lactofen (Cobra ™)
Recent development involving potential soilborne pathogens and glyphosate is of concern --

**Potential resistance to soil fungal pathogens by weeds may occur with simultaneous resistance developed to glyphosate**
(Schafer et al. 2013. Weed Science)

GR-Giant ragweed (*Ambrosia trifida* ‘Indiana biotype’)
Also resistant to soilborne pathogen (i.e., *Pythium*), relative to susceptible biotype that is readily infected.
Application of alternative herbicides to herbicide-resistant weeds may develop additional changes in soil microbial diversity – a possibility with auxin-like herbicides?

Figure 1. Populations of fluorescent Pseudomonas spp. in the cortex of wheat (var. Maris Dove) treated with mecoprop (10 kg ha⁻¹). Plants were grown in sand and populations counted by plate-dilution technique after maceration of washed roots. The arrow indicates time of spraying.

Greaves & Sargent. 1986. Weed Sci. 34 (Suppl. 1):50
Soil Microbial Structure and Biological Functions (“Functional Diversity”) Influenced by Plant Roots

• Release of systemic pesticides
• Release of transgenic DNA; “plant-incorporated proteins”
Possible fates of transgenic DNA released into soil

The DNA cycle in soil (From: Levy-Booth et al. 2007. Soil Biology & Biochemistry 39:2977-2991)

(A) Entry of DNA into Soil; (B) Persistence of DNA in Soil; (C) Transfer of DNA in Soil; (D) Degradation of DNA in Soil

All plant DNA is transient in soil – rapid degradation suggests limited opportunity for natural transformation of transgenic DNA into soil microbes – Gulden et al. 2008. Weed Science 56:767-774
Management Keys

• Can transgenic crops (and widespread use of a single herbicide) be sustainably managed to maintain/improve our soil resource and soil health?
Glyphosate-resistant cropping is one “tool” for use in production systems – responsible integration into the management system remains a critical issue.
Sufficient diverse functional activity requires **sufficient nutrients**

Nutrients are essential to physiological and biochemical functions, many common to *both* plants and microorganisms

<table>
<thead>
<tr>
<th>Nutrient elements</th>
<th>Biochemical/Physiological functions</th>
</tr>
</thead>
<tbody>
<tr>
<td>C, O, H, N, S</td>
<td>Major constituents of organic substances (carbohydrates, proteins, lipids, enzymes)</td>
</tr>
<tr>
<td>P, Ca, B</td>
<td>Linkage of major polymers in cell walls and membranes (phospholipids, nucleotides; cellulose); energy transfer</td>
</tr>
<tr>
<td>K, Mg</td>
<td>Cellular ion, pH balance; enzyme activation; photosynthetic activity</td>
</tr>
<tr>
<td>Mn, Fe, Cu, Zn, Mo, Ni</td>
<td>Activate/mediate numerous important <strong>enzymatic reactions</strong> in various metabolic pathways</td>
</tr>
</tbody>
</table>

**Note:** *Deficiency or immobilization* of an essential nutrient may affect one or more metabolic pathways, yet have consequences on **overall functioning** of plant or microorganism

Management practices to overcome adverse effects on Mycorrhizae

Table 1
AMF biomass estimated by the AMF fatty acid biomarker C16:1cis11 as affected by cover crop at Site 1 (Brookings).

<table>
<thead>
<tr>
<th>Cover crop</th>
<th>2009 FAME (nmol g(^{-1}) dry soil)</th>
<th>2009 Stats grouping(^a)</th>
<th>2010 FAME (nmol g(^{-1}) dry soil)</th>
</tr>
</thead>
<tbody>
<tr>
<td>None</td>
<td>58.12</td>
<td>E</td>
<td>27.44</td>
</tr>
<tr>
<td>Canola</td>
<td>82.59</td>
<td>DE</td>
<td>40.34</td>
</tr>
<tr>
<td>Oat</td>
<td>146.50</td>
<td>BCD</td>
<td>83.55(\textcolor{red}{*})</td>
</tr>
<tr>
<td>Vetch</td>
<td>111.06</td>
<td>CDE</td>
<td>41.73</td>
</tr>
<tr>
<td>Oat–canola</td>
<td>213.15</td>
<td>A</td>
<td>76.89(\textcolor{red}{*})</td>
</tr>
<tr>
<td>Oat–vetch</td>
<td>176.05</td>
<td>ABC</td>
<td>103.25(\textcolor{red}{*})</td>
</tr>
<tr>
<td>Canola–vetch</td>
<td>83.92</td>
<td>DE</td>
<td>42.80</td>
</tr>
<tr>
<td>Oat–canola–vetch</td>
<td>179.97</td>
<td>AB</td>
<td>111.51(\textcolor{red}{*})</td>
</tr>
</tbody>
</table>

\(^a\) Means with an identical letter are not significantly different based on LSD (0.05) comparison.

Lehman et al., 2012
Summary

Transgenic crops may interact differently with soil/rhizosphere microbial community relative to non-transgenic crops.

Rhizosphere interactions may be influenced by transgenic crop and/or continuous use of herbicide.

Soil biological and ecological factors and their impact on soil health are basic to overall sustainable crop management regardless of crop type (transgenic or non-transgenic).

Cultural practices integrated with chemical-based approaches can improve soil quality and potentially reduce incidence of herbicide-resistance weeds.

Current weed management in major crops as a single-component approach has high probability for weed control failure.

A multiple-component, total weed management system needs to be re-considered for effective weed control.
ACKNOWLEDGMENT

Many thanks to my host Dr. Gavin Lu and American Chemical Society - Midland Section for invitation to visit Midland to participate in the Science Lecture.
“Soil quality is considered the major linkage between conservation management practices and achievement of major goals of sustainable agriculture” including weed suppression.


STRATEGY:
Cover Cropping
Residue management
Organic recycling
Integrated biological management

GOAL:
Sustainable Production
Resource conservation
Environmental health
Weed suppression
Disease suppression