


Healthy soils for productive and resilient farms: the untapped potential under our feet

Amélie Gaudin

Professor and Endowed Chair in Agroecology
Department of Plant Sciences
University of California Davis
agaudin@ucdavis.edu
gaudin.ucdavis.edu

Kate Scow

Distinguished Professor of Soil Science and Microbial Ecology
Dept. of Land, Air and Water Resources.
University of California Davis
kmscow@ucdavis.edu

A lack of emphasis on orchard soils has resulted in evitable management challenges

- Compaction
- Runoff and erosion
- Salinity challenges
- Soil borne disease pressure
- Untapped yield potential

There are lots of opportunities to build healthy soils that support ***regenerative*** & ***productive*** orchards

Up to + ~225 to 400 lbs/acre
(year 2 and 3 respectively)

Soil health refers to the capacity of soil to function as a *vital living* ecosystem that sustains plants, animals, and humans.

Soils are ***living and dynamic ecosystems*** that support many critical sustainability and productivity goals in avocado orchards

Healthy soils:

Have adequate fertility

Have good soil structure

Have active & diverse soil communities

Conserve and cycle nutrients and water

Sustainable agriculture

⬆ Water & nutrient use efficiency

⬆ Carbon storage potential

⬇ Leaching, salinity, some soil borne pests and soil loss potential

⬆ Productivity

Soil health: capacity of soil to function as a vital living ecosystem that sustains plants, animals, and humans

The health *metaphor*

- It is a measure of how well soil performs its essential functions
- Goes beyond soil composition itself to describe how well its thrives, respond to disturbances ect….
- Complex to measure, relies on a suite of indicators
- Health of a soil is dynamic (time, space)

Soil health: capacity of soil to function as a vital living ecosystem that sustains plants, animals, and humans

Determinants

- Our health
  - Parents (genes) x
  - Environment x
  - Actions (Diet, Exercise…)

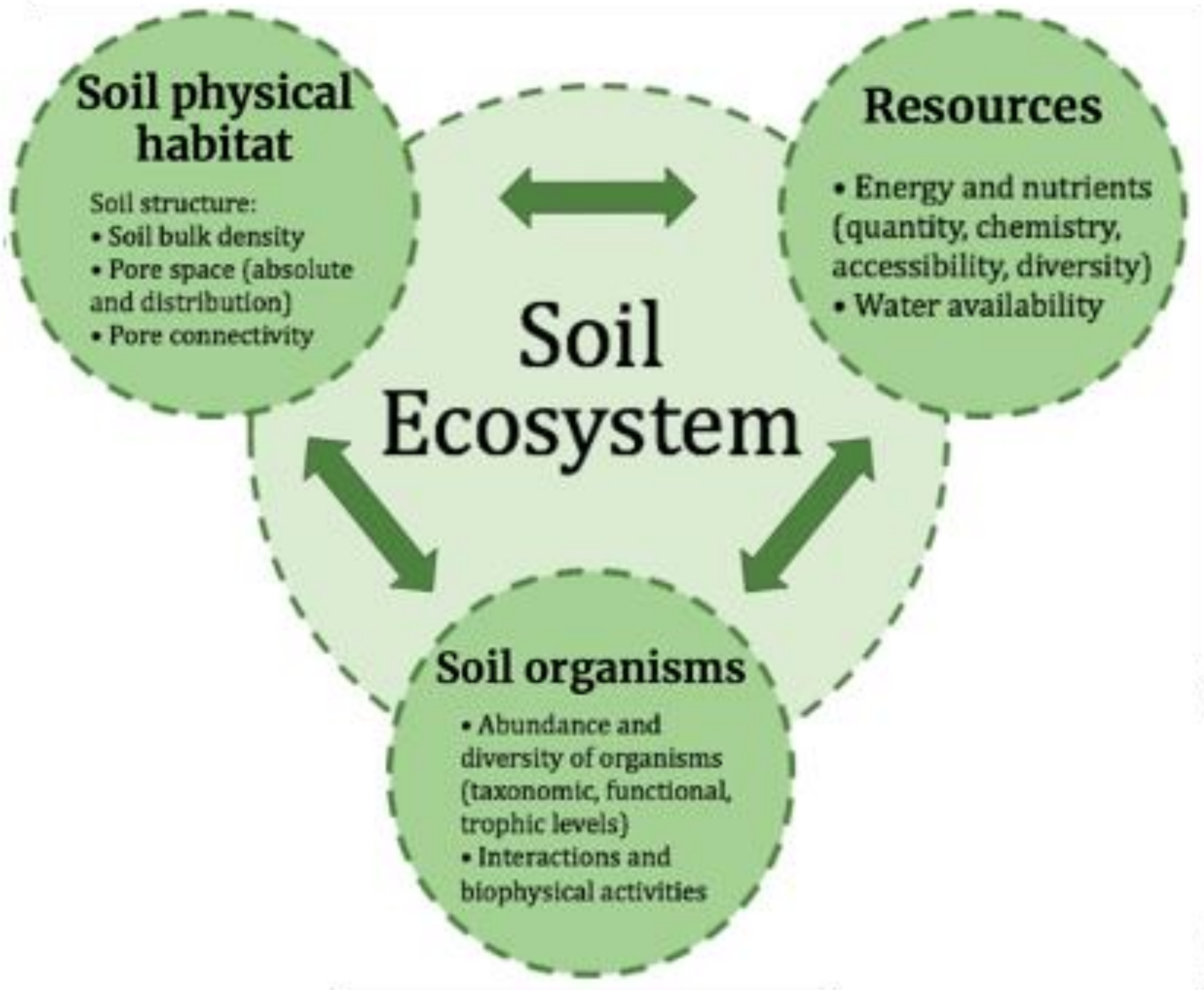
- Soil Health
  - Parents (rocks -- texture) x
  - Environment x
  - Actions (Ag management)

Actions impact dynamic properties
– soil life and organic matter --

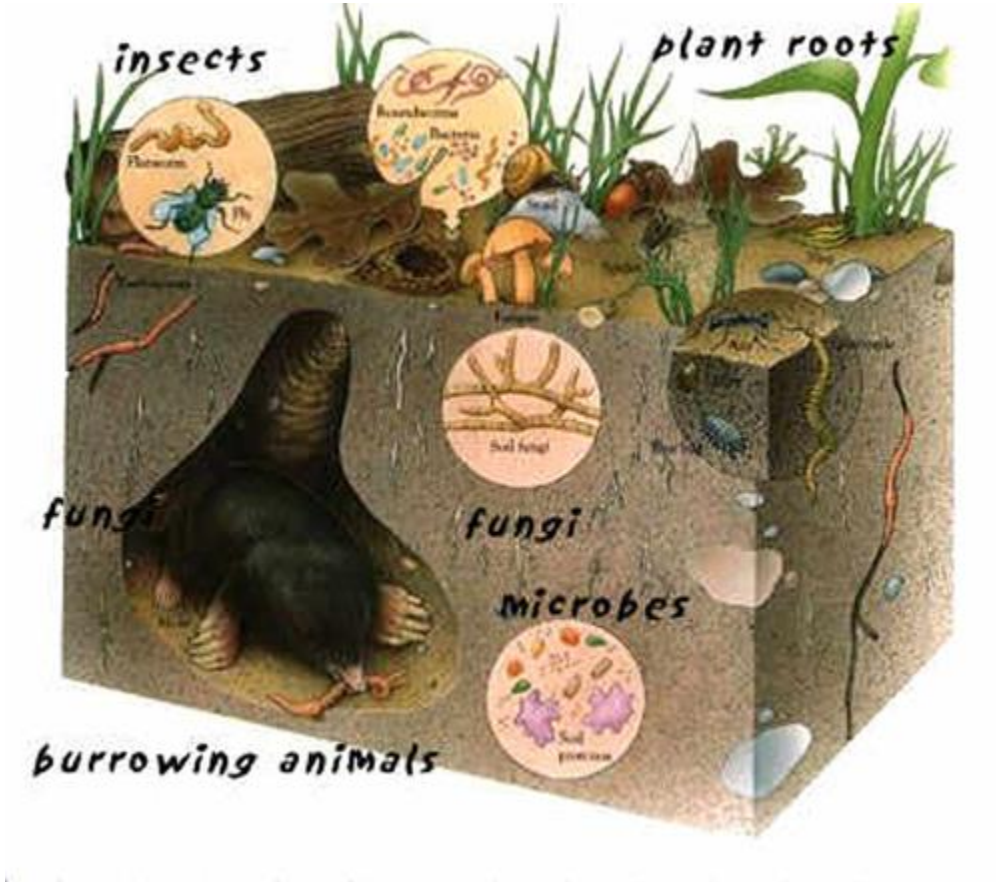





CHEMISTRY
SOIL HEALTH
PHYSICAL
BIOLOGY

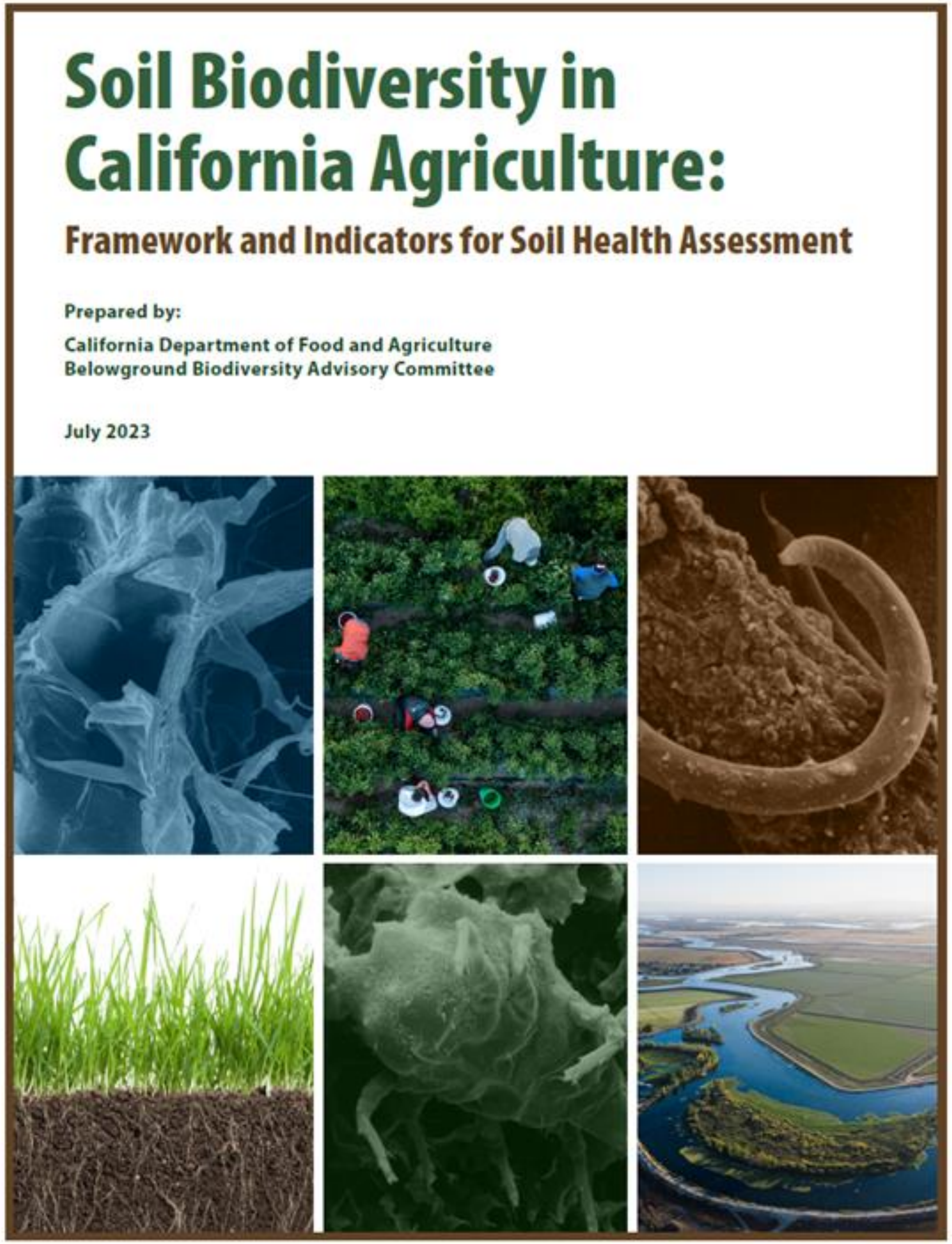

Soil physical habitat
Soil structure:
• Soil bulk density
• Pore space (absolute and distribution)
• Pore connectivity
Resources
• Energy and nutrients (quantity, chemistry, accessibility, diversity)
• Water availability
Soil Ecosystem
Soil organisms
• Abundance and diversity of organisms (taxonomic, functional, trophic levels)
• Interactions and biophysical activities

Soil biodiversity: the underpinning of soil health



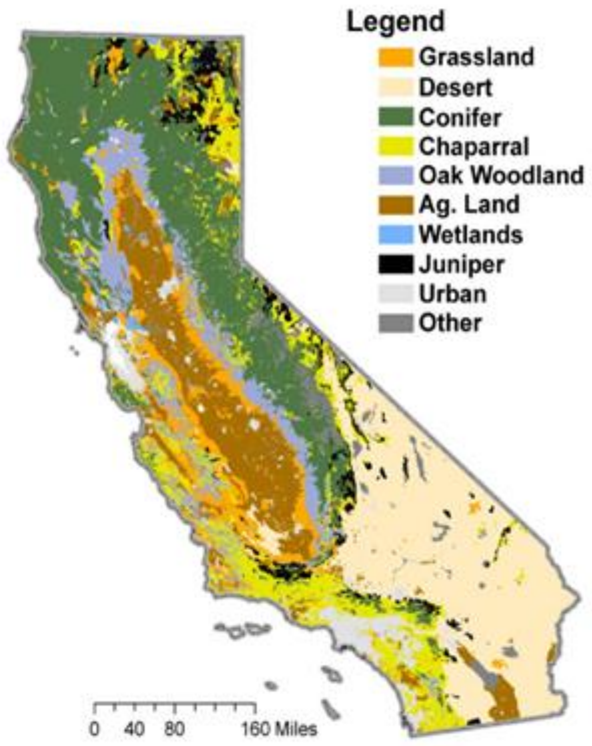
- Identify biodiversity indicators relevant to soil health in agroecosystems
- Develop a framework and provide example CA-based case studies to assist in biodiversity indicator selection.
- Provide recommendations and identify opportunities for collaboration, outreach and future research

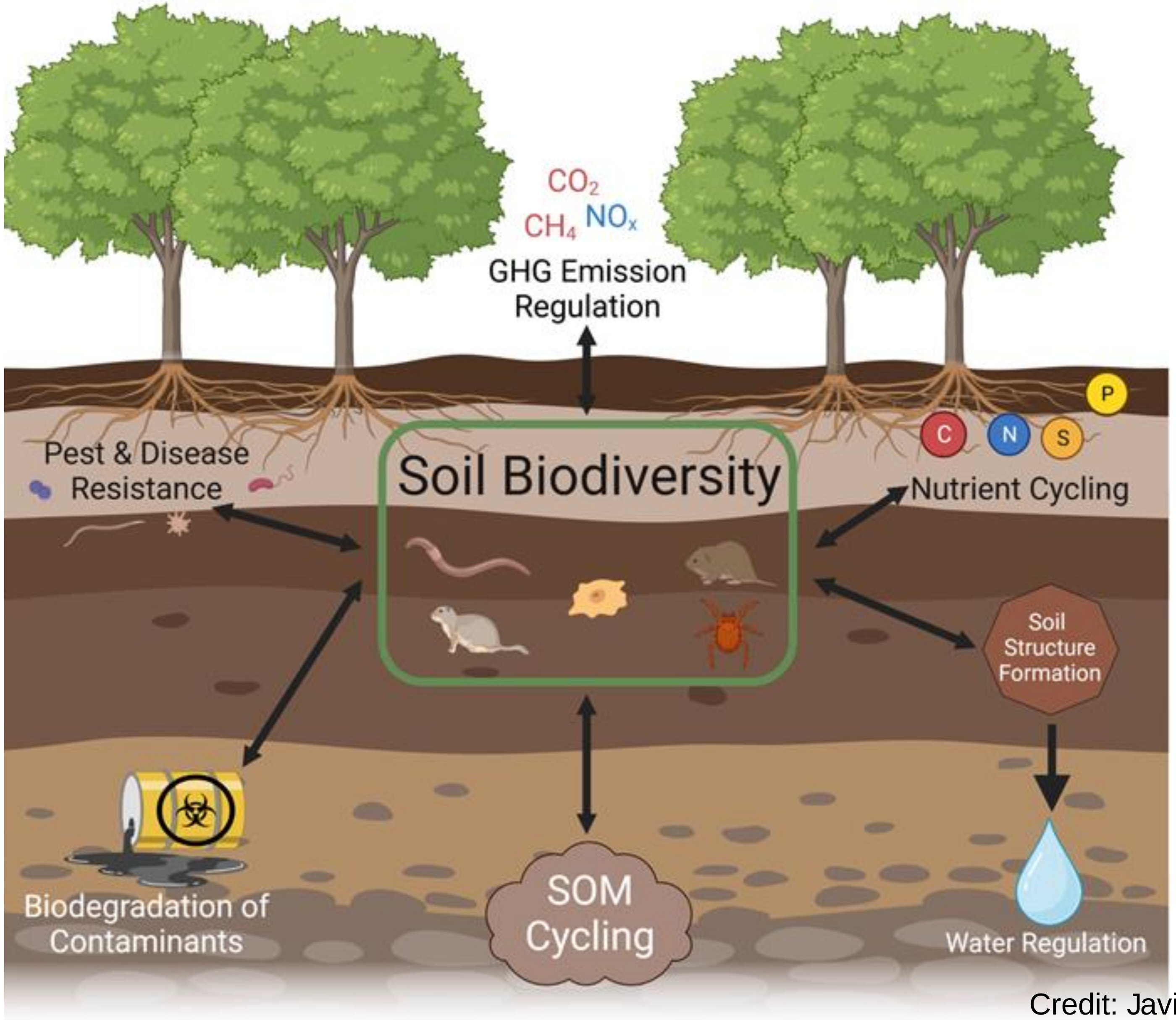
https://www.cdfa.ca.gov/oefi/biodiversity/docs/Soil_



Soil biodiversity is primary (unseen) driver of terrestrial ecosystems

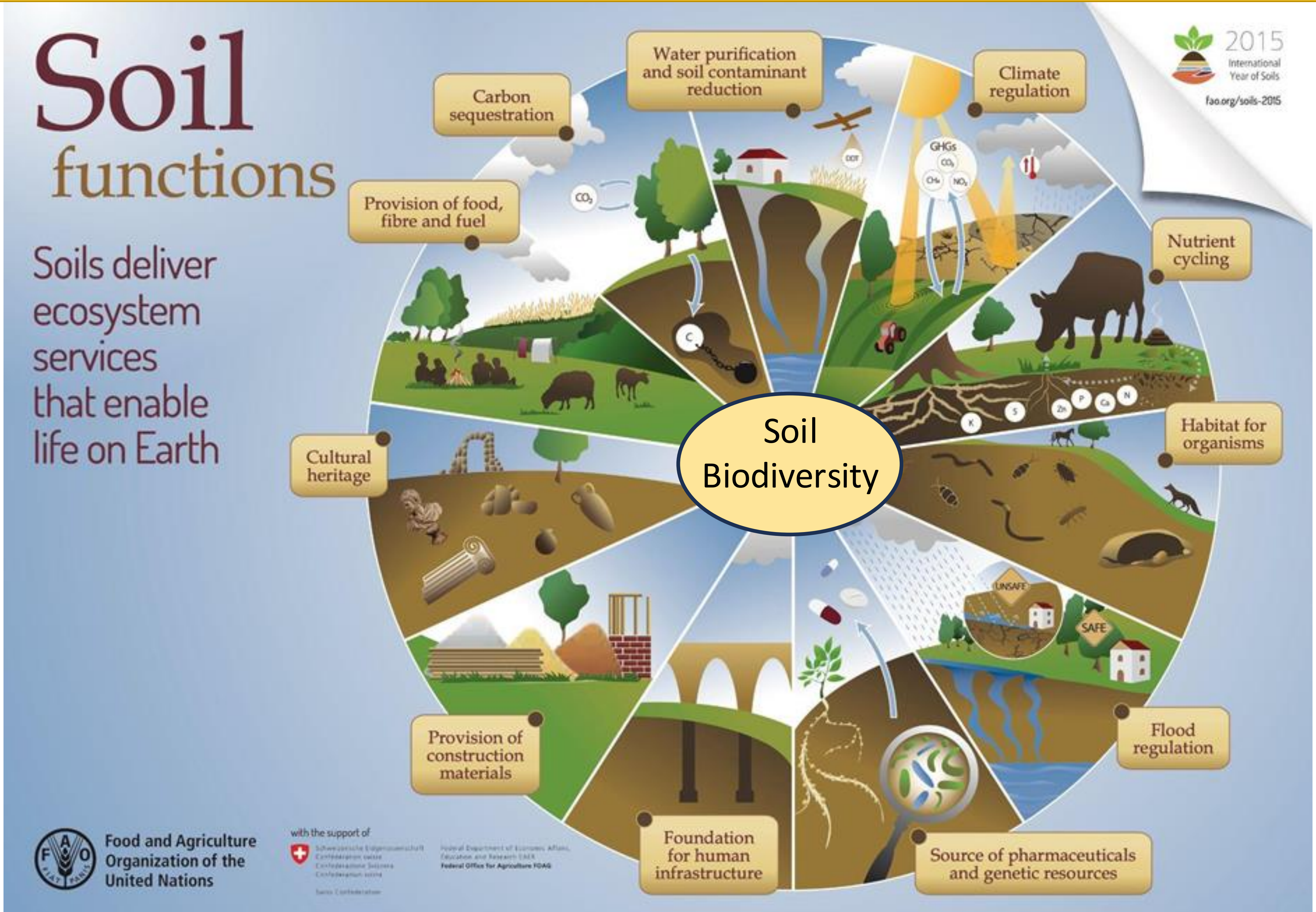
In all ecosystems



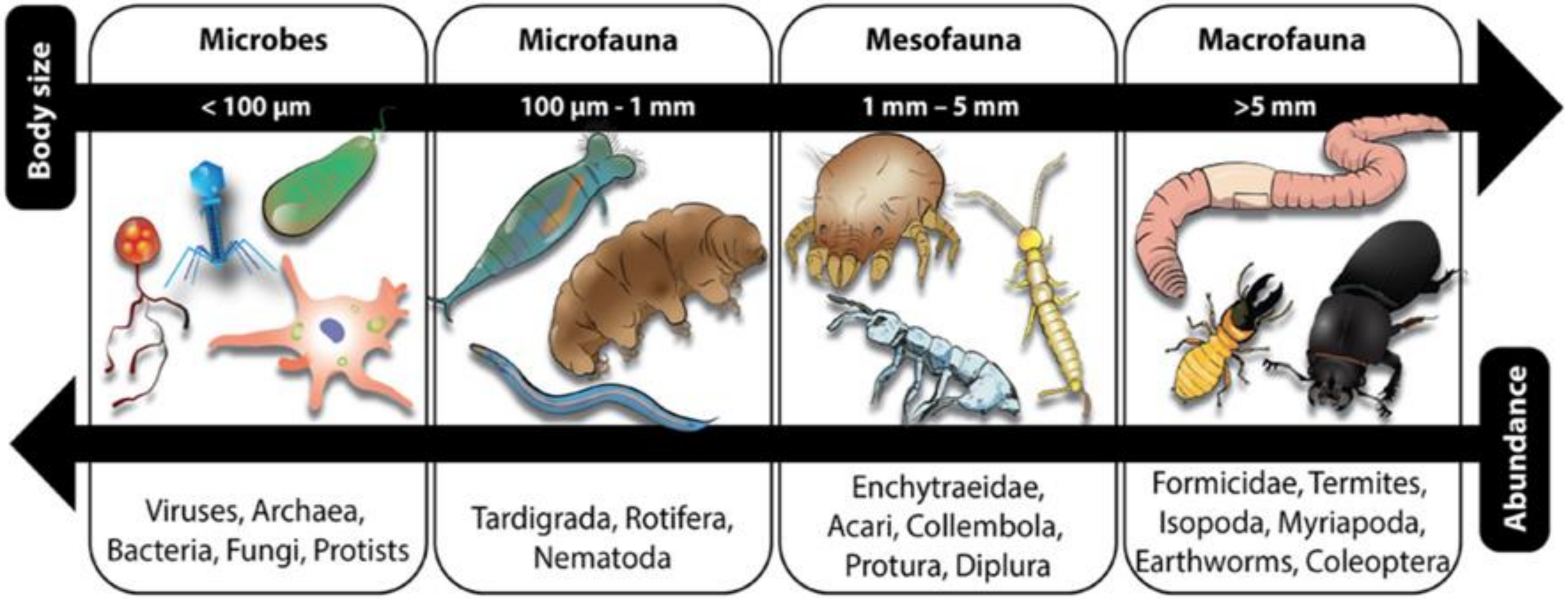


Credit: Javier A. Ceja-Navarro

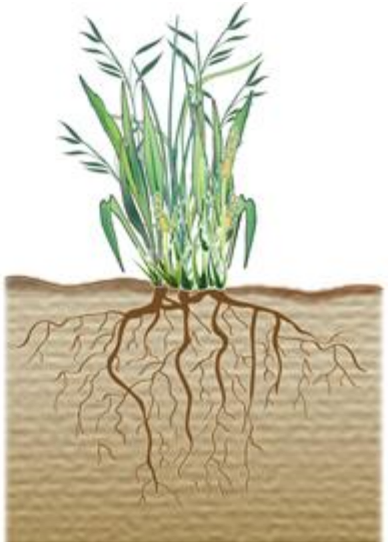
Soils provide ecosystem services at global scale too



The life inhabiting soil encompasses a vast range of sizes…

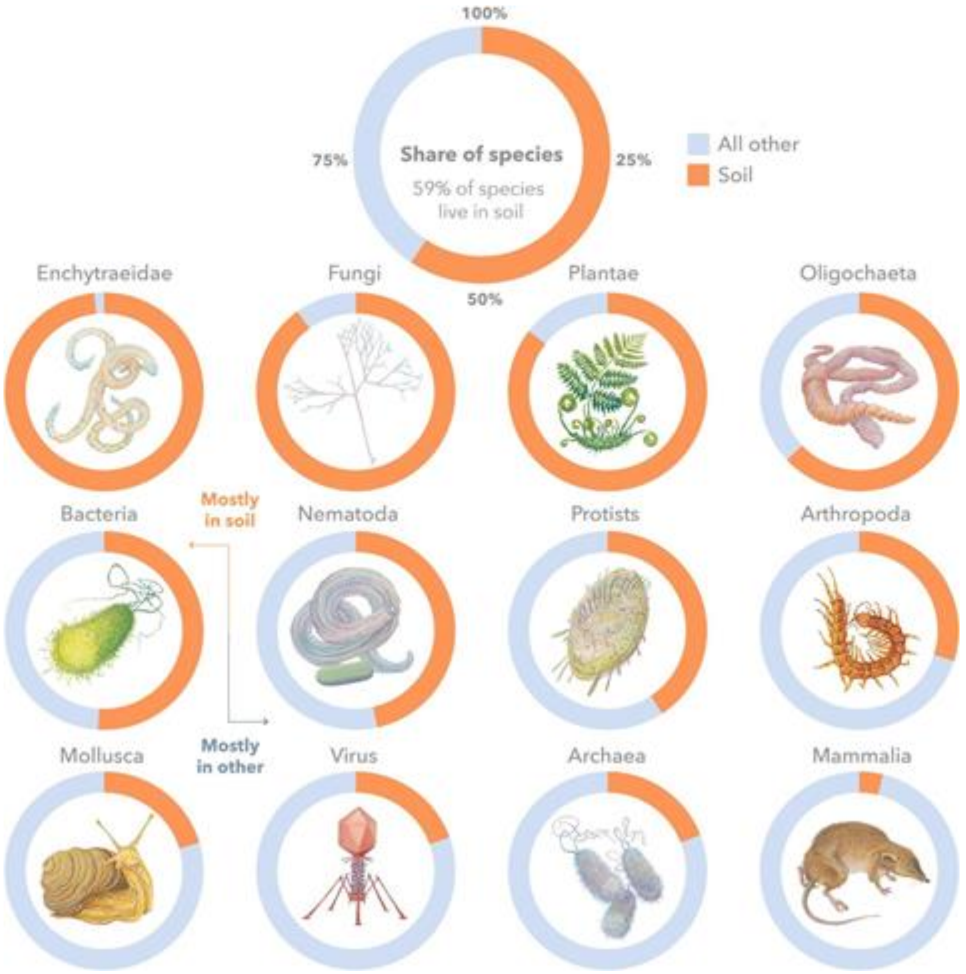


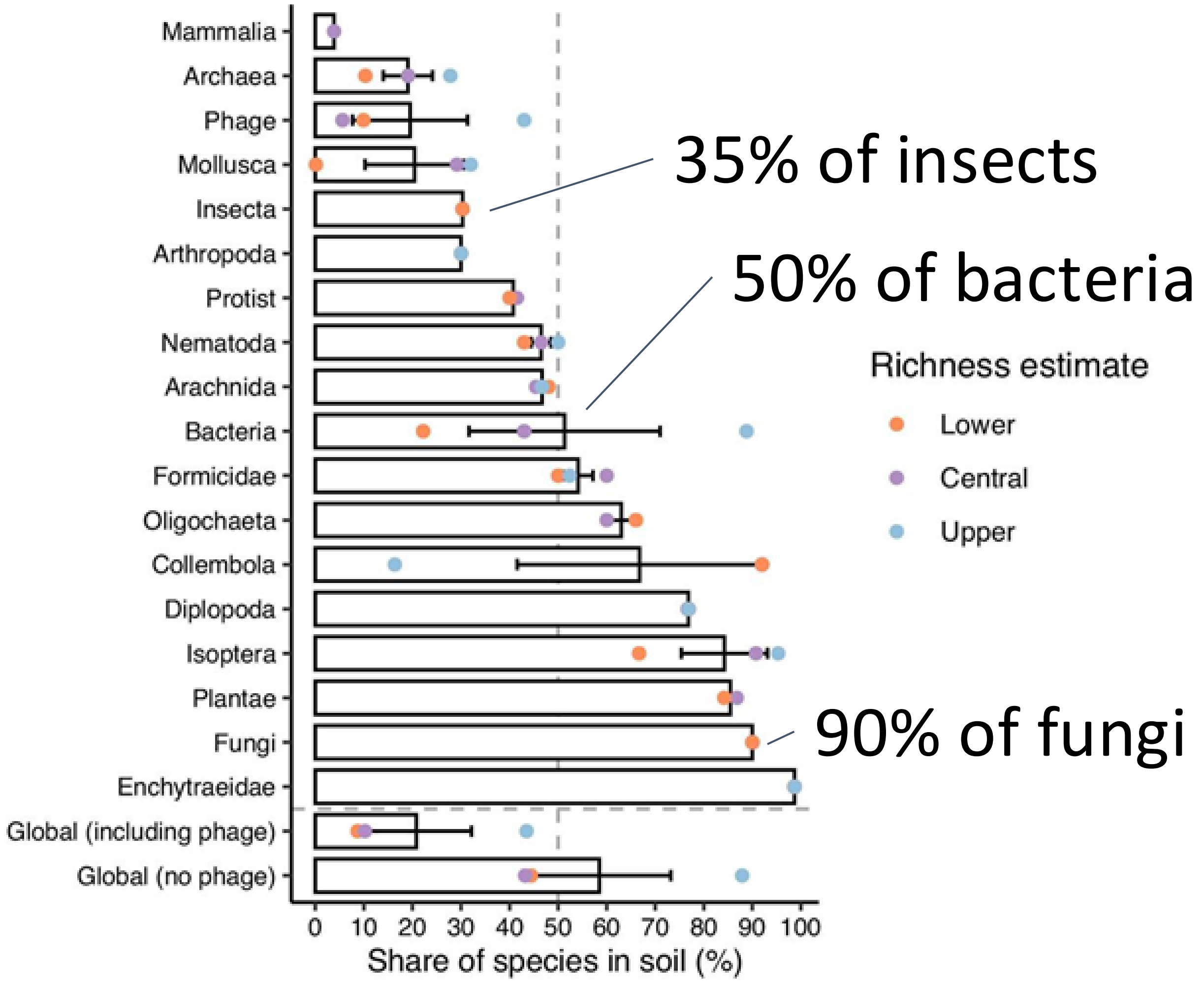
Credit: Javier A. Ceja-Navarro



…. contributing to essential soil functions and services

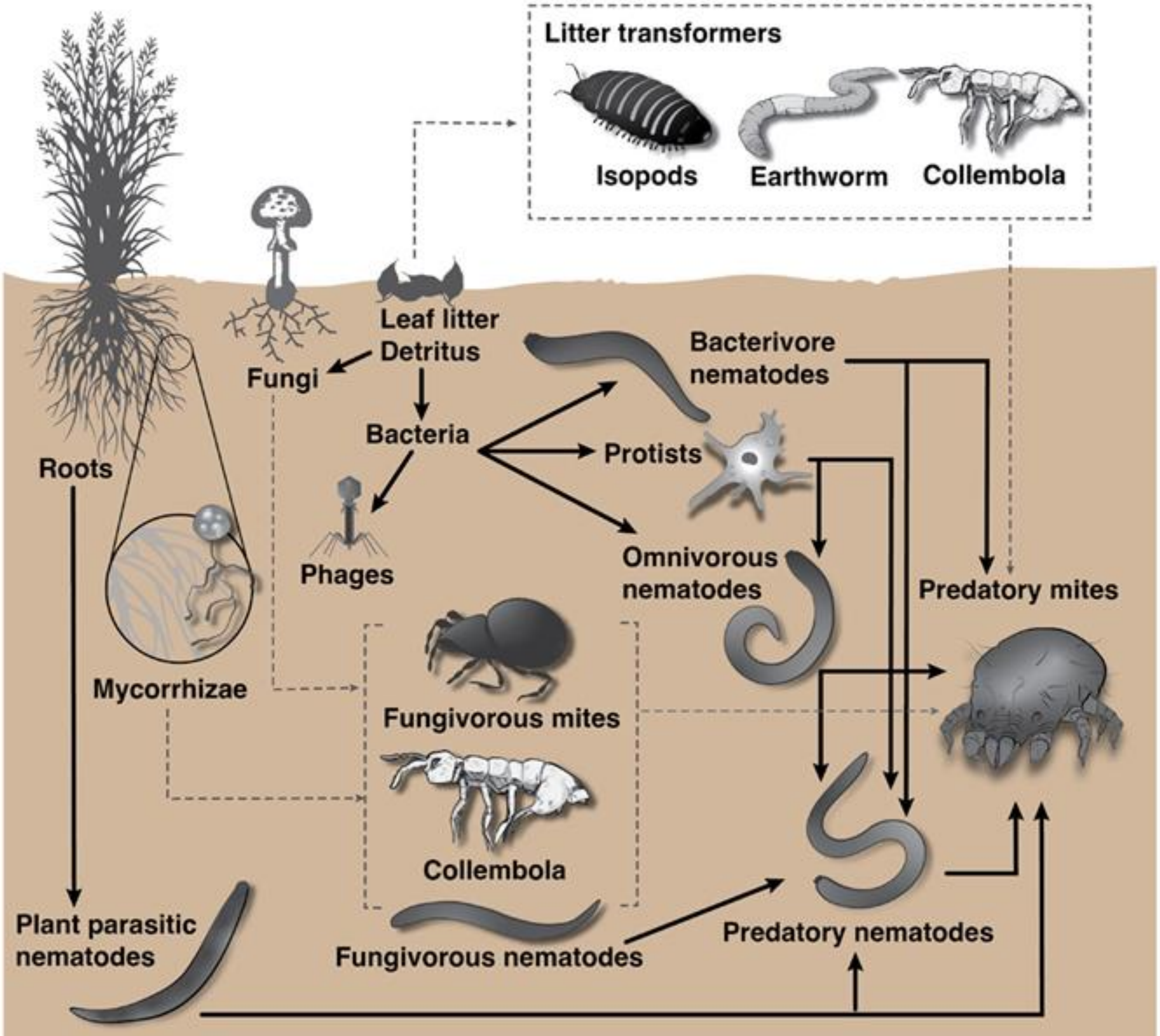
And in fact, soil (orange) is home to ~ 60% of earth's biodiversity





Anthony, M.A., Bender, S.F. and van der Heijden, M.G., 2023. Enumerating soil biodiversity. *Proceedings of the National Academy of Sciences of the United States of America*, https://doi.org/10.1073/pnas.2304663120

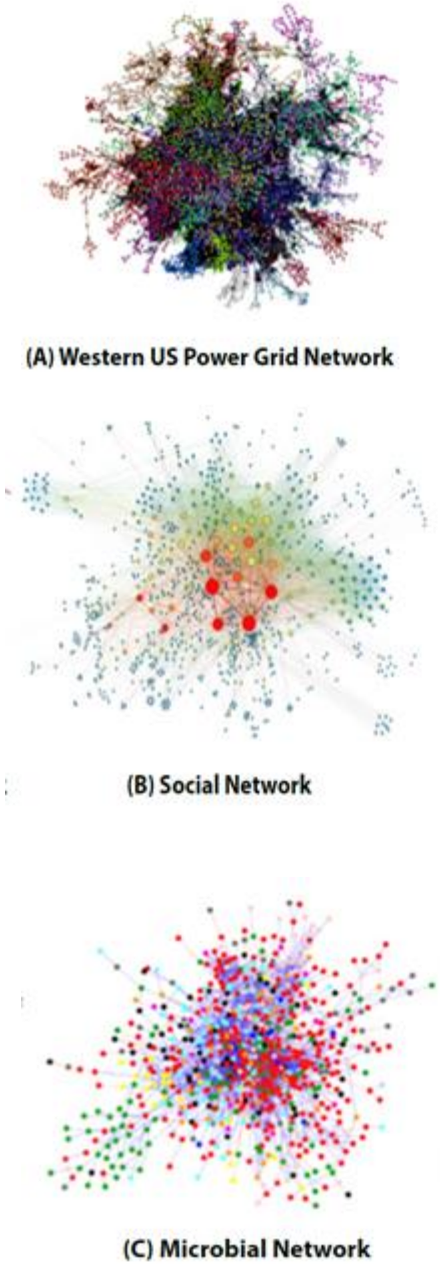
Soil organisms do not live in isolation…



Credit: Javier A. Ceja-Navarro

...but work together in interdependent network

(concept of "species" not usually relevant)



Soil biodiversity is far more than just body counts of organisms

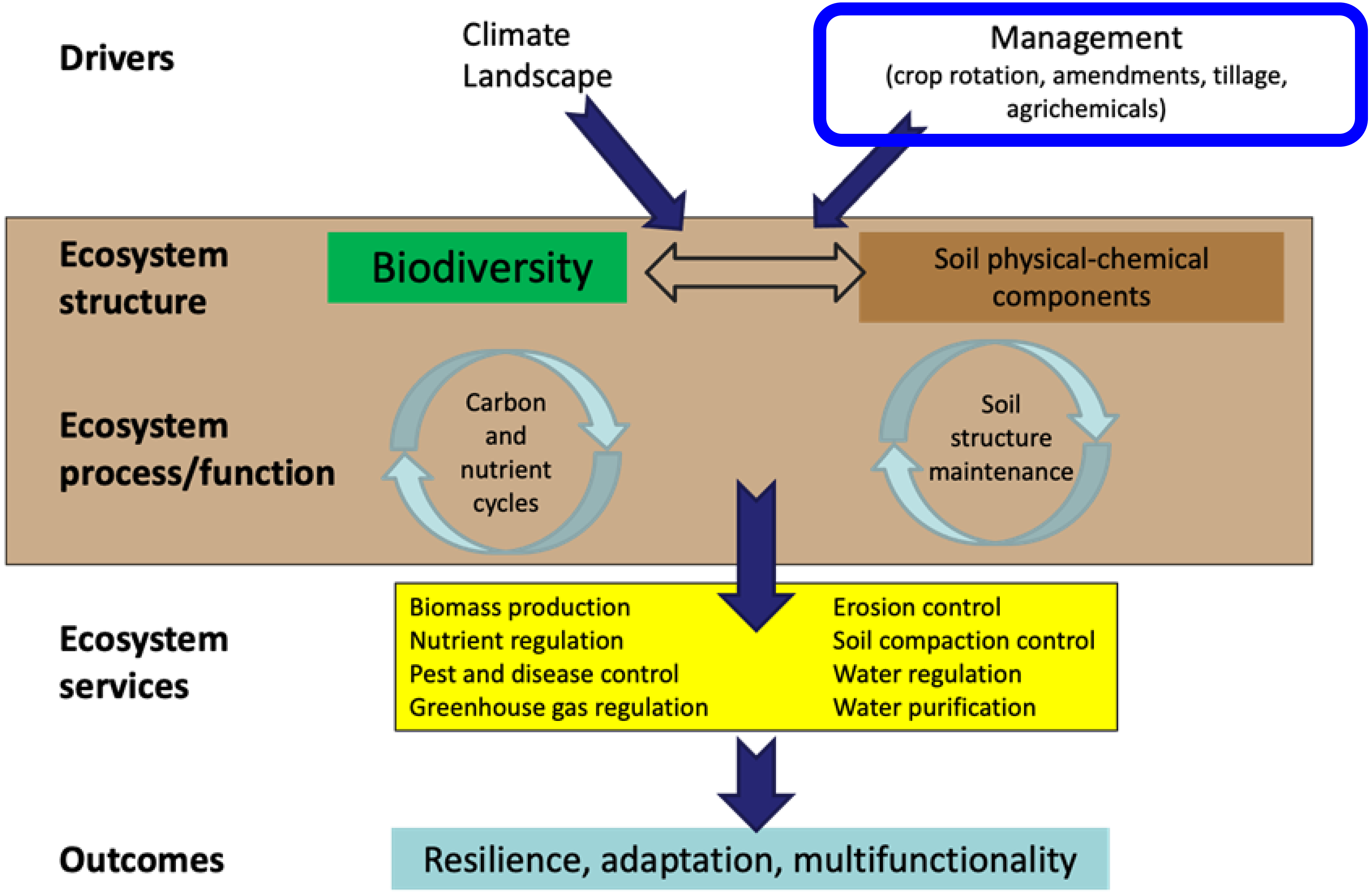
Definition

"The variety of life belowground, from genes and species to the communities they form, as well as the ecological complexes to which they contribute and to which they belong, from soil micro-habitats to landscapes "

(UN FAO)

….we will consider how we measure biodiversity later on……

Management practices directly influence the intimate relationships between soil biodiversity and soil's other properties and functions needed for SOIL HEALTH



Adapted from

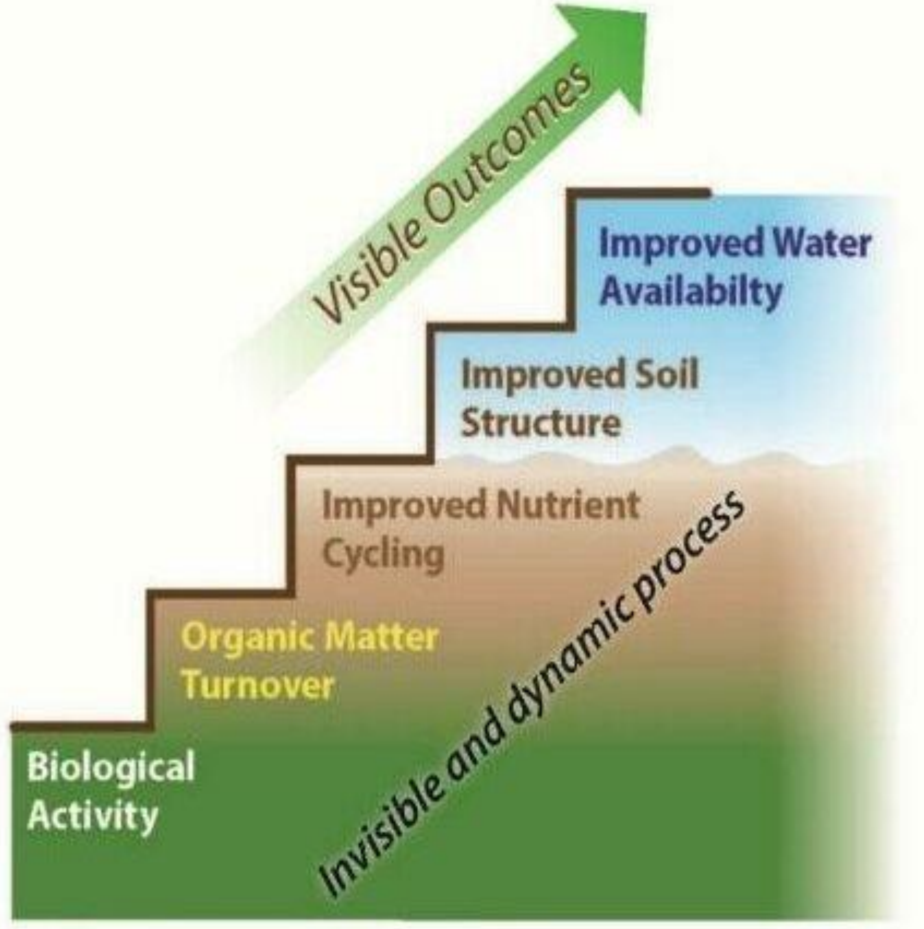
Agricultural soils can be chilly environments for soil biota due to management choices

- Not enough **carbon inputs**: removal of large portion of plant biomass (not returning stubble) or simply not enough plant biomass, not providing compost or mulch, root systems limited
- **Physical disturbance** from tillage (disturbs habitat and disrupts hyphal networks) and compaction from machinery
- **Bare soils** during fallow periods—no C, no protection from heat, no water?
- **Agrichemicals** decrease some groups –fungi, micro/macrofauna– and select others—e.g., some bacteria that degrade chemical or “bloom” after application
- **Fertilizer concentrations** too high for organisms symbiotic w/plants.
- Many recommended agricultural **practices** are cook book, based on rapid test targeting single issues rather than systems oriented: **address symptoms not underlying causes**
- **Short term perspective** (that season)

Main principles to build up soil health in orchard systems

What can we do to increase soil health?
Carbon – The building block of soil health

- Changes in soil health **begin with soil biology**
- **Carbon** is the primary source of energy to feed biological activity in the soil.
  - Plants (residues, more directly through exudates)
  - Soil (dissolved, in aggregates…)

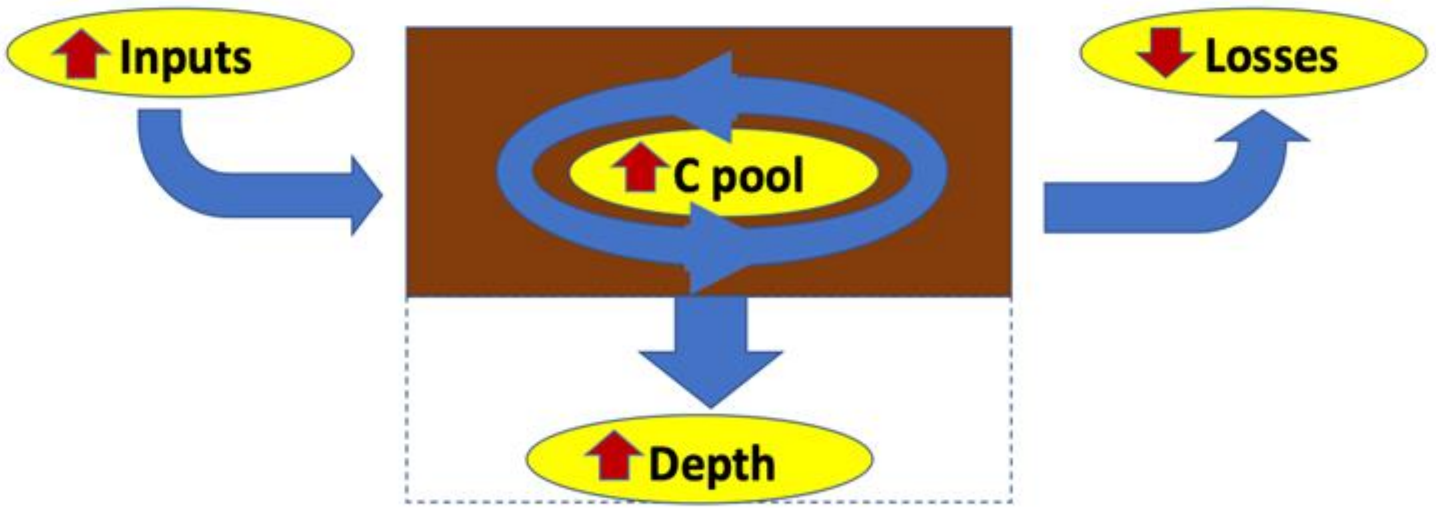


What can we do to increase soil health?

Carbon – The building block of soil health

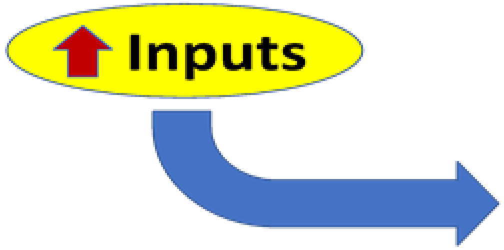
There are two ways to increase your “C stock”:

- 1 – Fix and deposit more
- 2 – Loose and withdraw less
- 3 – Long term storage



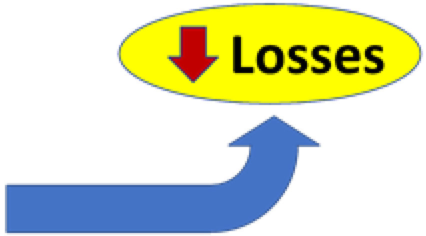
What can we do to increase soil health?

Carbon – The building block of soil health



steady food supply for microbes & the soil food web

- Diversity of Carbon inputs (form, timing…)
- Slow release of a variety of organic compounds over the course of the year
    - Amendments, living roots, residues, grazing
    - Not all carbon inputs are equal: are microbes getting all nutrients to build cells : N, P, K, S?



Reduce disturbance to habitat and C storage structures

- Break aggregates where C is stored
- Fungal symbiont network disturbance
- Real advantage of perennial orchard systems
    - Less / no tillage
    - Chemical disturbance
    - C incorporation into deeper soil layers

Basic soil health management principles

- Maintain living roots
- Keep soil covered
- Frequent and diverse input of organic matter
- Strategic minimal disturbances
- Maximize biodiversity
- Adaptation to landscape and communities

Measuring soil health: indicators and interpretation

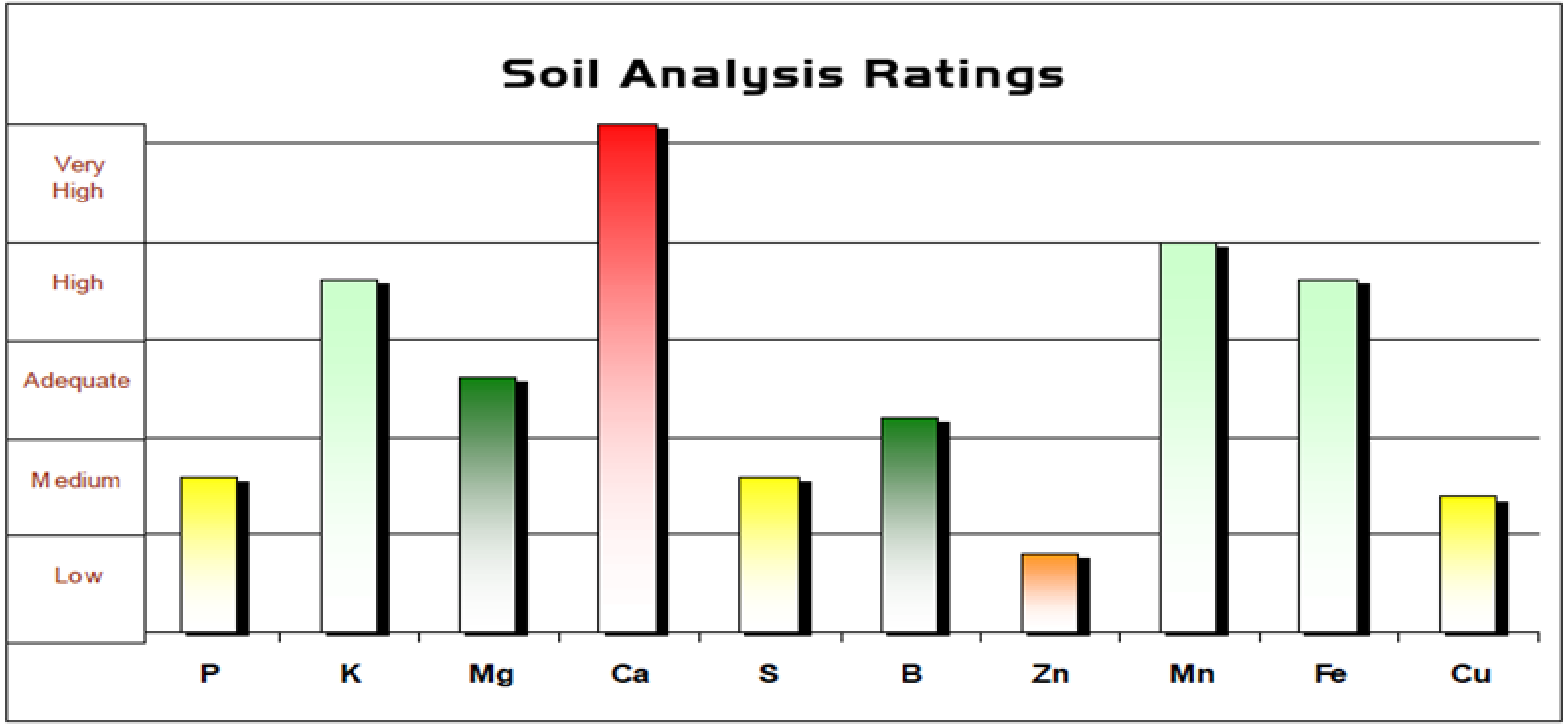
Typical Soil Test *(focused on fertility)*

Lab Results
lbs. per Acre

Lab Number: 135418SO

Target pH: 6.5
Test Method: Mehlich III

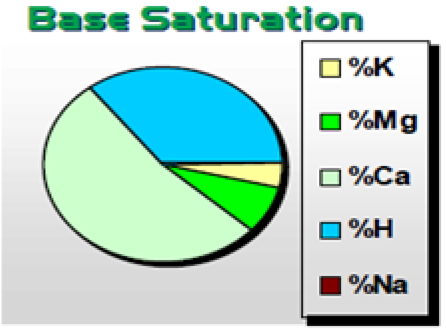
P Phosphorus	K Potassium	Mg Magnesium	Ca Calcium	Soil pH	Buffer pH	S Sulfur	B Boron	Zn Zinc	Mn Manganese	Fe Iron	Cu Copper
72 M	379 H	201 A	2407 VH	5.6	7.50	36 M	1.6 A	3.1 L	395 H	282 H	2.0 M
Aluminum	Sodium	Nitrate N	Soluble Salts mmhos/cm	Organic Matter 3.02 %	ENR 60.4						



Cation Exchange Capacity 11.3 meq/100g

Base Saturation

K: 4.3 %
Mg: 7.4 %
Ca: 53.1 %
H: 35.3 %
Na: %



What are characteristics of a healthy soil (from Cornell Assessment)

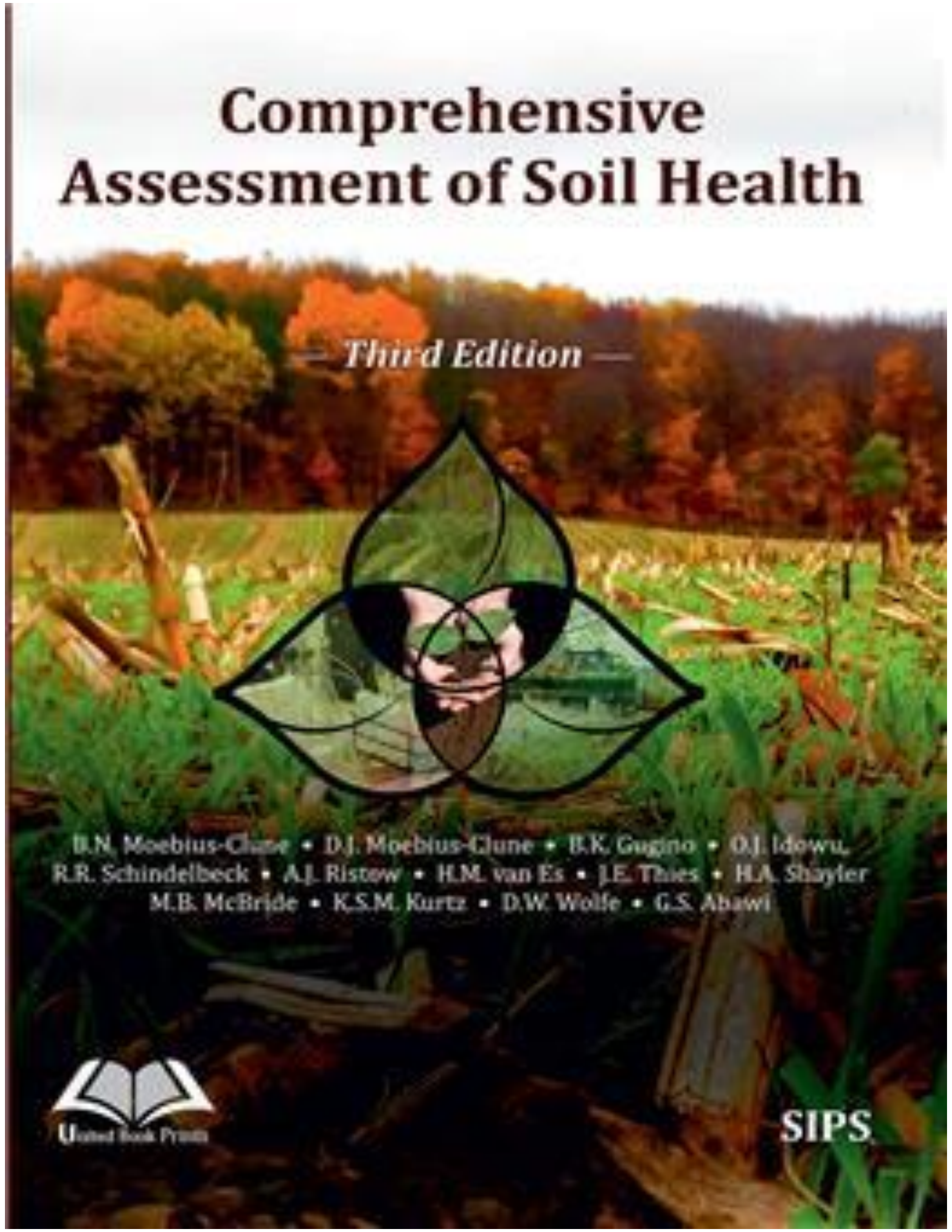
1. Good soil tilth
2. Sufficient depth
3. Sufficient but not excess supply of nutrients
4. Small population of plant pathogens and insect pests
5. Good water storage and good drainage
6. Large population of beneficial organisms
7. Low weed pressure
8. Free of harmful chemicals and toxins
9. Resistant and resilience to degradation

Various categories of Soil Health Assessment tools for different users and purposes

1. **Qualitative Scorecards** - observable soil indicators (often developed by farmers) qualitatively evaluated by land managers. e.g. NRCS Soil Quality web site
2. **Field Test Kits** - in-field soil analyses tests of simple parameters provide semi-quantitative data. **Soil Quality Test Kit**.
3. **Lab-based assessments** - assessments based on indicators requiring more specialized equipment or precise measurement; e.g. microbial biomass carbon, phosphorus or potentially mineralizable nitrogen. e.g., **Soil Management Assessment Framework** and **Cornell Soil Health Assessment**.
4. **Landscape-level assessments** - satellite and remote sensing to assess resource quality at large spatial scales.
5. **Multi-factor sustainability tools** combine environmental, economic and social indicators, to evaluate relationship between **soil quality and sustainability**.

From http://soilquality.org/tools.html

Cornell Soil Health Assessment Program is pioneer and model



HOW IS HEALTHY SOIL MEASURED?

The Cornell Soil Health Testing Lab uses these indicators to provide a comprehensive assessment of soil health:

CHEMICAL MAKEUP

- **pH**
  phosphorus, potassium, magnesium, and zinc

BIOLOGICAL CHARACTERISTICS

- **Organic Matter:** Carbon-rich material derived from living organisms
- **Soil Protein:** Nitrogen bound in the soil
- **Soil Respiration:** Rate at which the microbial community breaks down organic matter
- **Active Carbon:** Organic matter that can serve as a food source for soil microbes

PHYSICAL PROPERTIES

- **Soil Texture:** Makeup of sand, silt, and clay
- **Water Capacity:** How much plant-available water the soil can hold
- **Aggregate Stability:** How well soil particles can hold up to disturbances
- **Soil Compaction**

FOUR SOIL HEALTH PRINCIPLES

1. Minimize Disturbance
2. Maximize Continuous Living Roots
3. Maximize Biodiversity
4. Maximize Cover

Interpreting soil health indicator values

- Once indicator is measured, need to consider it in comparison to known values or ranges for that indicator
- Compare value to scoring function for soil health parameter: e.g., low, optimum, high, undesirable levels (based on previous measurements and literature)
- Reference database needs to be representative of region and climate

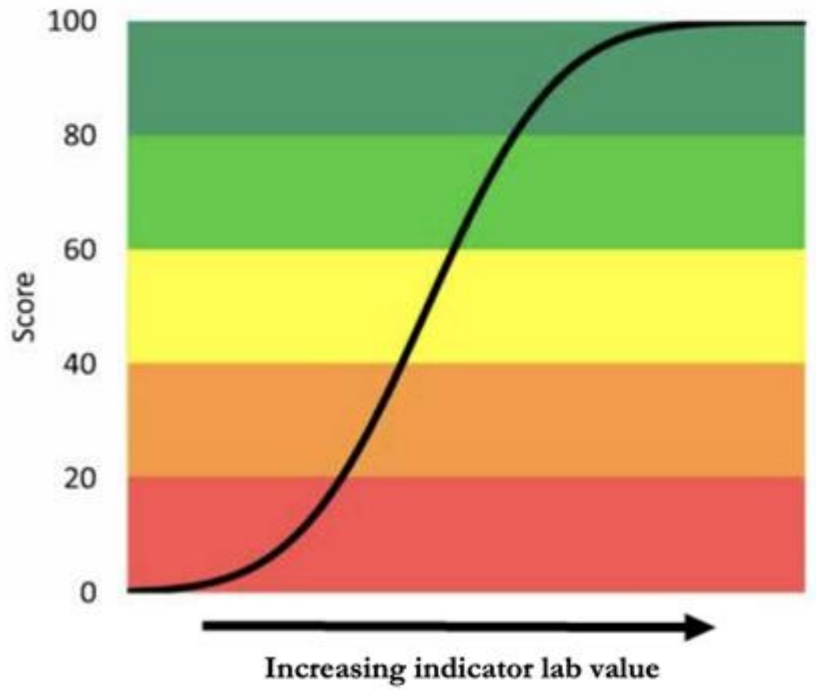


Figure 3. Example of CASH scoring curve. In this situation, the higher the measured value of the indicator, the higher the score until a maximum score of 100 is attained.

Example soil health assessment

Measured Soil Textural Class: **loam**

Sand: **44%** - Silt: **42%** - Clay: **13%**

Group	Indicator (2)	Value (3)	Rating (4)	Constraints (5)
physical	Predicted Available Water Capacity	0.23	86	
physical	Surface Hardness	114	71	
physical	Subsurface Hardness	287	54	
physical	Aggregate Stability	9.3	11	Aeration, Infiltration, Rooting, Crusting, Sealing, Erosion, Runoff
biological	Organic Matter Soil Organic Carbon: 2.20 / Total Carbon: 2.22 / Total Nitrogen: 0.15	3.4	68	
biological	ACE Soil Protein Index	8.3	70	
biological	Soil Respiration	0.6	43	
biological	Active Carbon	623	74	
chemical	Soil pH	6.7	100	
chemical	Extractable Phosphorus	8.1	100	
chemical	Extractable Potassium	153.5	100	
chemical	Additional Nutrients Ca: 1099.7 / Mg: 209.2 / S: 13.0 Al: 31.4 / B: 0.32 / Cu: 0.01 Fe: 8.1 / Mn: 3.8 / **Zn: 0.2**		88	

Overall Quality Score: **72** / High

Management Suggestions for Physical and Biological Constraints

Aggregate Stability Low	• Incorporate fresh organic materials • Use shallow-rooted cover/rotation crops • Add manure, green manure, mulch	• Reduce tillage • Use a surface mulch • Rotate with sod crops and mycorrhizal hosts
Active Carbon Low	• Add fresh organic materials • Use shallow-rooted cover/rotation crops • Add manure, green manure, mulch	• Reduce tillage/mechanical cultivation • Rotate with sod crop • Cover crop whenever possible
Soil Respiration Low	• Maintain plant cover throughout season • Add fresh organic materials • Add manure, green manure • Consider reducing biocide usage	• Reduce tillage/mechanical cultivation • Increase rotational diversity • Maintain plant cover throughout season • Cover crop with symbiotic host plants

Specific location and context of SH assessment tool **matters**: e.g., Northeast US may not be relevant to California and other locations

1. Most approaches developed in Midwest and NE US.
2. Mediterranean vs temperate climate: differences in C magnitude and sequestration capacity; hot climate, irrigated; diversity of soil types
3. Operational constraints –>can impact attainable targets (ie. drip irrigation systems).
4. Large diversity of agricultural systems in CA (Perennial vs annuals; rangelands).

Need to use relevant indicators (though many are universal), relevant *reference values* (specific to location) and recommend appropriate management practices (lots of knowledge already on these)

Other considerations: Methodologies and parameters matter!
(C as the example)

- SAMPLING DESIGN: Adoption of standard protocols for sampling permits comparisons over time and across locations and studies
- TIME: When is best time to sample? Seasonal variations can be large
- LOCATION: Random? Targeted areas?
- DEPTH: Differences with depth--usually surface layer measured but deeper is important e.g. for C; Also, importance to considering bulk density
- INDICATORS: Continue to be developed. e.g., newer methods to measure carbon (total C, fractions, DOC, POM, PoxC….)

Other soil health frameworks and tools

Soil Health Institute (SHI) Framework:

- SHI offers a detailed framework for soil health measurement, focusing on physical, chemical, and biological indicators. They provide tools and protocols for on-farm testing.

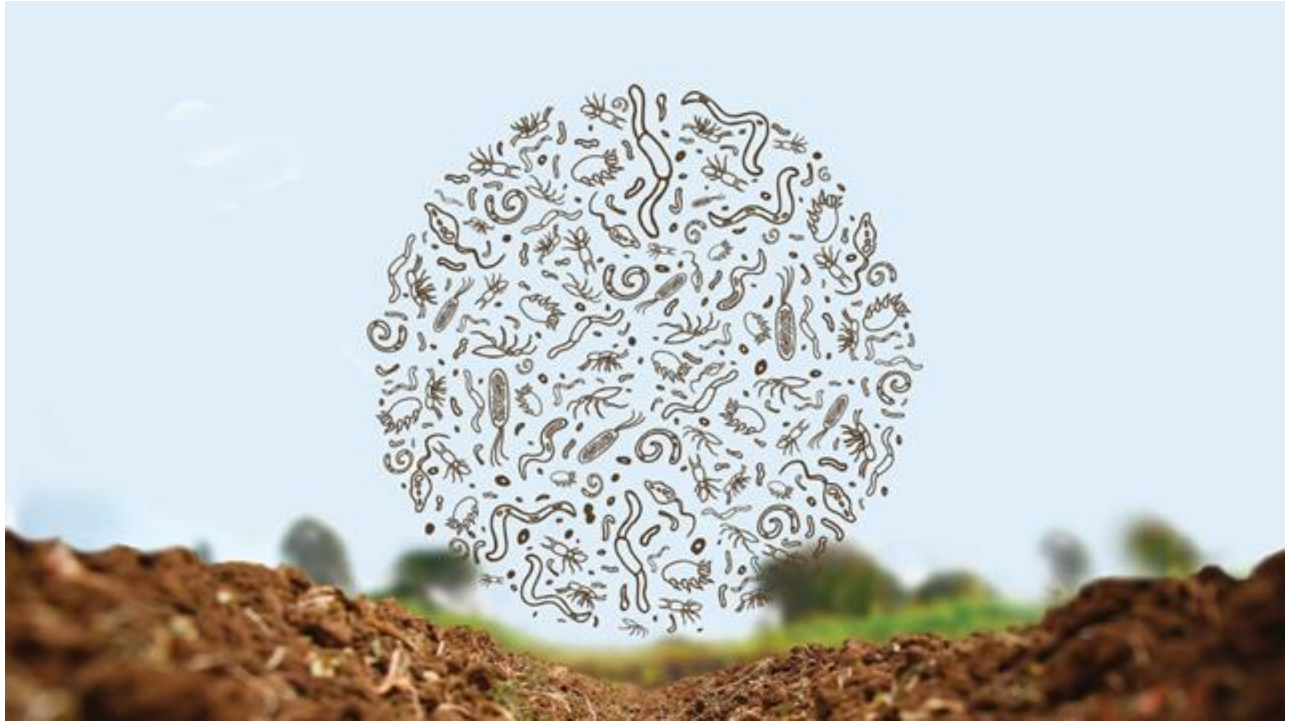
NRCS Soil Health Assessment:

- The USDA's Natural Resources Conservation Service (NRCS) has developed a set of soil health indicators, protocols, and tools for both field and lab measurements.

Haney Soil Health Test (Haney Test)

- The Haney Test integrates biological, chemical, and physical indicators to provide a holistic measure of soil health. It assesses soil respiration, water-extractable organic carbon (WEOC), and nitrogen (WEON), as well as other key nutrients.

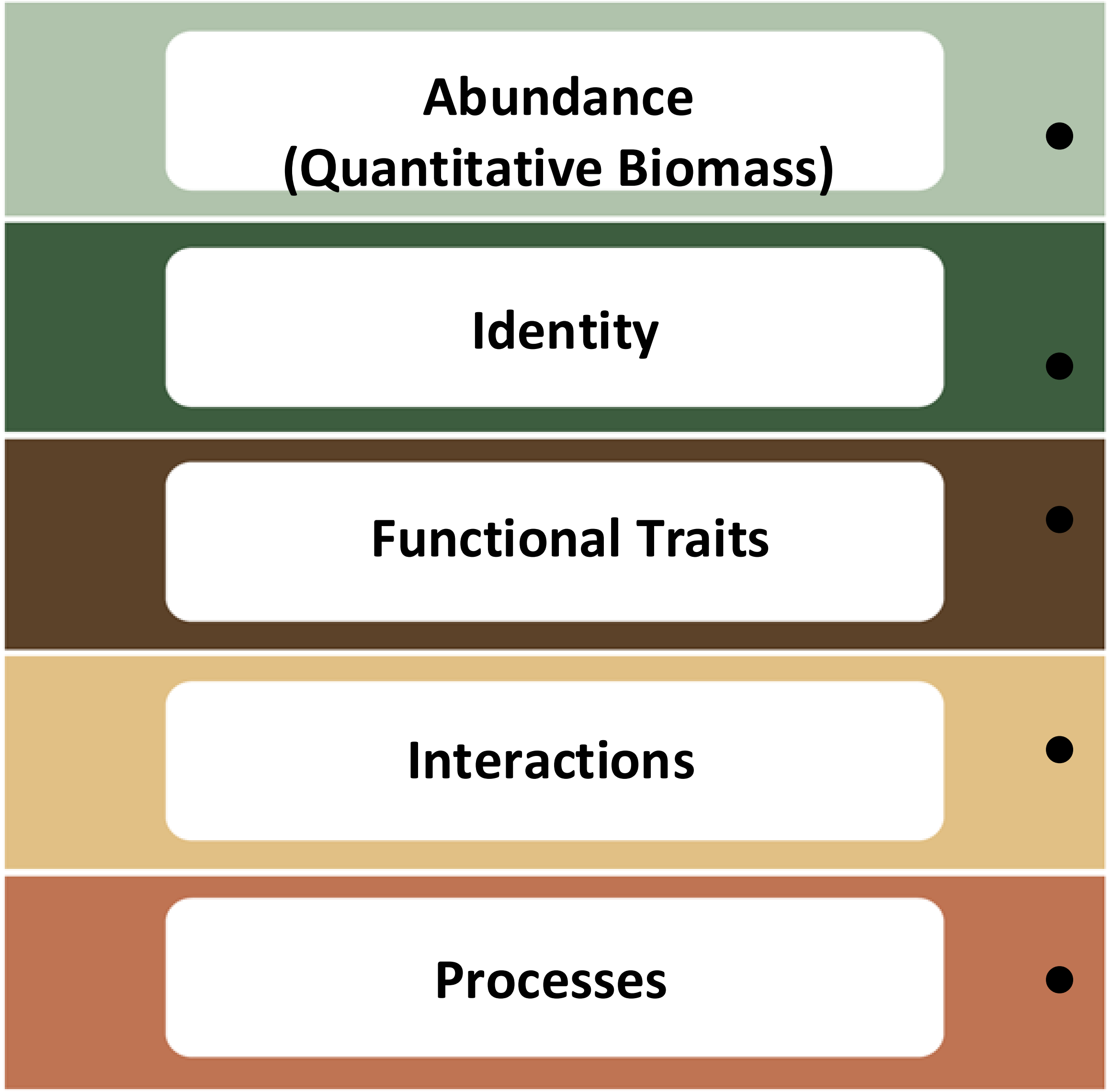
Soil Biodiversity Indicators



https://openknowledge.fao.org/handle/20.500.14283/cb1928en

(optional)

We measure soil biodiversity with indicators



- How many living organisms are present?
- Who are they? (often DNA-sequence based)
- What functions do they contribute?
- How do they work together to influence the functioning of soils and ecosystems?
- What are the outcomes of their work?

Figure 4.2. Categories of biodiversity indicators in soil ecosystems. Under each indicator category are listed some examples of methods (marked as bullets) used to measure these indicators.

Example methods (metrics) for measuring indicators

Abundance (Quantitative Biomass)	Fumigation- extraction, total PLFA, nematode abundance, total DNA
Identity	DNA Metabarcoding, PLFA/FAME, morphology
Functional Traits	Metagenomics, metaproteomics
Interactions	Network analysis, co-occurrence patterns
Processes	Nitrate content of soil, Nitrous oxide emissions

Which indicators to choose? It depends……..

Four example scenarios or "use cases" were developed to illustrate different applications of soil biodiversity assessments

1. **Status of California soil biodiversity**: Creating an inventory of California state biodiversity under different land uses, including agriculture.

1. **Assess impacts of the CDFA Healthy Soils Program (HSP) on soil biodiversity**: Do healthy soil practices improve a soil's overall biodiversity and functioning?

1. **Assist growers to manage specific functions of healthy soils**: How can soil biodiversity info help guide decisions regarding particular functions; e.g. disease suppression, reducing N loss, building soil carbon

1. **Enliven soil biodiversity for growers, gardeners, ranchers, and consumers**: How can we engage the general public in the importance of soil biodiversity.

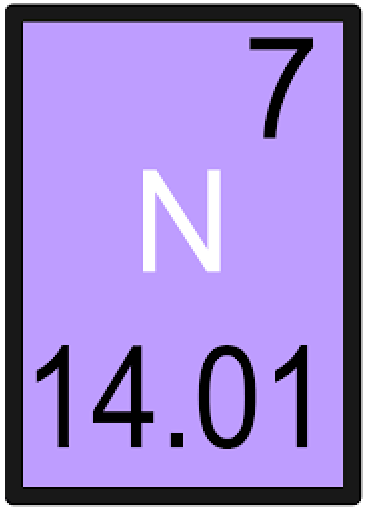
Example Study: Can knowledge of soil biota improve management of N in soils?

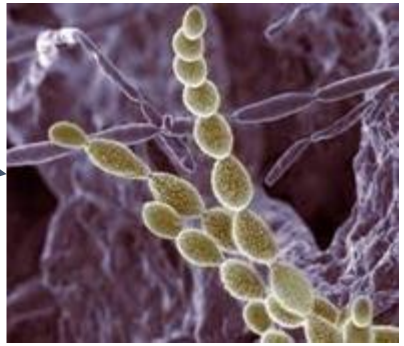
Problem:
How to manage N more efficiently in healthy soils?

Goal:
Adjust N inputs to meet crop needs while reducing losses

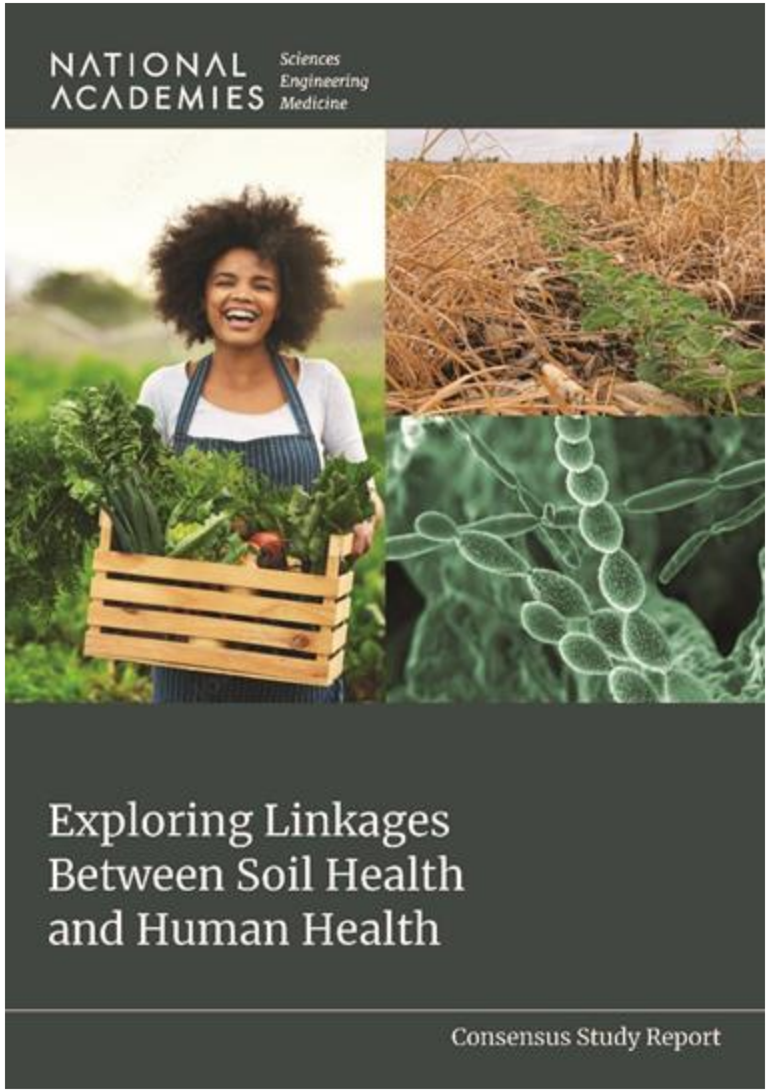
Audience:
Growers, TA providers, land managers

Recommendations:
Measure populations of N cycling microbes (nitrifiers, denitrifiers), microbial biomass and N fluxes





Another recent and relevant report: Soil Health and Human Health

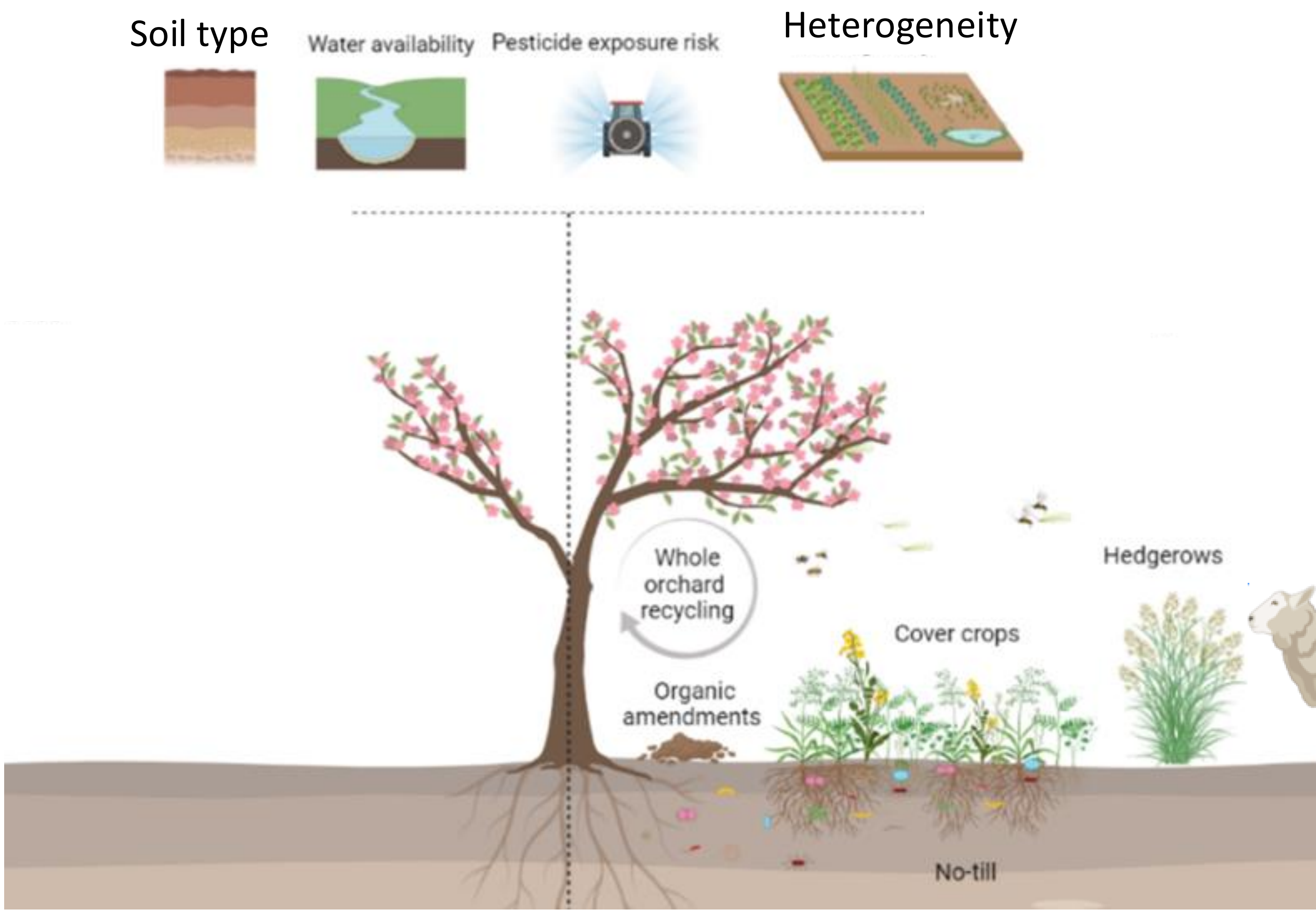


We have a lot to build on – These systems already exist !

PRACTICES

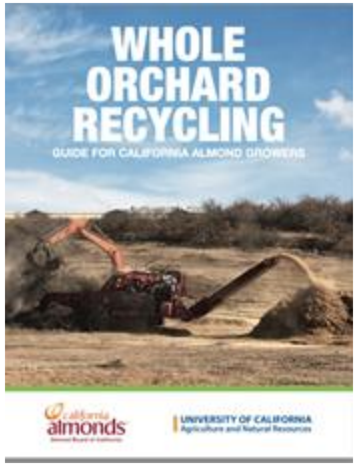
- Field margin habitat
- Whole orchard recycling
- Organic amendments and composts
- Understory covers
- Chips/mulches hulls and shells
- Biochars
- Grazers

(…)



Case study: Practices and soil health potential of CA Almond orchard systems

Whole orchard recycling



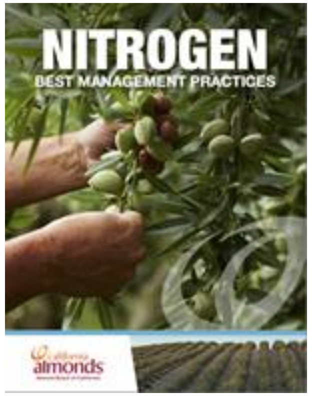
After 9 years, compared to burned

- Greater water holding capacity (+32% Field capacity)
- Improved infiltration rate : 2 folds
- Reduced soil compaction (-%14)
- Improved soil aggregation (+%19)
- Maintain higher tree water status and water use efficiency
- + 20% yield benefits under deficit irrigation
- Reduces nitrate leaching potential by 52%

- No yield trade offs if follow fertilization guidelines
- Low pest/disease potential

Jahanzad et al_2020, Jahanzad et al_2022, Holtz et al_2017
https://orchardrecycling.ucdavis.edu

Compost, hulls and shells amendments



After 2-3 years, compared to unamended

- Short term soil fertility
- Relevant sources of nutrients
  - N/P Nutrient management guidelines
  - Hulls and shells = Potassium
- Increases in soil organic carbon
- Associated benefits (CEC, topsoil volumetric water content – stem water potential)
- More biological activity
- Hulls and Shells mulch effect : lower soil evaporation; higher water infiltration

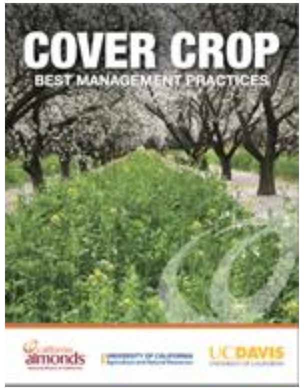
Leptch et al_2019, Villa et al_202, Khalsa et al_2021
Andrews et al_2023; Andrews et al_submitted

Winter planted cover crops

After 4 years, compared to bare soil

- Living roots and soil cover
    - In season increases in water infiltration
    - Aggregation (+22%),
    - Compaction (-41%)
    - Labile C and N pools
    - More biological activity , more diverse soil ecosystem
    - No increases in SOM or SOC
- Forage for pollinators
- Weed suppression
- Reduce spring emergence and NOW egg deposition

Wauters et al_2023, DeVincentis et al_2020, Wilson et al_2023, Wauters et al_2024 in prep



Stacking principles and practices




Marshall et al_under review_Applied Soil Ecology

12 organic Almond orchards, Similar soil type and texture (Yolo silt loam)
Along a management gradient
None, few or stacked adoption of soil health principles

Group A


Bare soils
Composts
Almond hulls and shells

Group B


Living covers
Planted, resident veg
Winter, summer residue mulch

Group C


Winter or continuous living covers with sheep grazing

Group A

Bare soils
Composts
Almond hulls and shells

Group B

Living covers
Planted, resident veg
Winter, summer residue mulch

Group C

Winter or continuous living covers with sheep grazing

Subset of indicators -- Alley (0-30 cm) --

Service	Indicator	Group A	Group B	Group C
Lower compaction	Bulk density (g/cm^3)	1.71a	1.62ab	1.56b
Store C	Total soil C (g C/kg dry soil)	8.78a	13.43b	17.47b
Nutrient cycling	Respiration (mg $C0_2$/g dry soil)	0.29a	0.39ab	0.53b
	Soil proteins (mg N/g dry soil)	1.81a	2.01a	5.89b
Nutrient availability	Total N (g N/kg dry soil)	0.85a	1.27a	1.63b
	Available P (ppm)	4.64a	20.12b	57.59c
Conserve water	Water Holding Capacity (gH2O. g soil)	0.23a	0.26a	0.23a

In addition to the direct benefits of these practices for building soil health, there are many other co-benefits that tackle additional sustainability and productivity challenges

Pest and disease regulation

Weed suppression

Water conservation

Sustainable nutrient management

Pollinator resources and habitat

Towards realising the potential in Avocado orchards

- Low to no tillage for the most part
- Multiple designs in space and time are feasible
- Potential yield lags are minimal compared to annual systems; if well managed

---

- **Unknowns:** link between SH and biodiversity, potential
- **Implementation:** technical assistance, equipment, flexibility, exchange
- **Context specific:** experiment together, locally and on farm
- **Cost:** incentives and motivations

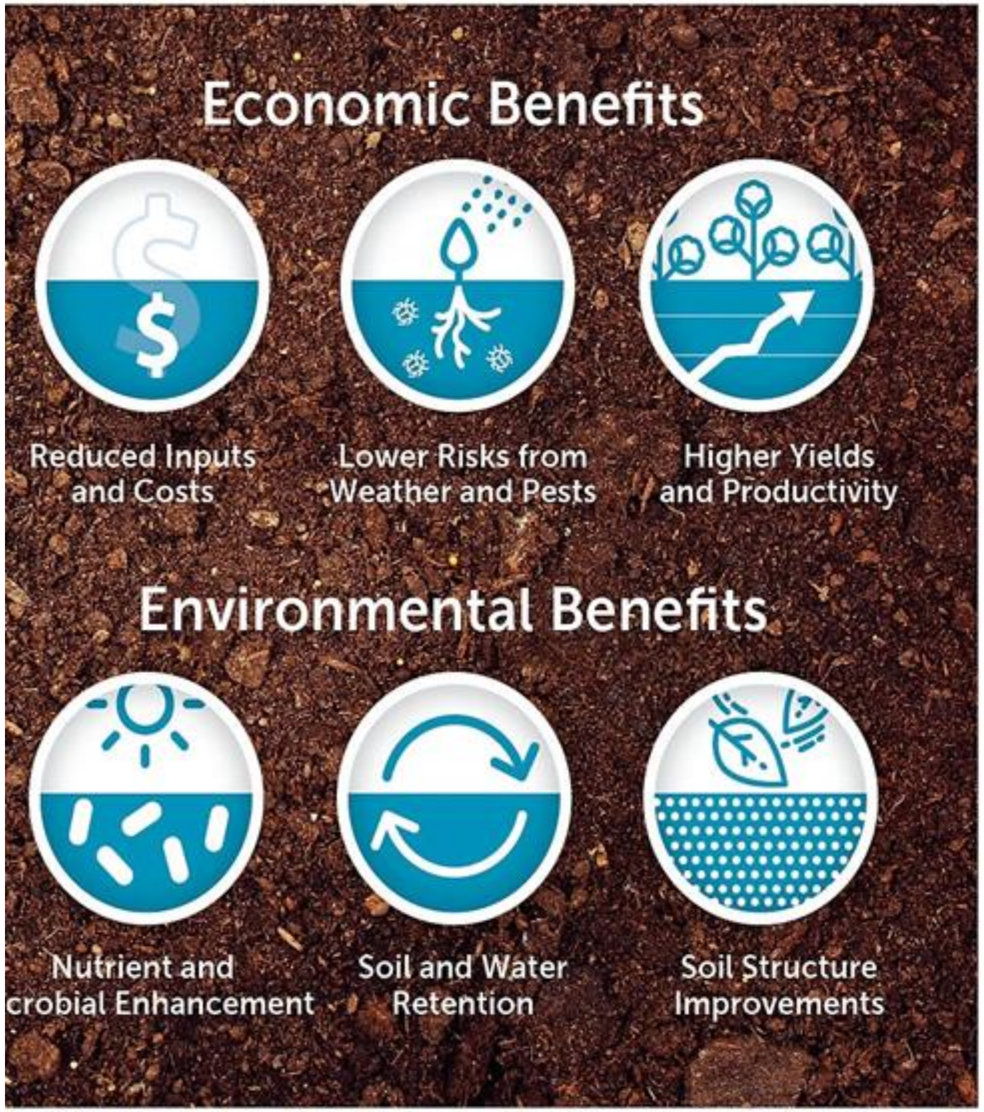
Thank you
thoughts and/or questions ?

EXTRA SLIDES

Healthy soil for sustainable Agriculture

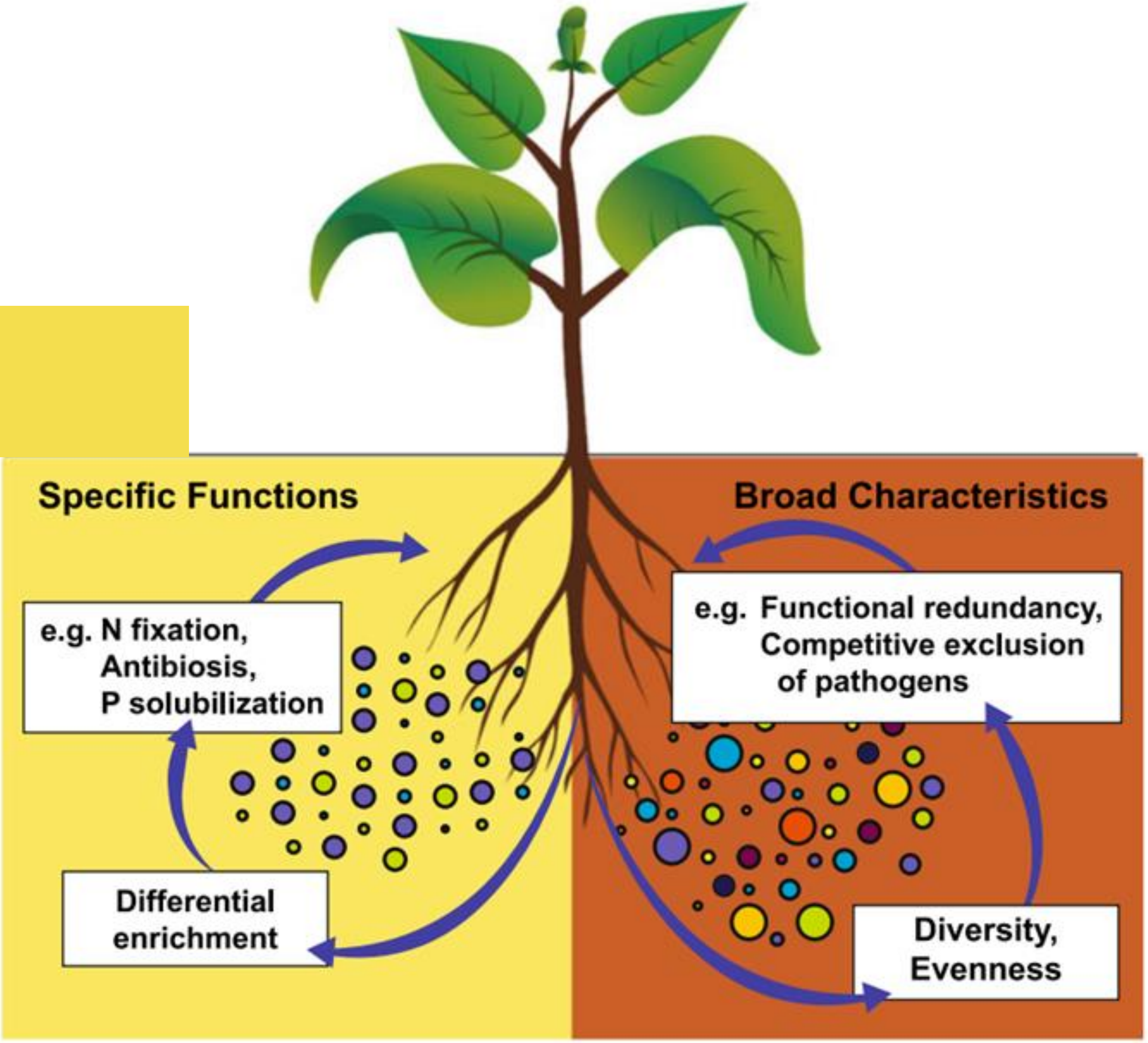
Healthy soils should:

- Accumulate and store C
- Provide and cycle nutrient
- Conserve & cycle water
- Improve soil structure
- Support diverse and active soil communities



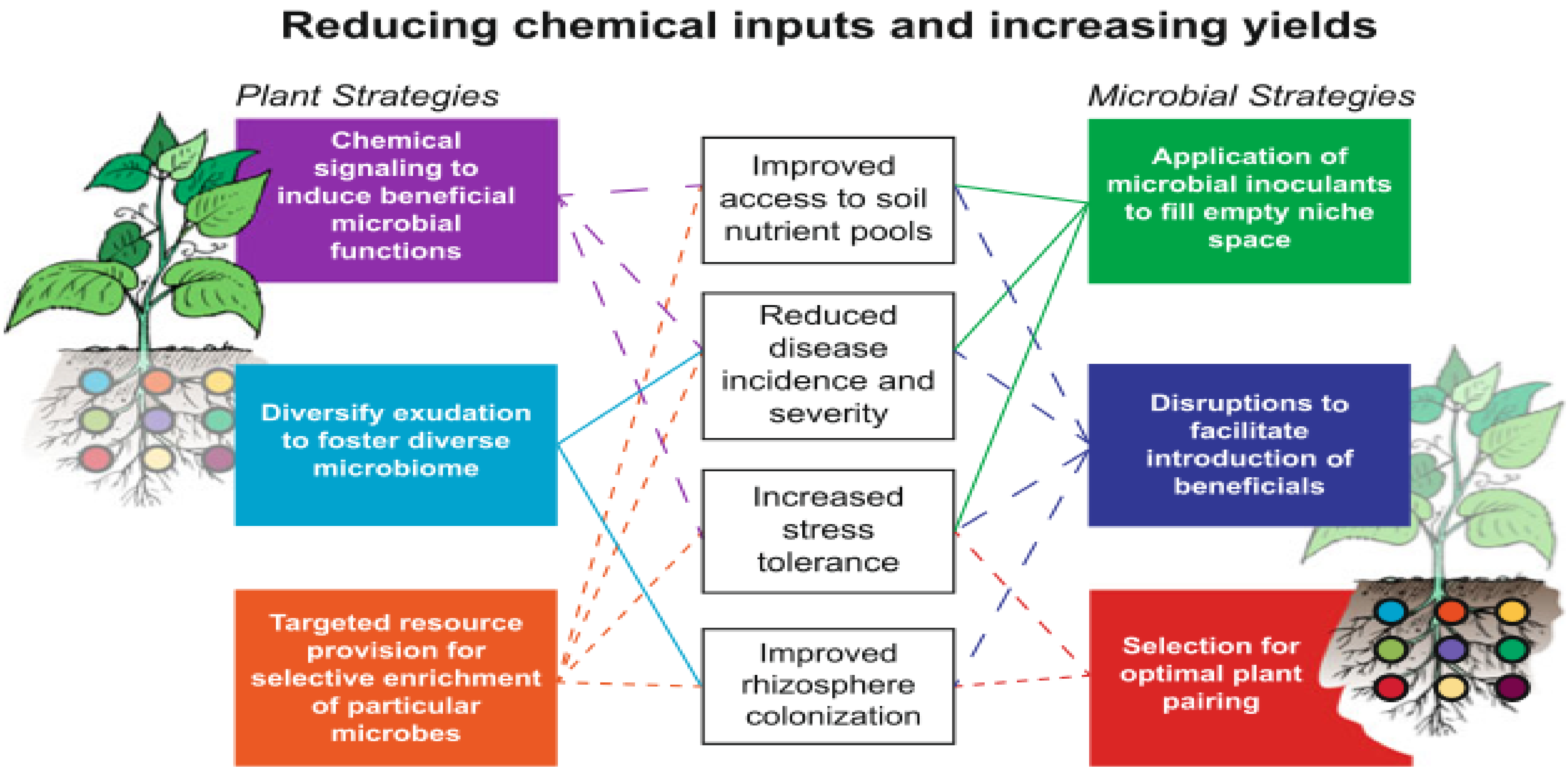
Inoculation

Inoculation more promising here?



Bakker, M.G., Manter, D.K., Sheflin, A.M., Weir, T.L. and Vivanco, J.M., 2012. Harnessing the rhizosphere microbiome through plant breeding and agricultural management. *Plant and Soil*, *360*(1-2), pp.1-13.

Increase success of inoculation in consort with plant?



Bakker, M.G., Manter, D.K., Sheflin, A.M., Weir, T.L. and Vivanco, J.M., 2012. Harnessing the rhizosphere microbiome through plant breeding and agricultural management. *Plant and Soil*, *360*(1-2), pp.1-13.

WHY DOES INOCULATION OFTEN FAIL?

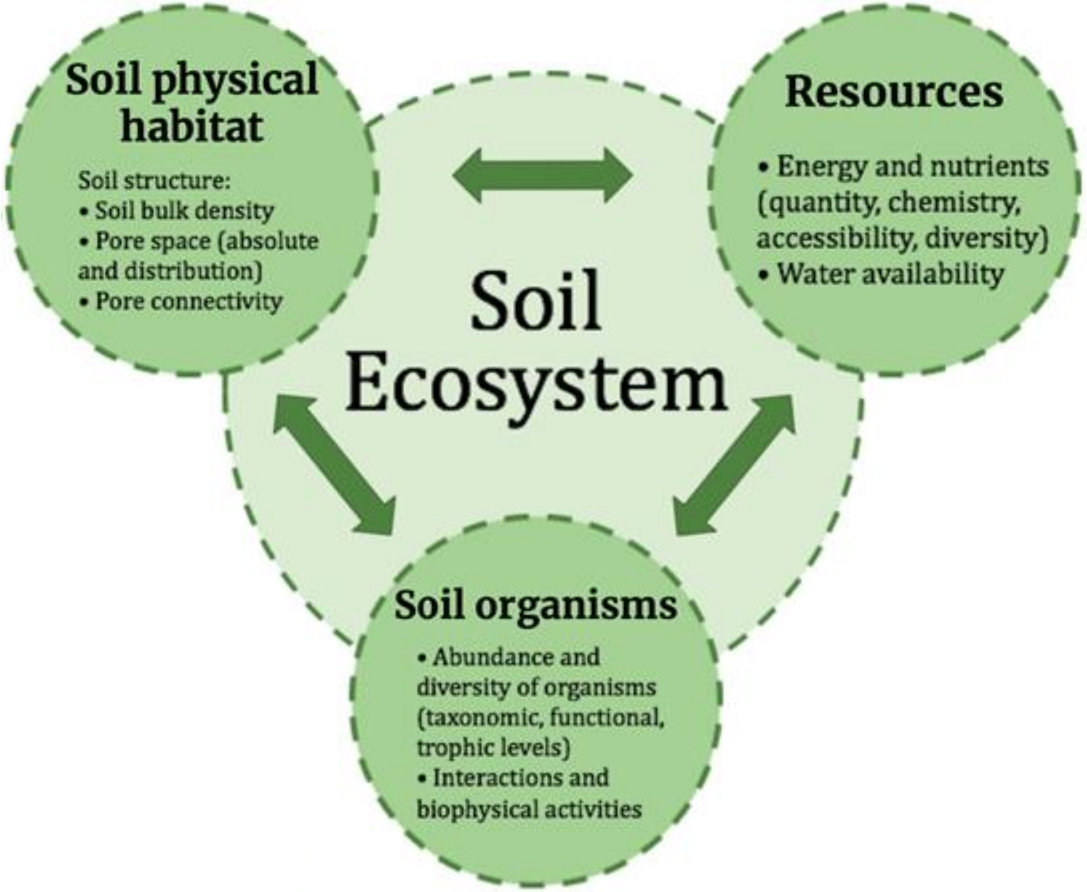
- Incomplete understanding of their abiotic requirements
- Incomplete understanding of their biotic requirements – may need to be added w/complementary organisms not present in community or whom they can't "find"
- Conditions not conducive to establishment at time of introduction (no rain, no food, etc.)
- Application method does not place inoculum into microhabitats where they'd thrive (e.g., need microaggregates, but added as aqueous slurry that quickly flows through preferential flow paths and macropores)
- Intense predation or competition by resident organisms (e.g., protozoa)
- Just adding inoculants is likely not successful first time--requires experimentation to get right doses, timing, placement
- Inoculum usually commercially produced under optimum conditions for growth—does this prepare them for what lies ahead?

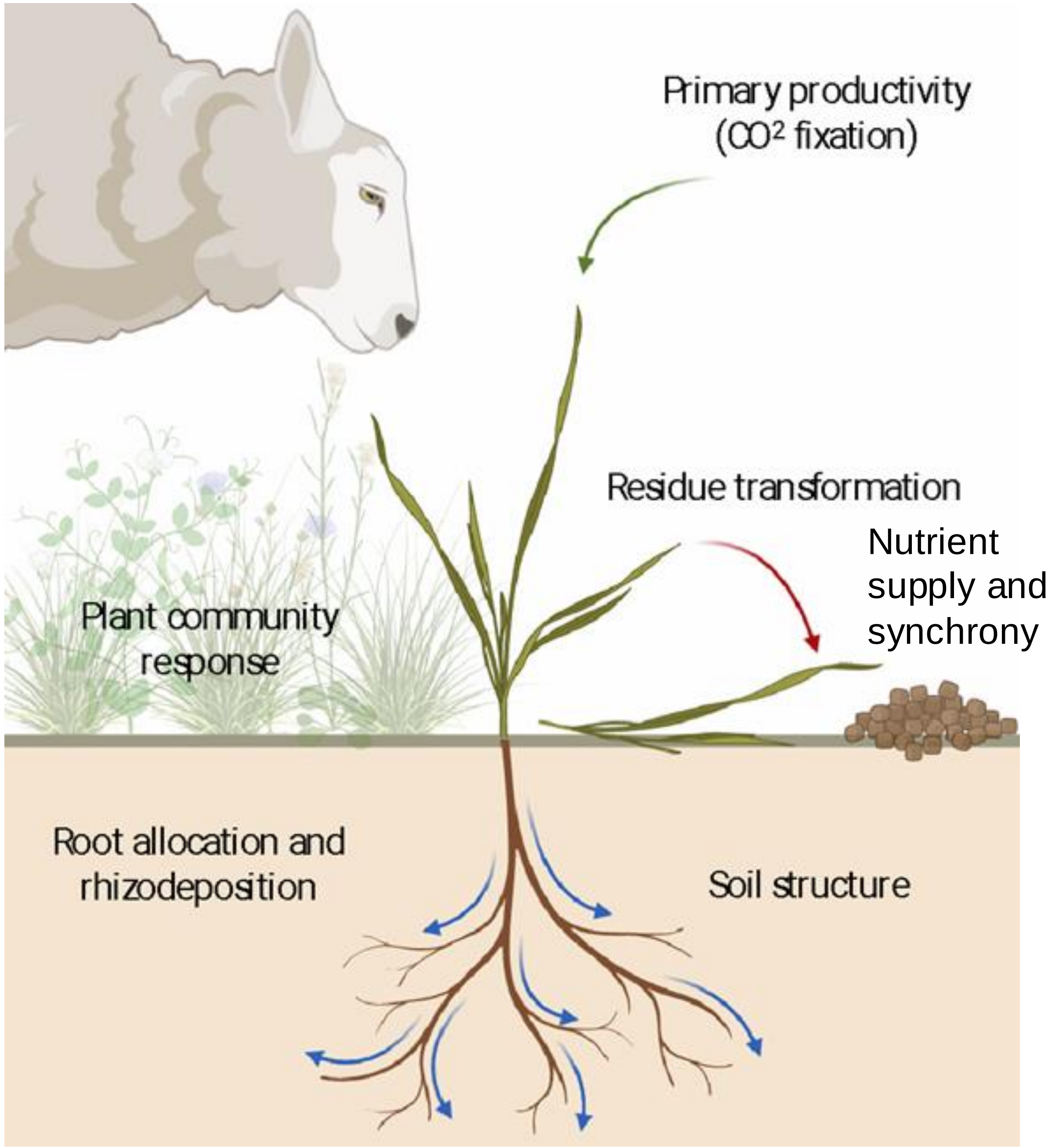
Inoculation in avocado seedlings

Barra, P.J., Inostroza, N.G., Mora, M.L., Crowley, D.E. and Jorquera, M.A., 2017. Bacterial consortia inoculation mitigates the water shortage and salt stress in an avocado (Persea americana Mill.) nursery. *Applied Soil Ecology*, *111*, pp.39-47.

endophytic and rhizosphere bacterial strains from avocado trees, and formulated four consortia with IAA- and ACCD- producing halotolerant bacteria improved growth and antioxidant activity of avocado trees grown under salt stress and water shortage conditions in a commercial nursery from central Chile.

Livestock grazing has the potential to profoundly shifts soil ecosystem functioning

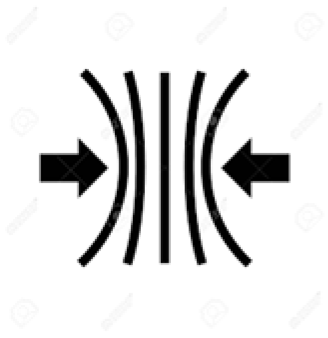




Brewer, Gaudin (2020) Soil Biology and Biochemistry 149:107946

Pushing the boundaries of diversification

- Sustainability and resilience potential
- From field/systems to landscapes



- Wildfire suppression
- Pest suppression
- Weed control
- Portfolio effect

- Cover crop termination
- Nutrient cycling
- Residue management
- Forage nutrient value
- Soil biodiversity and functions