Reframing the conversations around agricultural soil carbon

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Take-home points

1. Changes in farm practices may (or may not) influence soil organic carbon content
2. Even when carbon content doesn't change, farmers and the environment can strongly benefit from diversified cropping systems
3. Despite the "buzz" around soil carbon, we should assess environmental benefits of farming practices from a holistic perspective

Context:
A new spotlight on agricultural soil management as a climate solution

- Billions of dollars in funding is now directed at soil management to "sequester" carbon
- Need to constrain these markets with sound science
- Need to consider how soil carbon relates to farm management and broader environmental issues

Table 1. How Voluntary Agricultural Carbon Programs Address Critical Structural Considerations

	Agoro	Bayer	CIBO	Corteva	ESMC	Gradable	Indigo	Nori	SWOF
PAYMENTS: Per output	✔		✔	✔	✔	✔	✔	✔	✔
Per practice		✔							

Plastina 2022: The US Voluntary Agricultural Carbon Market

Questions for you:

- How many of you have measured any of the following at your farm:
  - Soil *organic matter*
  - Soil *carbon*
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  - What about *potentially mineralizable carbon* or *soil respiration*?

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    - Useful for comparing soils over time, or within a region (with similar mineralogy)
  - **Cautions**:
    - Influenced by mineral composition
    - Not a direct measure of carbon
    - Measurements often not comparable among labs (different combustion temperatures)
    - Typically not suitable for carbon markets

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  - **Cautions**:
    - Measurements can be expensive
    - Need to test whether carbonate is present, and remove it or measure it
      - pH < 7, carbonate is unlikely (unless lime was recently applied)
      - pH >7, carbonate is possible
      - pH > 7.5, carbonate is likely
    - Accounting for carbonate is controversial even in the soil research community
    - Dealing with carbonate is an underappreciated challenge for commercial labs

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2. Even when carbon content doesn't change, farmers and the environment can strongly benefit from diversified cropping systems
3. Despite the enormous "buzz" around soil carbon, we should assess environmental benefits of farming practices from a holistic perspective

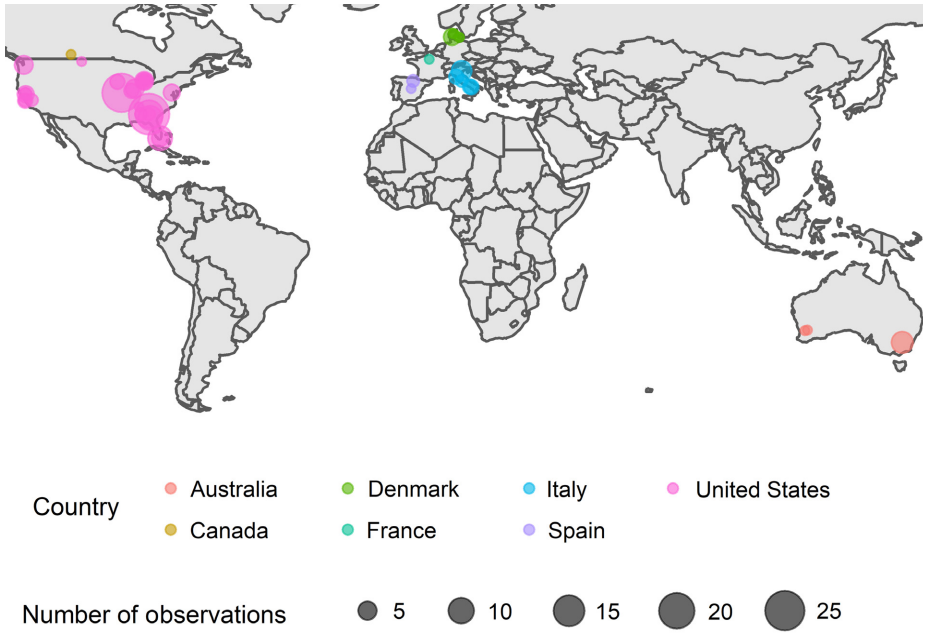
Questions for you:

- How much do you expect SOC to increase in a conventional corn/soybean system following adoption of:
  - A winter rye cover crop
  - No-till management

- Please express your answer as an annual percent change from the initial soil carbon value

SOC often increases with cover crops

- Summary of SOC change (0-30 cm) with cover crops (any species), at global scale



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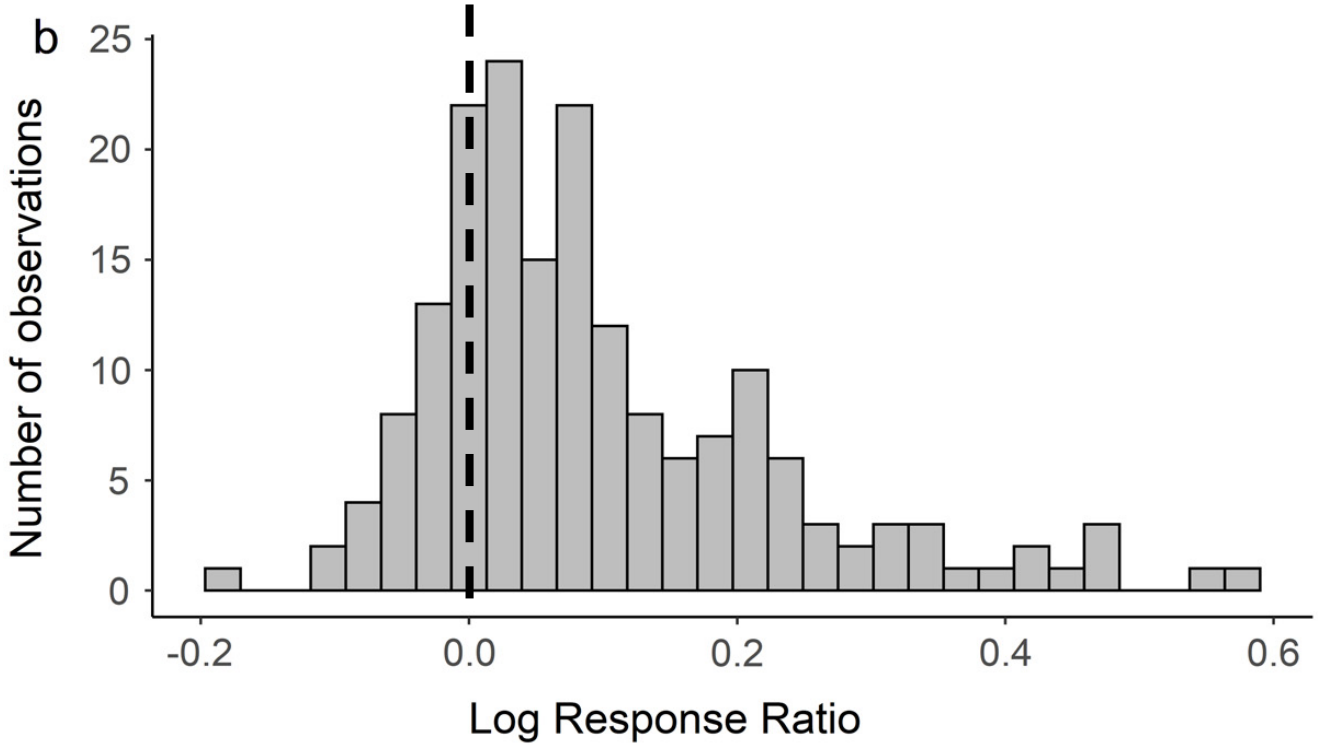

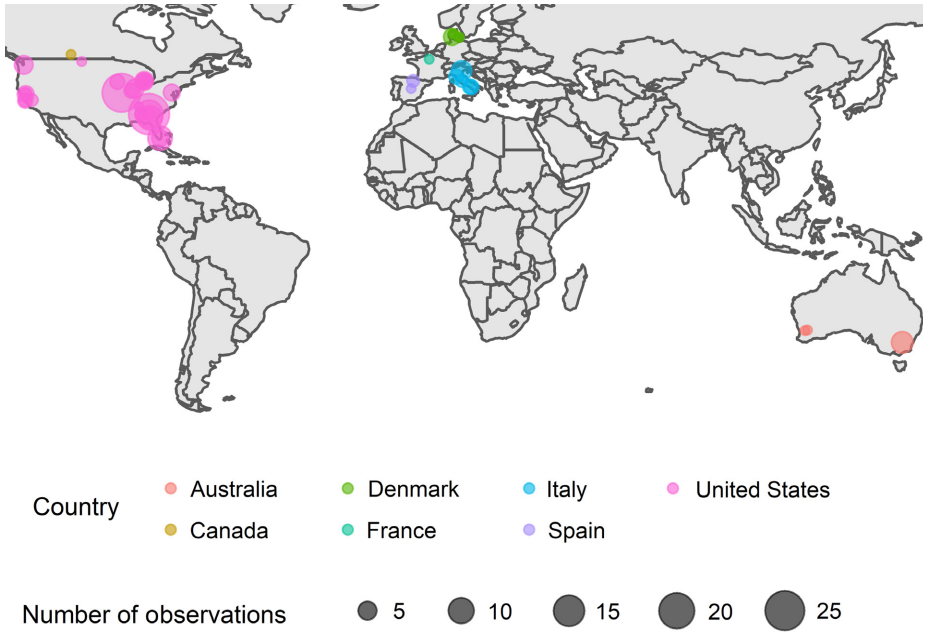

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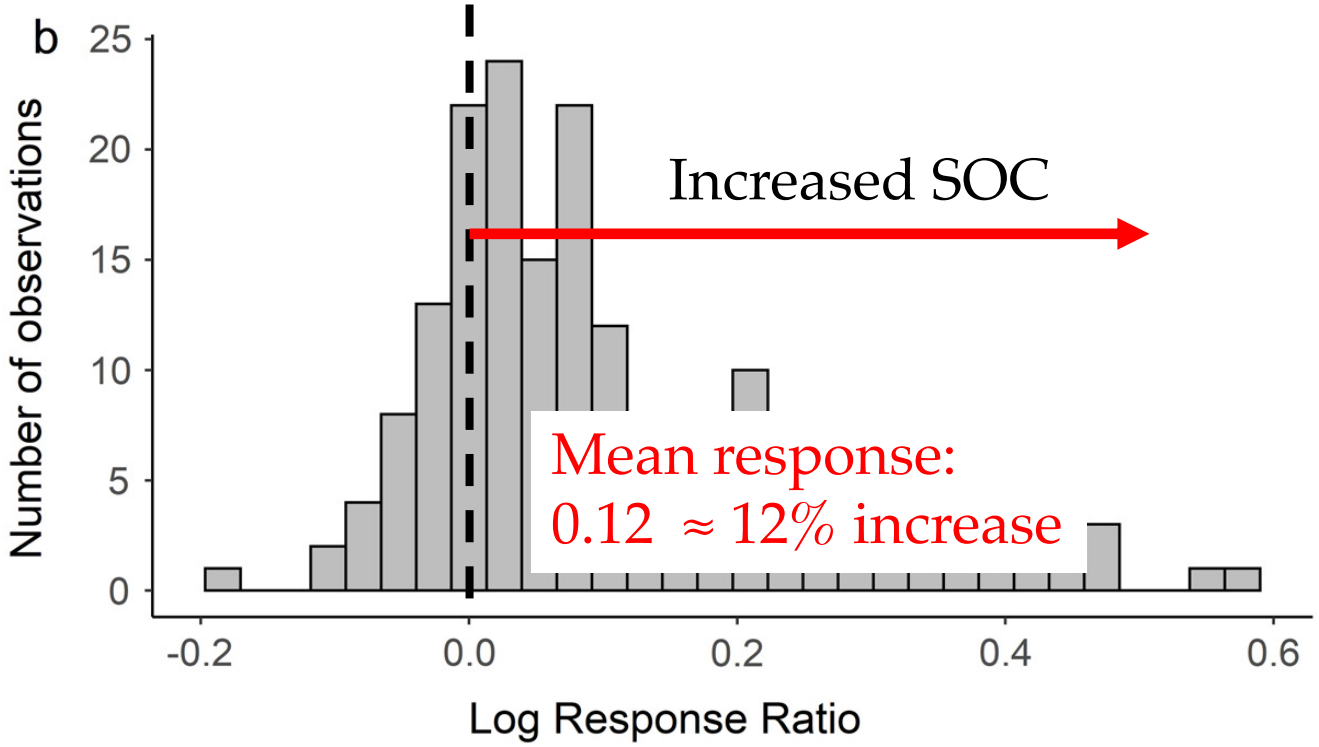

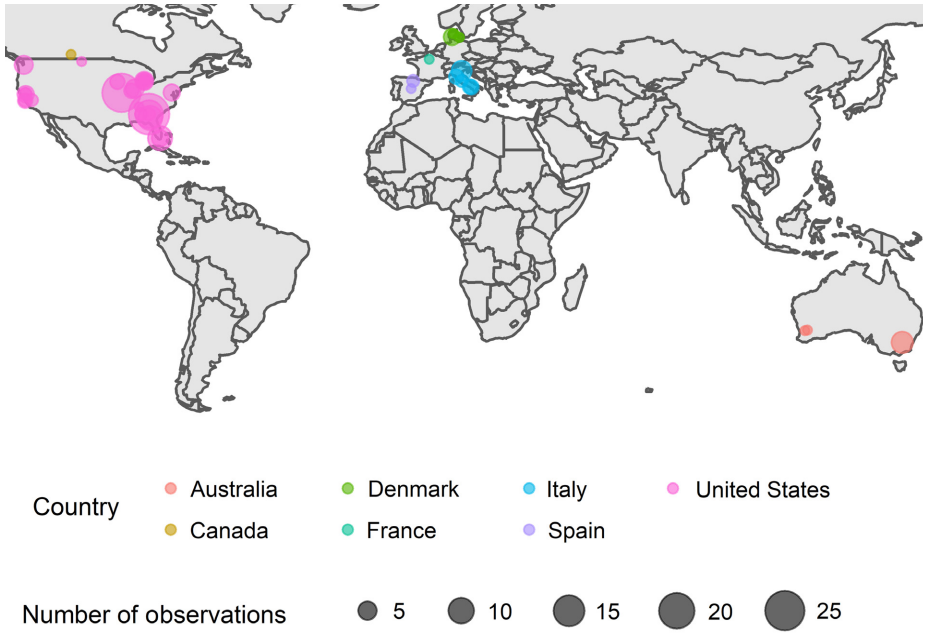

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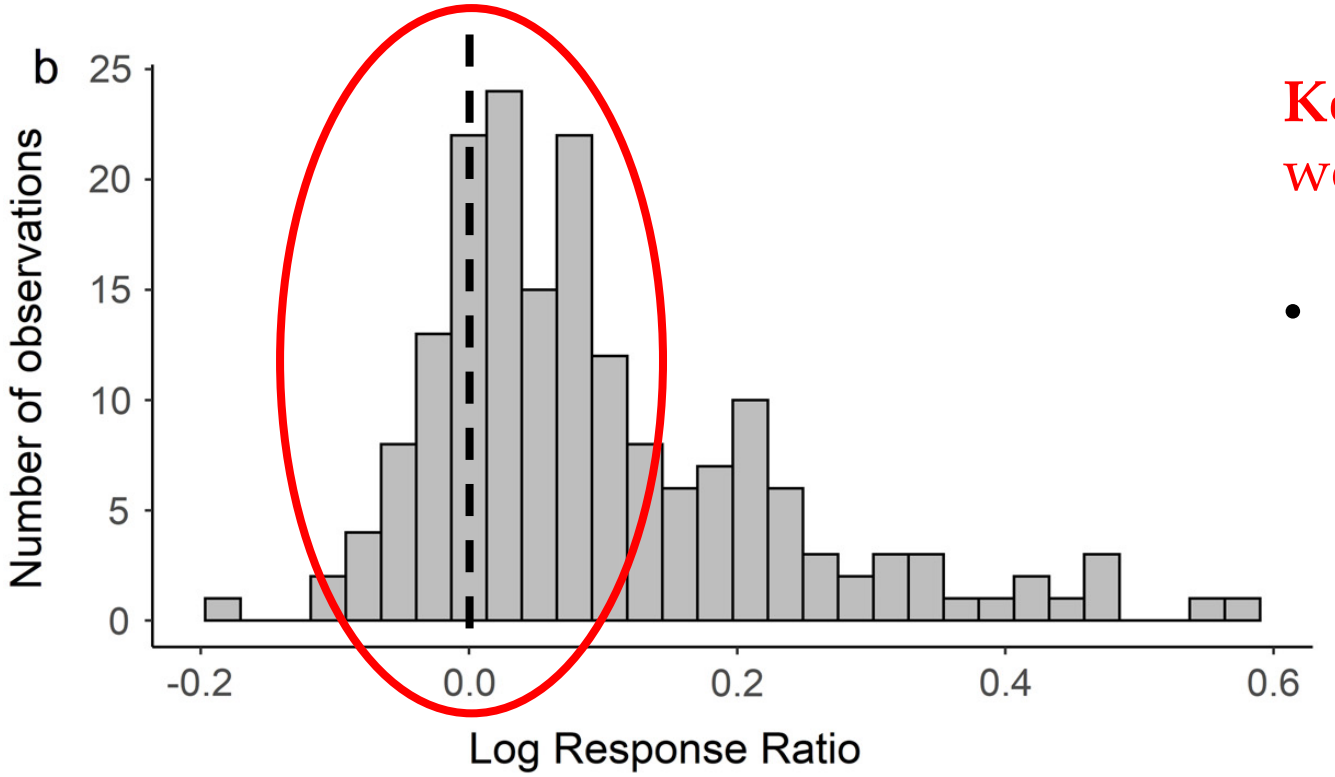

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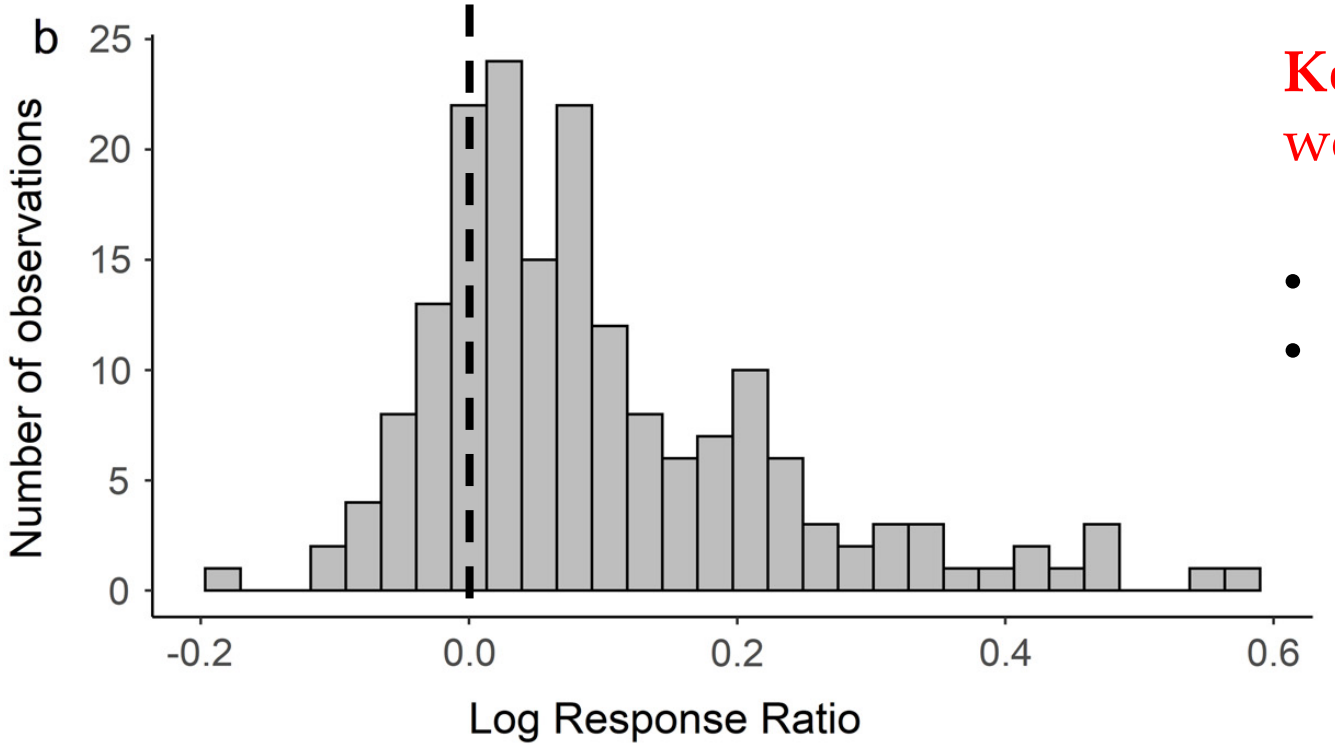

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- Compare to typical 0-30 cm SOC stock of **~100** Mg C ha^{-1} for north-central Iowa

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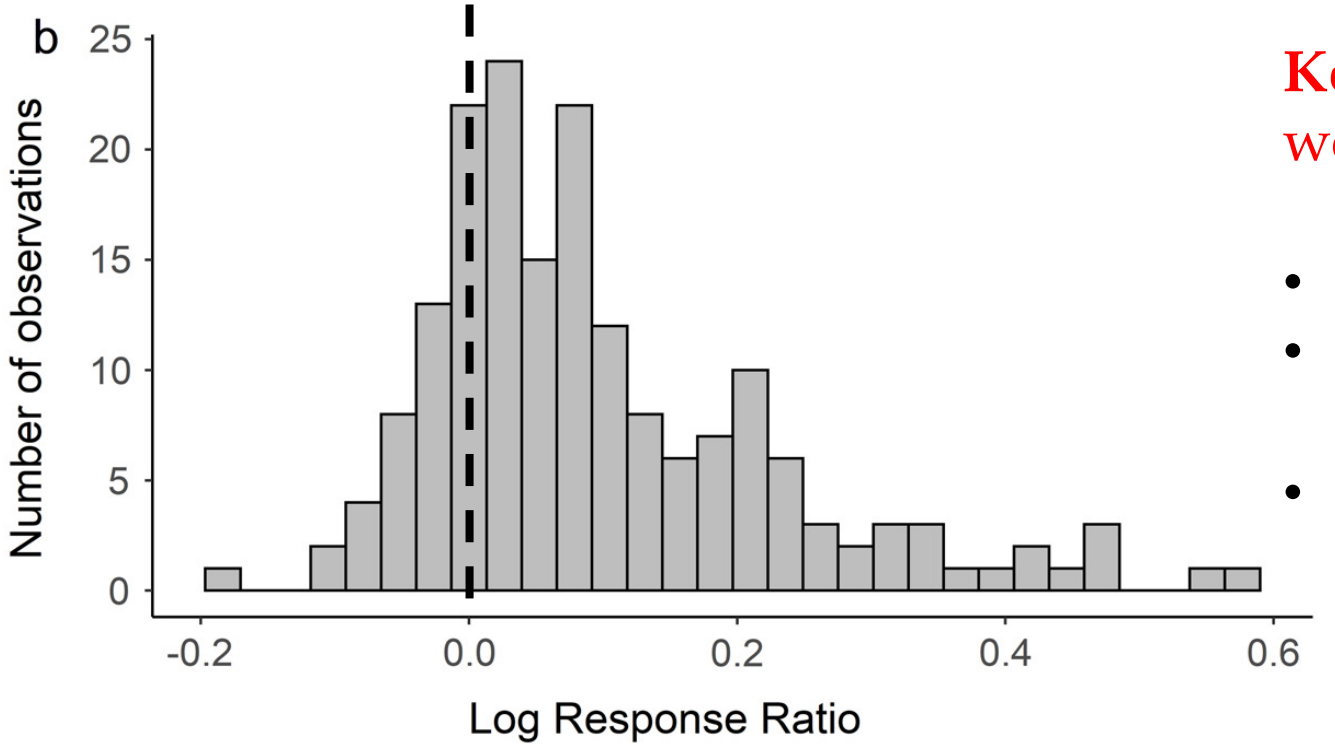

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A local example of limited SOC change following 10 y of cover crop management

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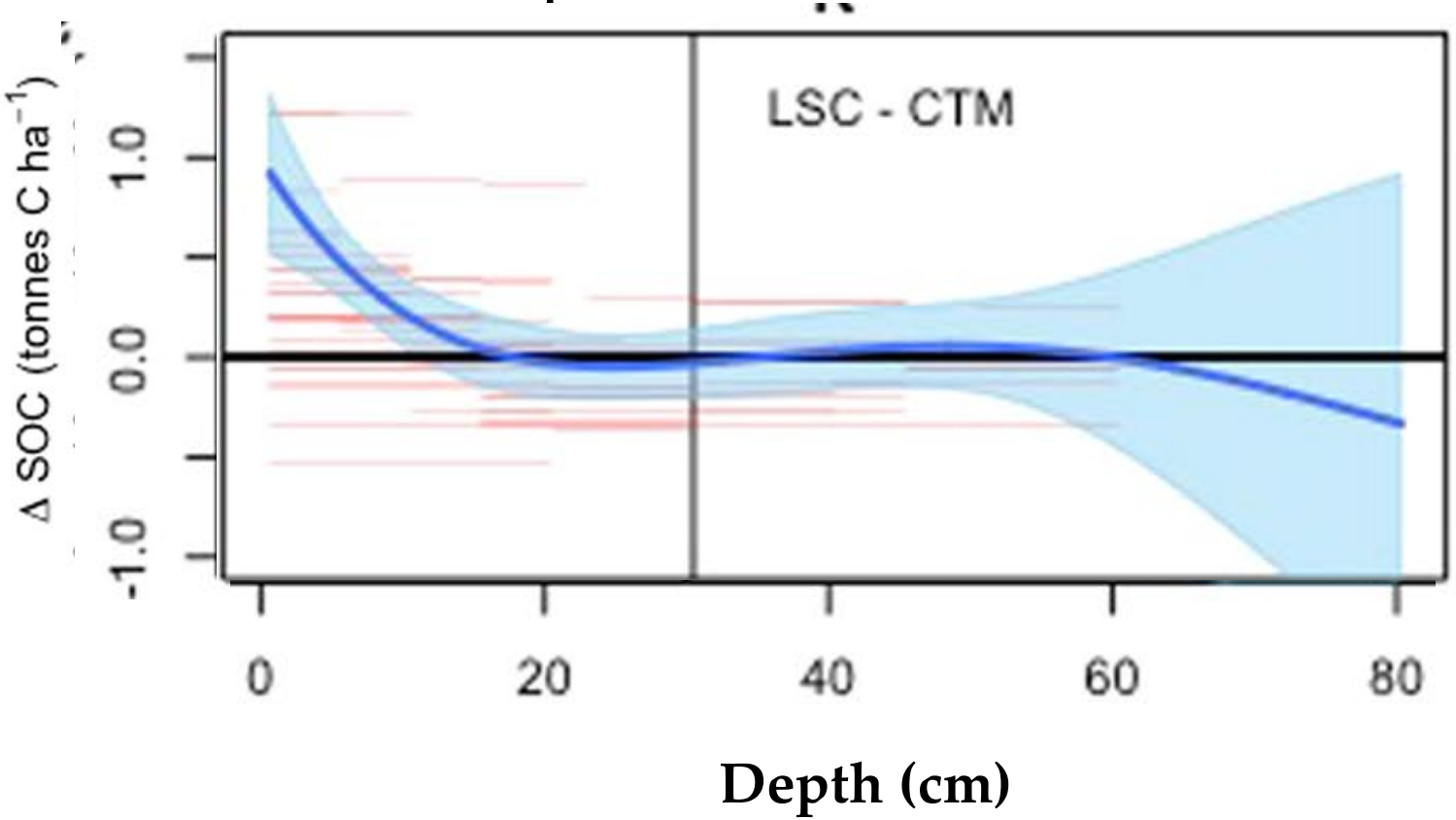
All treatments managed with no-till

	Treatment	Depth (cm)	pH	SOC (mg/g)
Continuous corn	CC	0–25	6.7 (0.1)^{aA}	18.9 (1.5)^{aA}
		25–50	6.6 (0.2)^{aA}	11.1 (2.2)^{aB}
		50–75	7.2 (0.2)^{aAB}	4.7 (1.4)^{aBC}
		75–100	7.7 (0.0)^{aB}	2.5 (0.6)^{aC}
Continuous corn with cereal rye cover crop	CCW	0–25	6.5 (0.2)^{aA}	16.8 (2.2)^{aA}
		25–50	6.4 (0.1)^{aA}	9.6 (2.2)^{aAB}
		50–75	6.6 (0.1)^{aAB}	5.2 (1.6)^{aB}
		75–100	7.1 (0.2)^{aB}	2.9 (1.0)^{aB}

Ye and Hall 2020 GCB-Bioenergy

SOC often increases with no-till management

- Summary of SOC change following no-till in fine-textured soils in cool temperate moist climates



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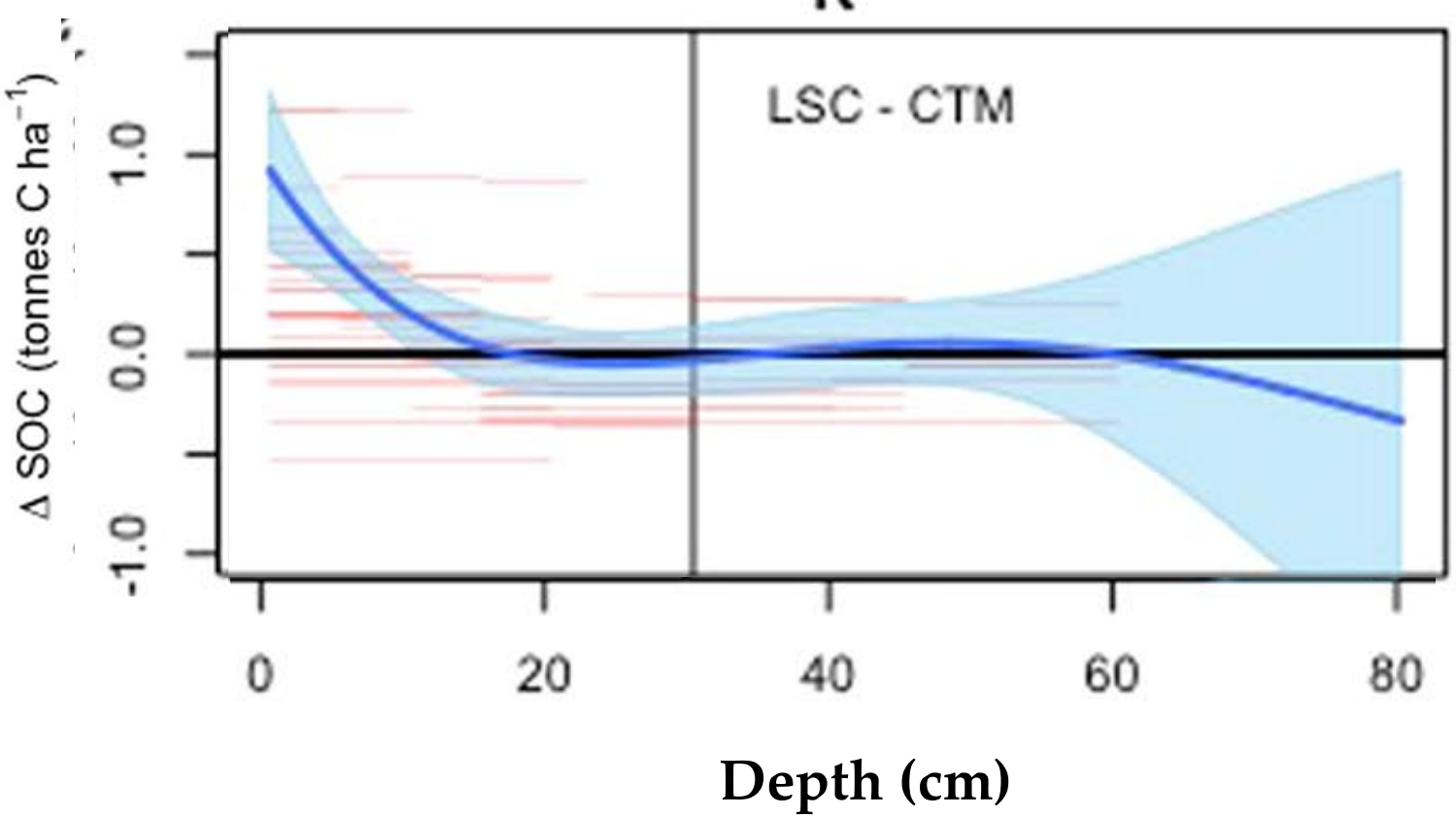

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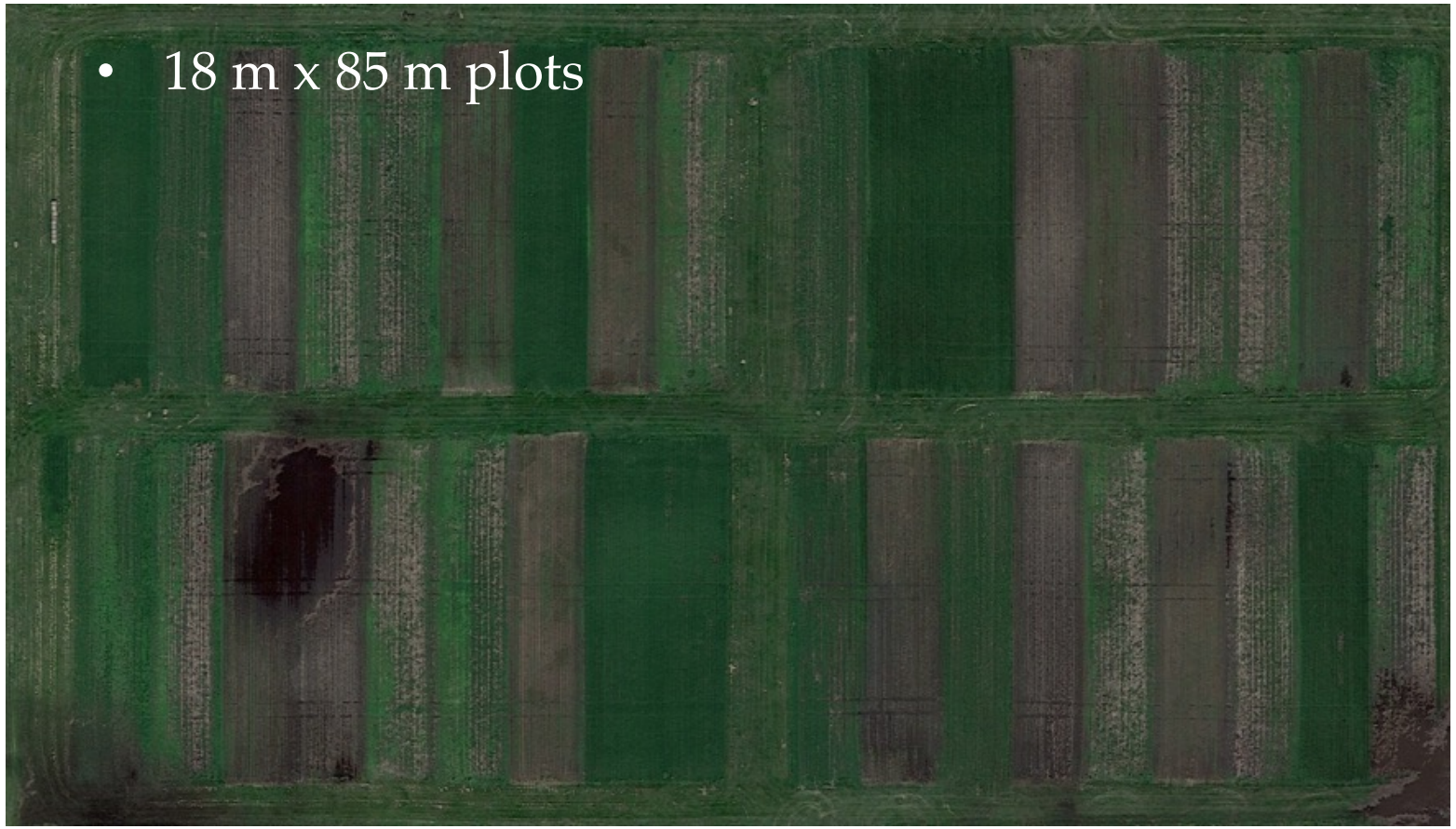
Questions for you:

- How do *diversified cropping systems* impact SOC?

- How much do you expect SOC to increase in a typical corn/soybean system after…
  - Including a small grain and clover (three-year rotation), + manure
  - Including a small grain, and then alfalfa (four-year rotation) + manure

- Please express your answer as an annual percent change from the initial soil carbon stock

A local example of limited SOC change following 20 y of diversified rotations



- Marsden farm experiment near Boone, IA
- Initiated by Matt Liebman at ISU
- 2, 3, and 4-y rotations
- Each phase of the rotation is replicated each year
- All managed with tillage

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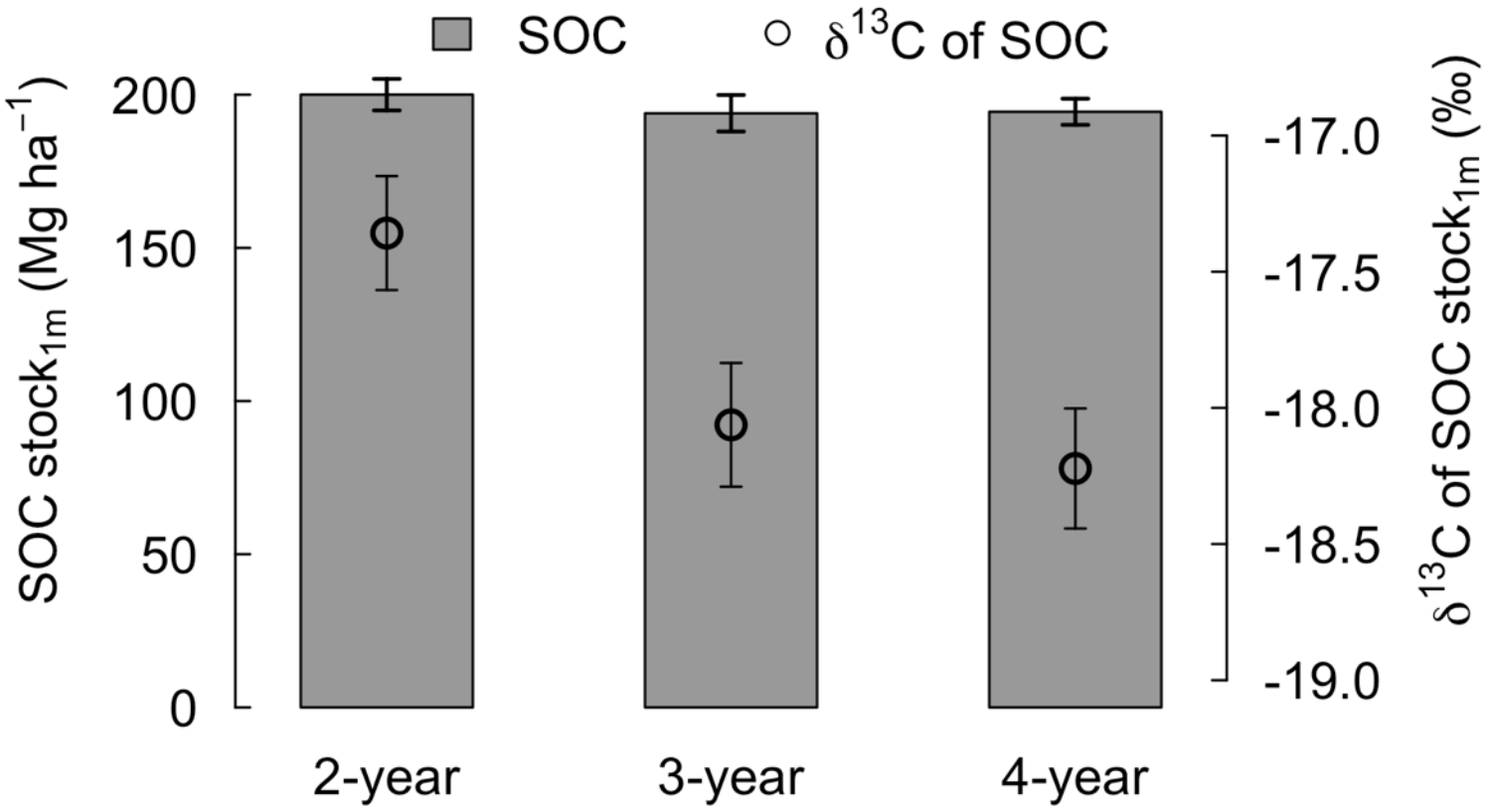

Corn-soybean

+ oats, clover

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+ alfalfa

- Soil sampled in fall 2021 to 1 m depth
- Extended rotations had lower SOC, on average, than the two-year rotation
- 194 vs. 200 Mg C ha^{-1}

Huang et al., unpublished

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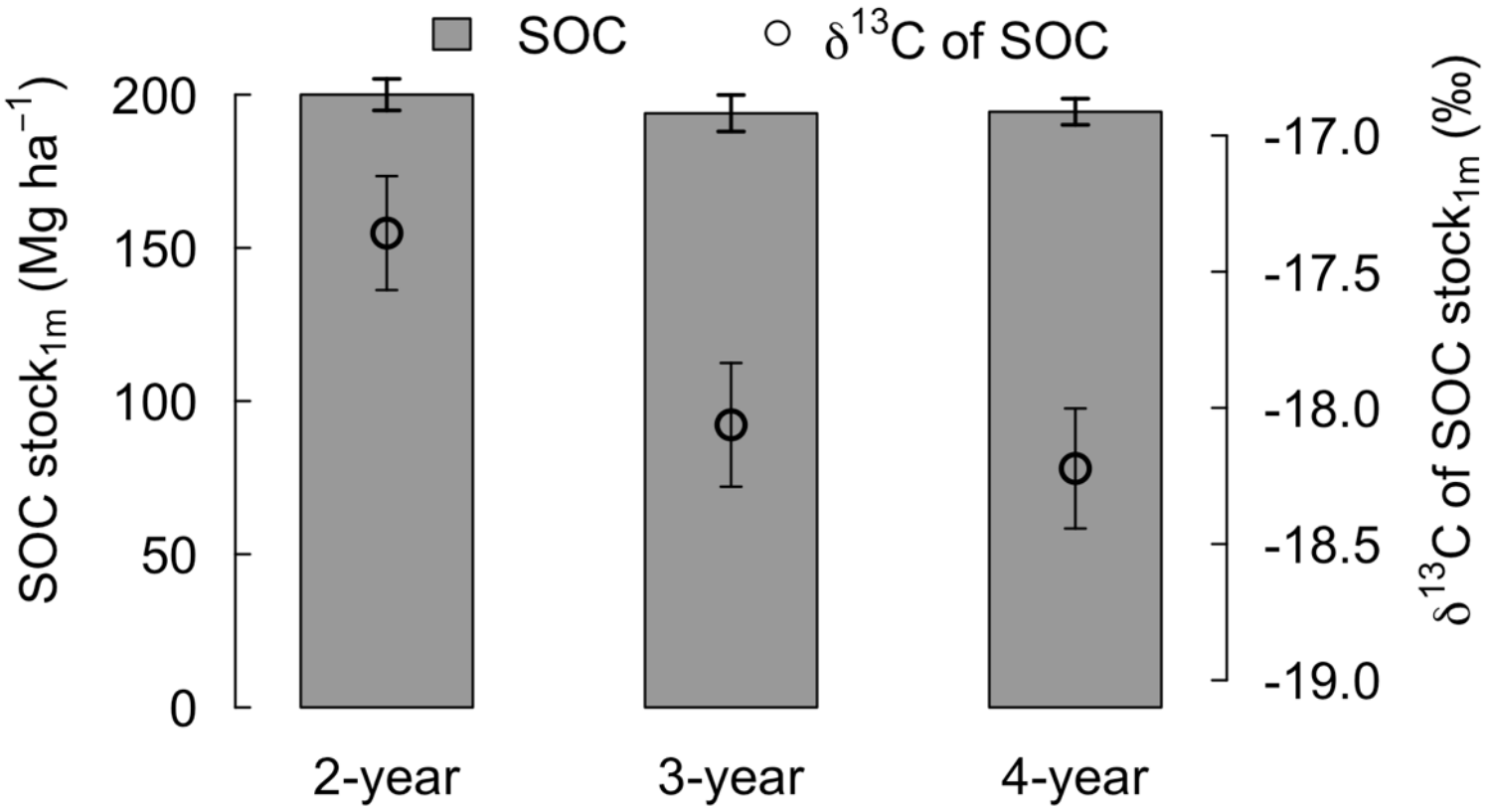

- Soil sampled in fall 2021 to 1 m depth
- Extended rotations had lower SOC, on average, than the two-year rotation
- 194 vs. 200 Mg C ha^{-1}
- Similar trend as previous data from 2014 (Poffenbarger et al. 2020, Agr. Eco. Envir.)

Huang et al., unpublished

How to interpret the lack of SOC change in a diversified cropping systems experiment?

- Was there simply no change in carbon cycling among treatments?
  - No; the extended rotations had greater root inputs, but slightly lower overall residue inputs

How to interpret the lack of SOC change in a diversified cropping systems experiment?

- Was there simply no change in carbon cycling among treatments?
  - No; the extended rotations had greater root inputs, but slightly lower overall residue inputs
- How might differences in root inputs impact carbon cycling?

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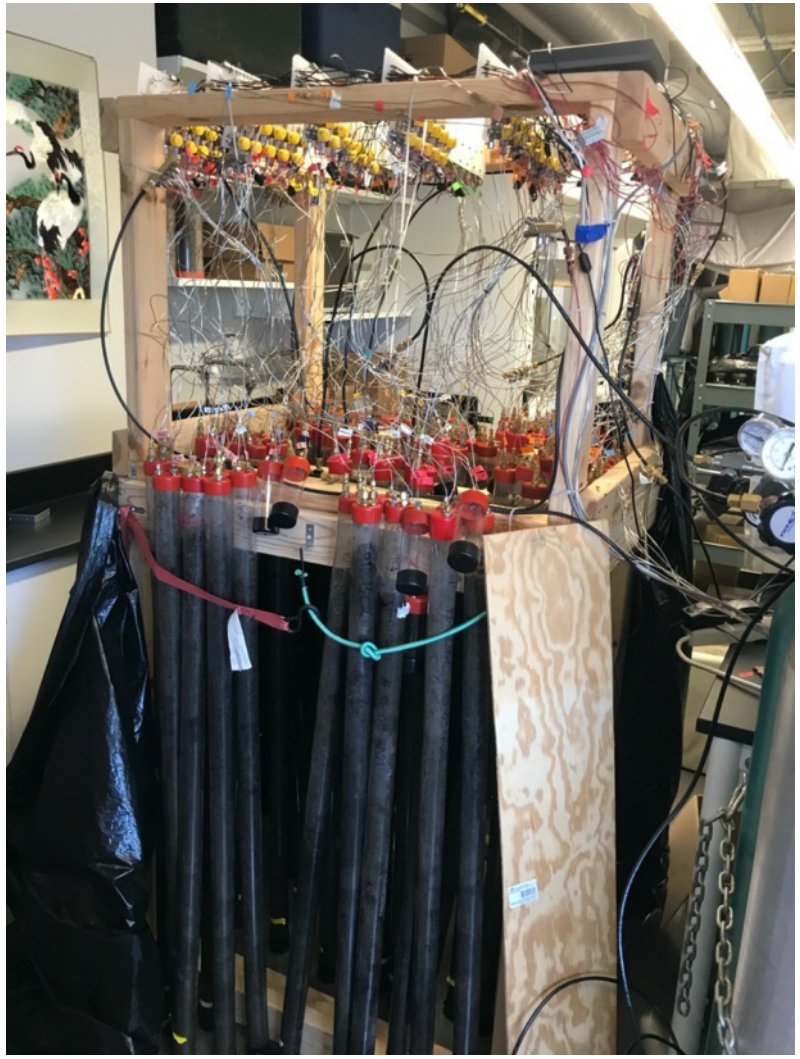
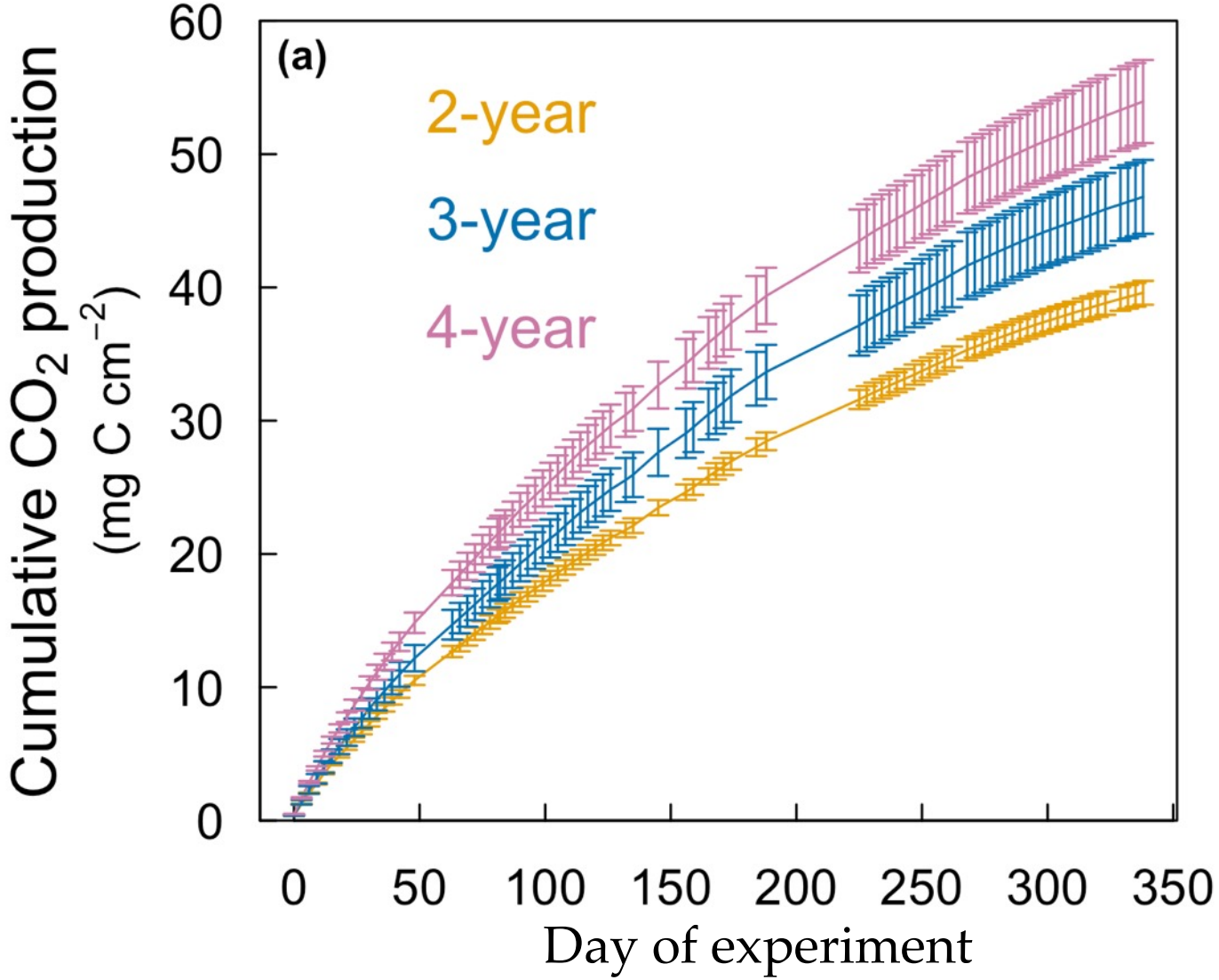
Respiration (CO_2 production) is a useful soil health metric

- Microbes respire oxygen and release carbon dioxide (CO_2) when they decompose organic matter
- Some commercial labs measure "potentially mineralizable carbon" (CO_2 produced after wetting dry soil)
- Researchers often measure CO_2 production from soils in the lab to assess microbial activity



Soil respiration (CO_2 production) increased in extended crop rotations

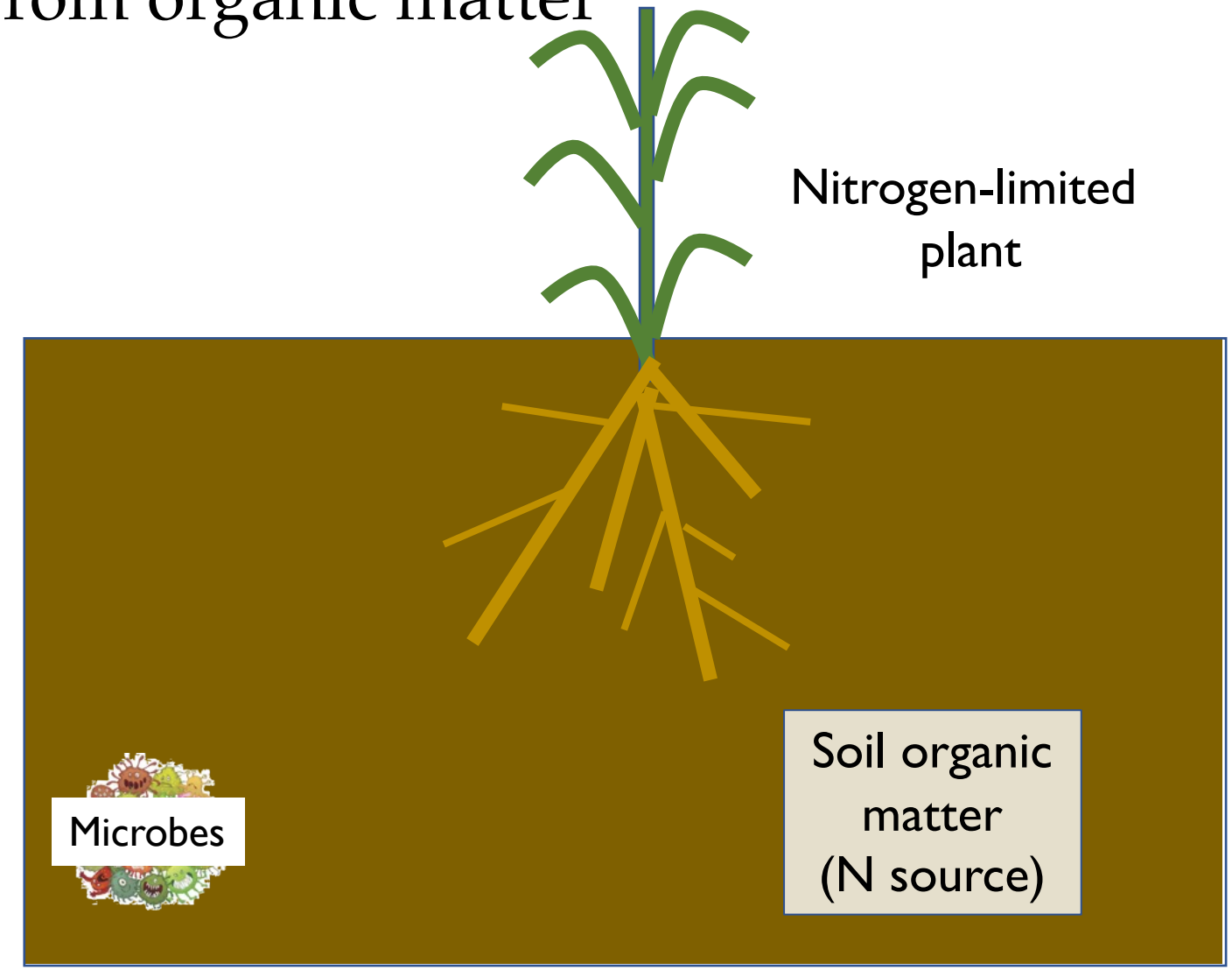


- We incubated intact soil cores in the laboratory for almost one year
- Greater CO_2 production indicates a combination of greater residue inputs and greater microbial activity
- How then might we explain the lack of SOC change?

Huang et al., unpublished

Simple cartoon illustrating potential tradeoffs between SOC storage and N supply from organic matter

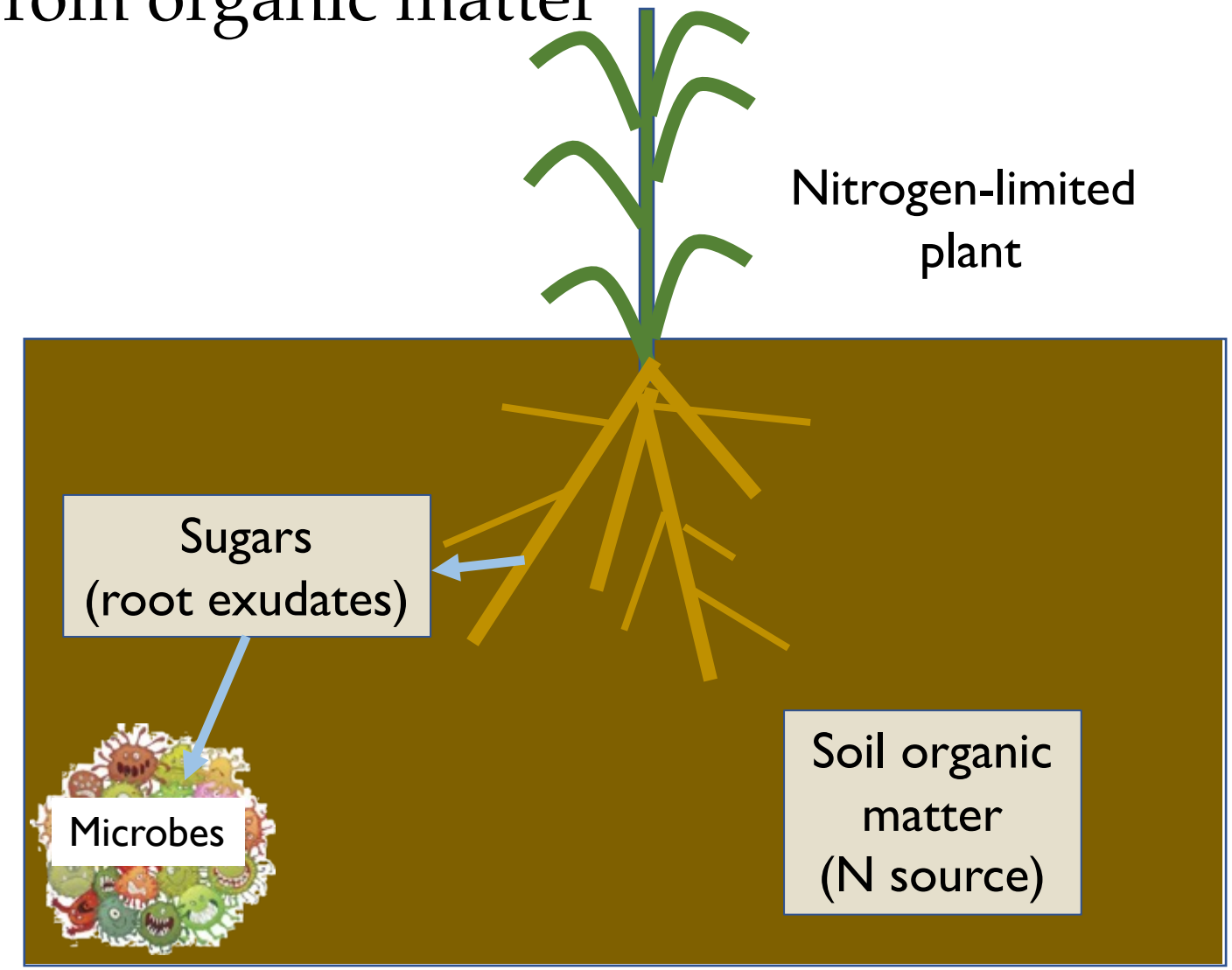
Recall that the overwhelming majority of soil N is stored in organic matter



Simple cartoon illustrating potential tradeoffs between SOC storage and N supply from organic matter

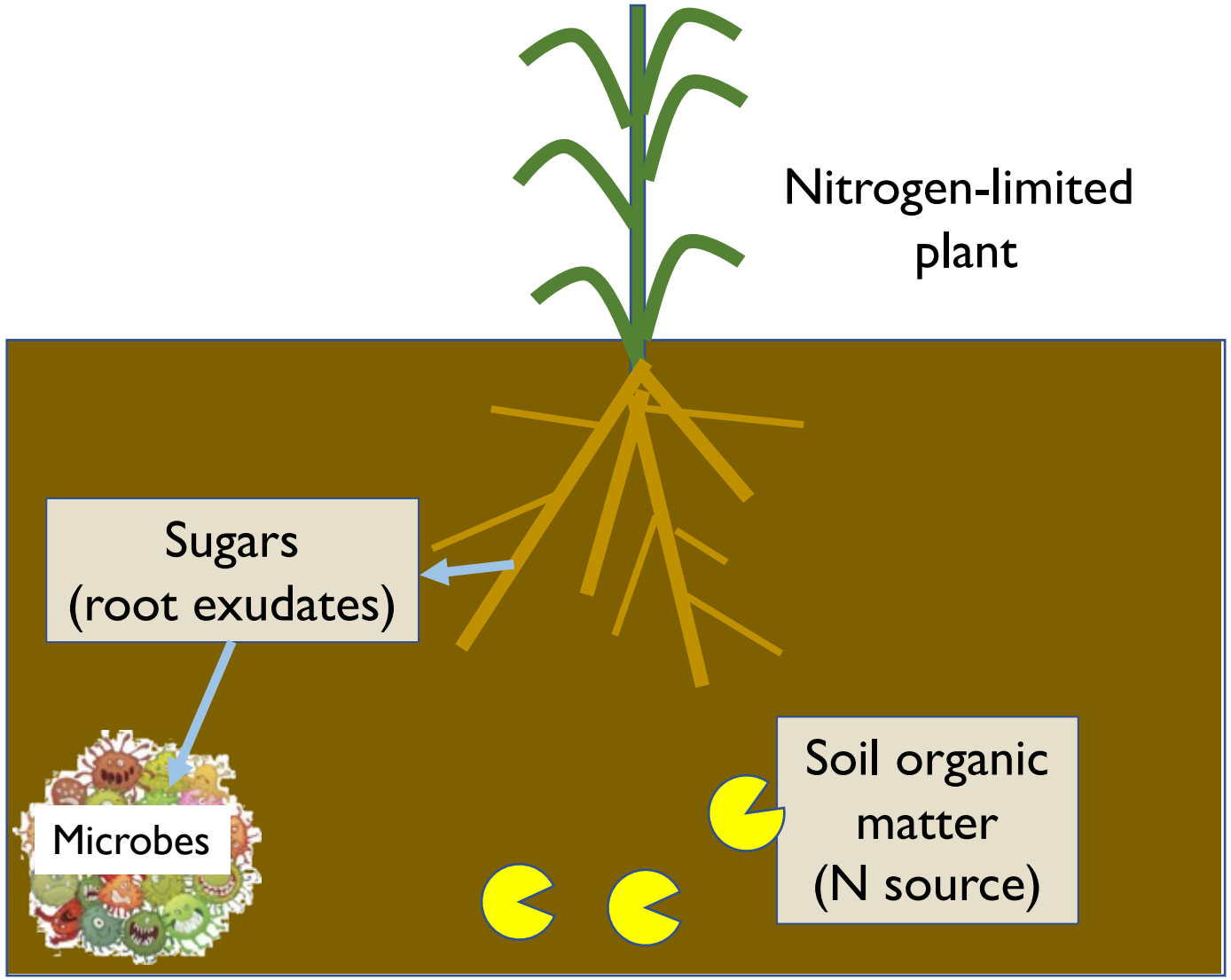
Plants release sugars known as "exudates" to feed their microbiome

Microbial growth



"Priming" of soil organic matter decomposition

- As microbes grow, they require more N
- They can get it by attacking SOM

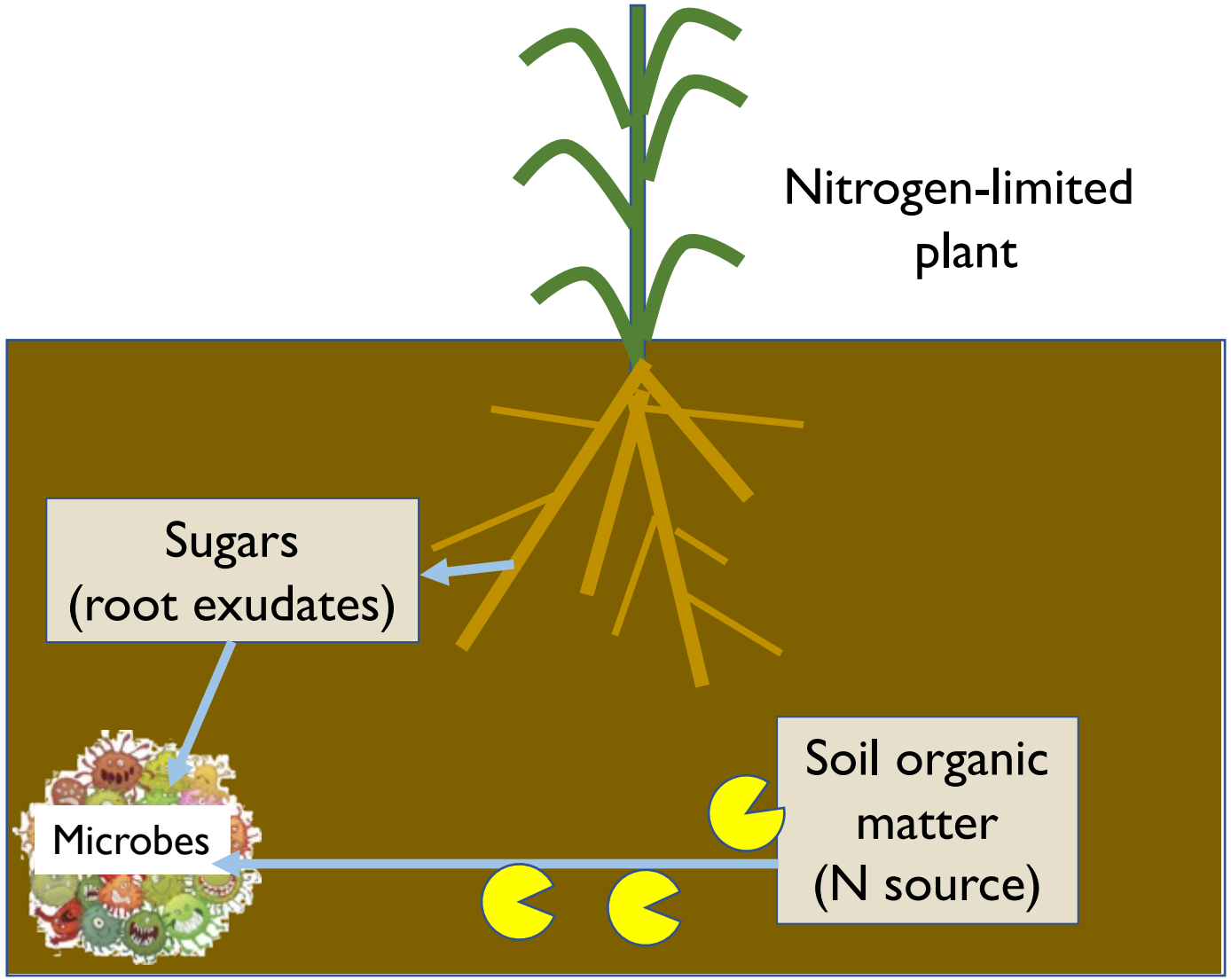


Microbial growth (N limitation)

Increased SOM depolymerization

"Priming" of soil organic matter decomposition

- Microbes can then take up the soluble organic matter



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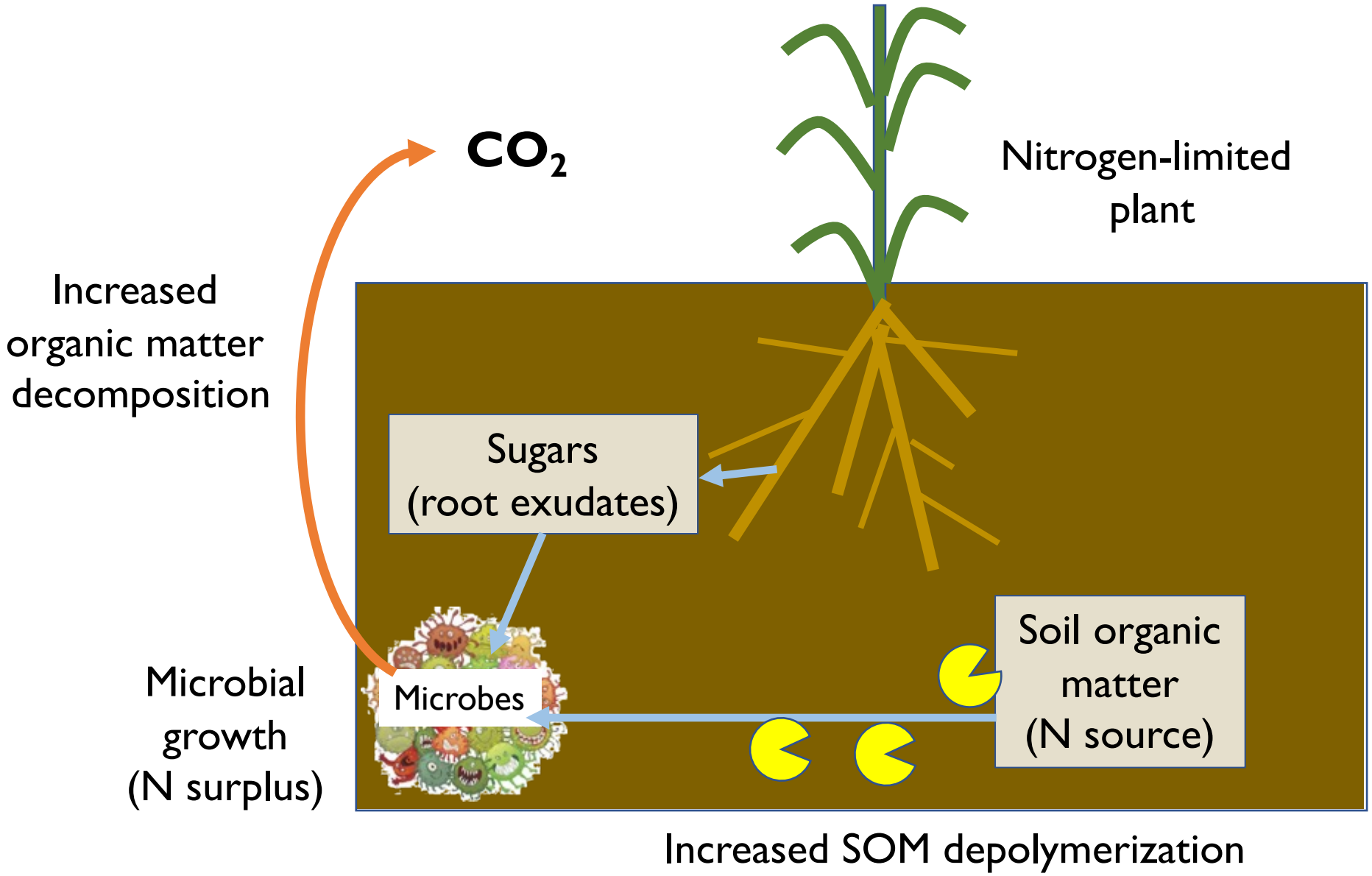

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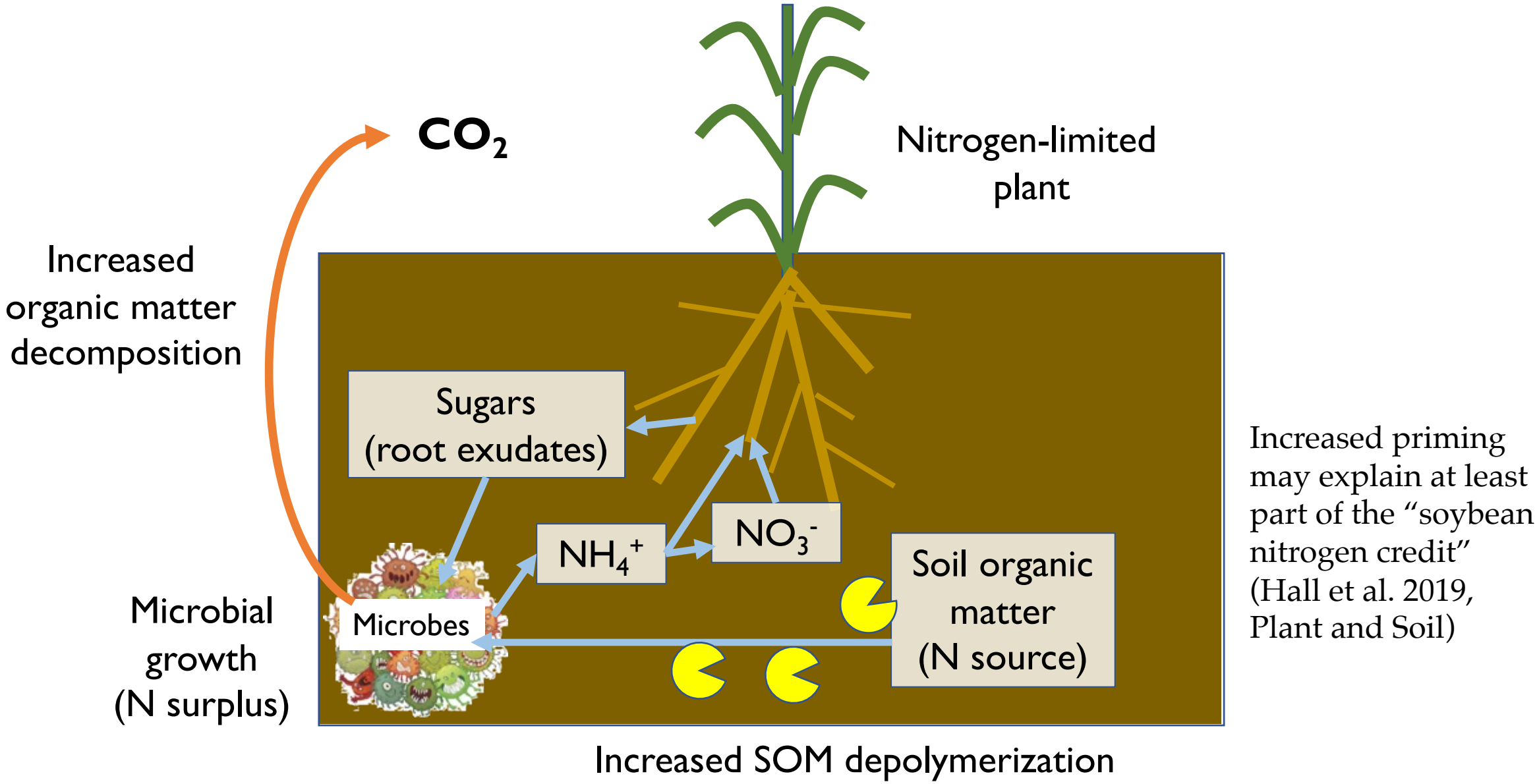

Increased priming may explain at least part of the "soybean nitrogen credit" (Hall et al. 2019, Plant and Soil)

Evidence that diversified rotations can increase the decomposition of SOC

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- Carbon has two stable isotopes: ^{12}C and ^{13}C
- Warm-season grasses such as corn are "C_4 plants" and differ from most other plants ("C_3 plants") in the ratio of these isotopes

Evidence that diversified rotations can increase the decomposition of SOC

- Carbon has two stable isotopes: ^{12}C and ^{13}C
- Warm-season grasses such as corn are "C_4 plants" and differ from most other plants ("C_3 plants") in the ratio of these isotopes
- We can use stable isotopes to measure C inputs and losses from soil!
- Specifically, we can say how much carbon from corn the microbes decomposed, vs. other sources

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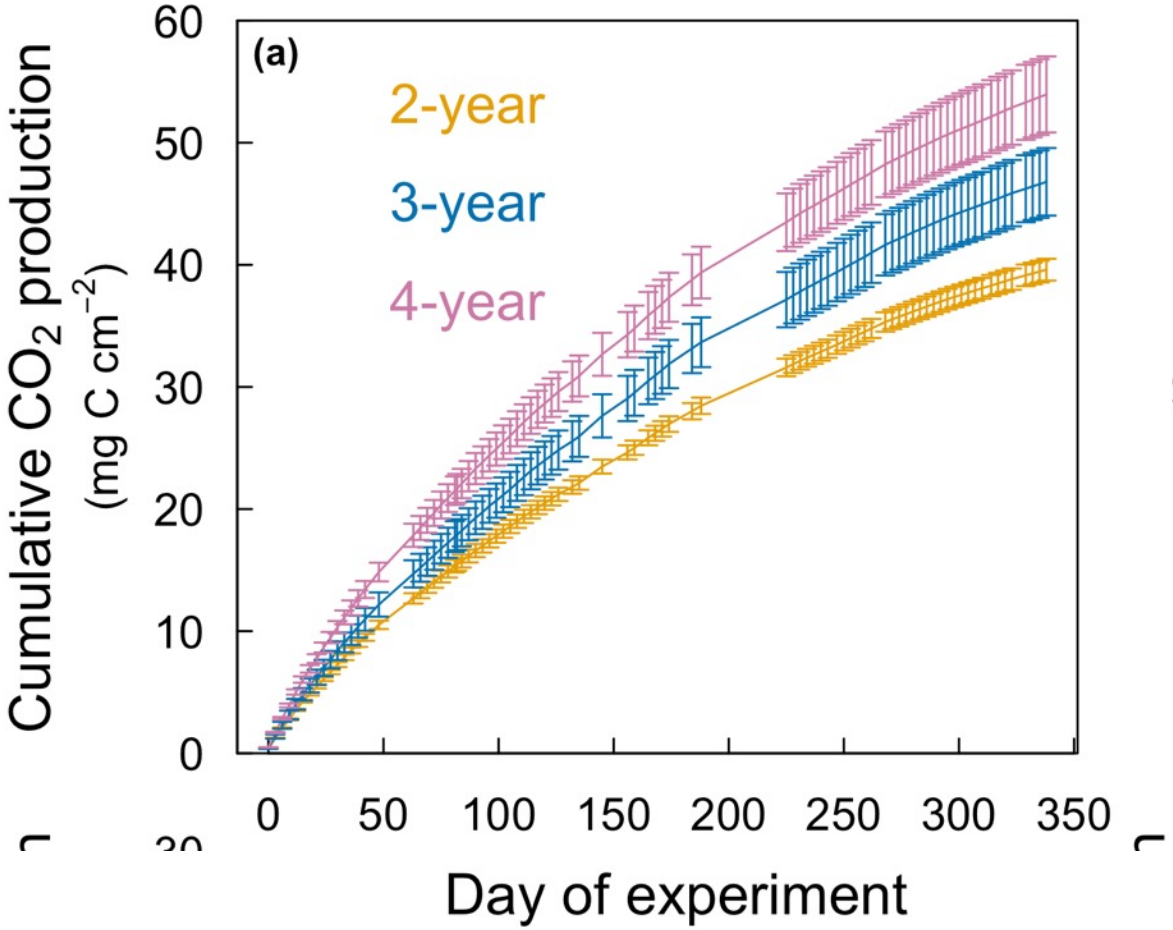
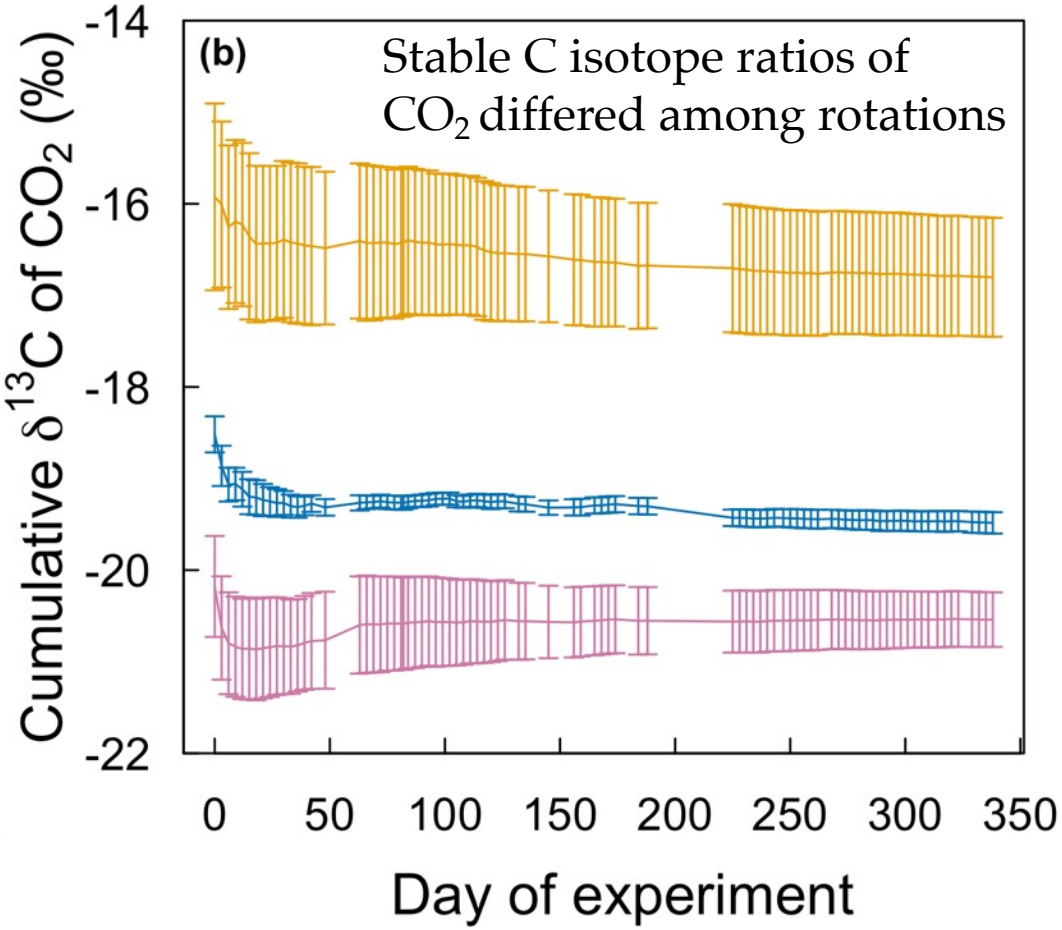
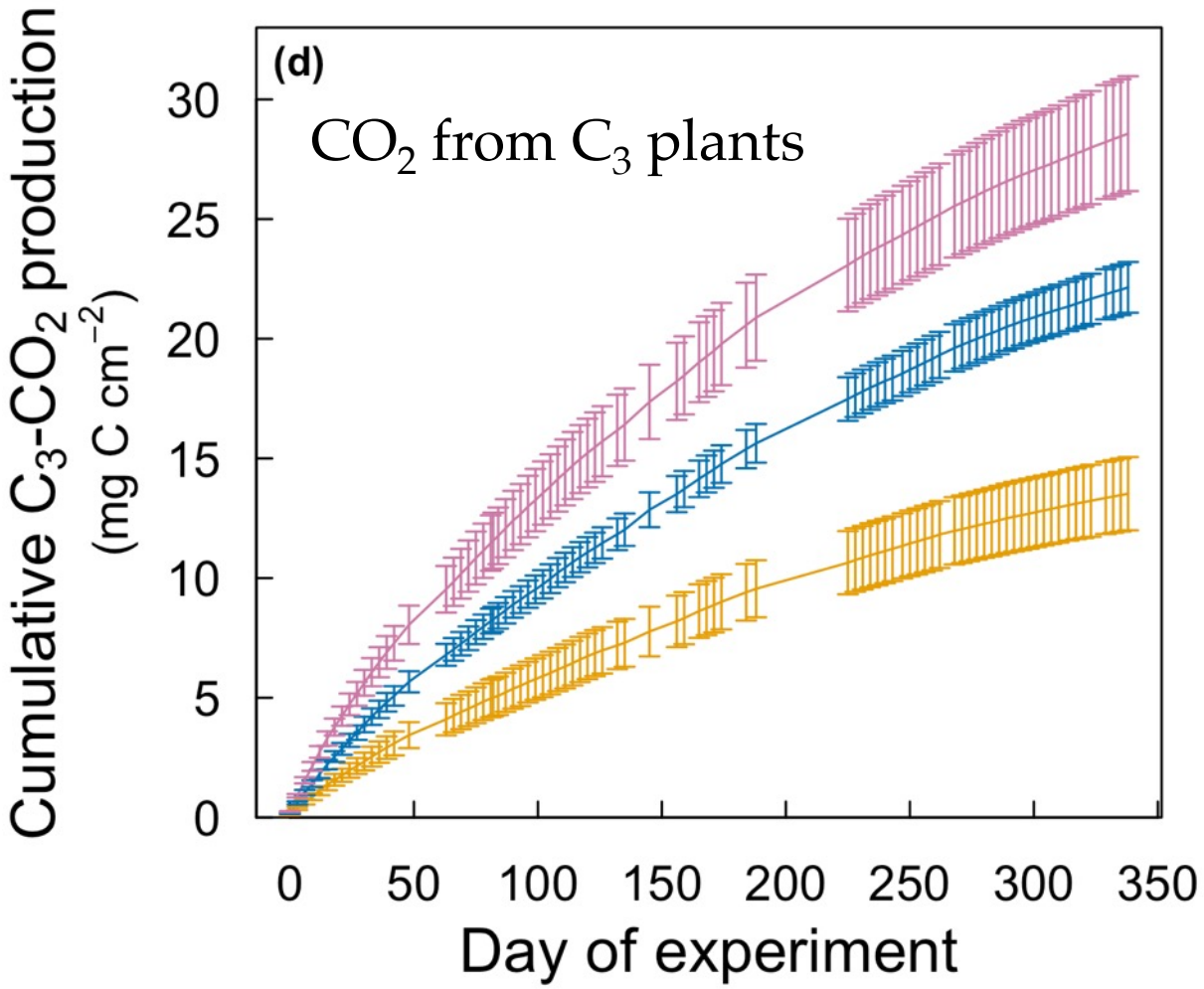




Corn

Soybean, Oats / clover, Alfalfa

Evidence that extended rotations can increase the diversified of SOC



- As expected, the extended rotations decomposed more C derived from C_3 plants
- This is because soybeans, oats, clover, and alfalfa are all C_3 plants

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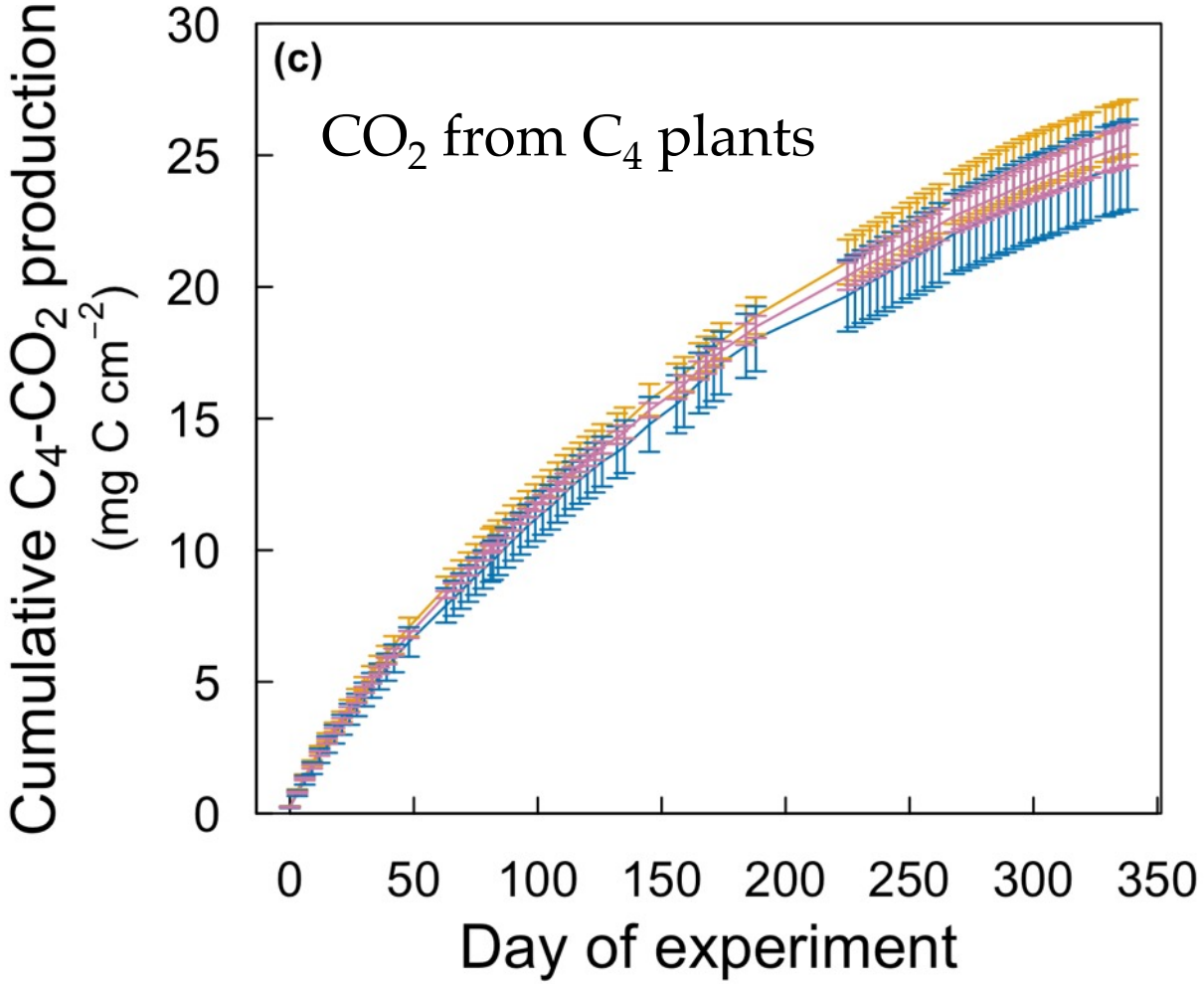


- Corn C inputs to the four-year soils are about half as much as in the two-year soils
- Yet, the extended rotations decomposed just as much C from C_4 plants as the conventional rotation!
- This means that soils in the extended rotations are likely decomposing *older* SOC…

How to think about agricultural soil carbon?

- **Soils are not just buckets for storing organic matter**
- SOC doesn't necessarily increase simply because residue inputs increase
- Increased decomposition may offset increased residue inputs
- However, there are key benefits of increased microbial activity…

These diversified crop rotations required lower N fertilizer inputs

Table 1. Nutrient N and P Applications via Fertilizer and Composted Manure During 2008–2016 Averaged over All Crop Phases of Each Rotation System

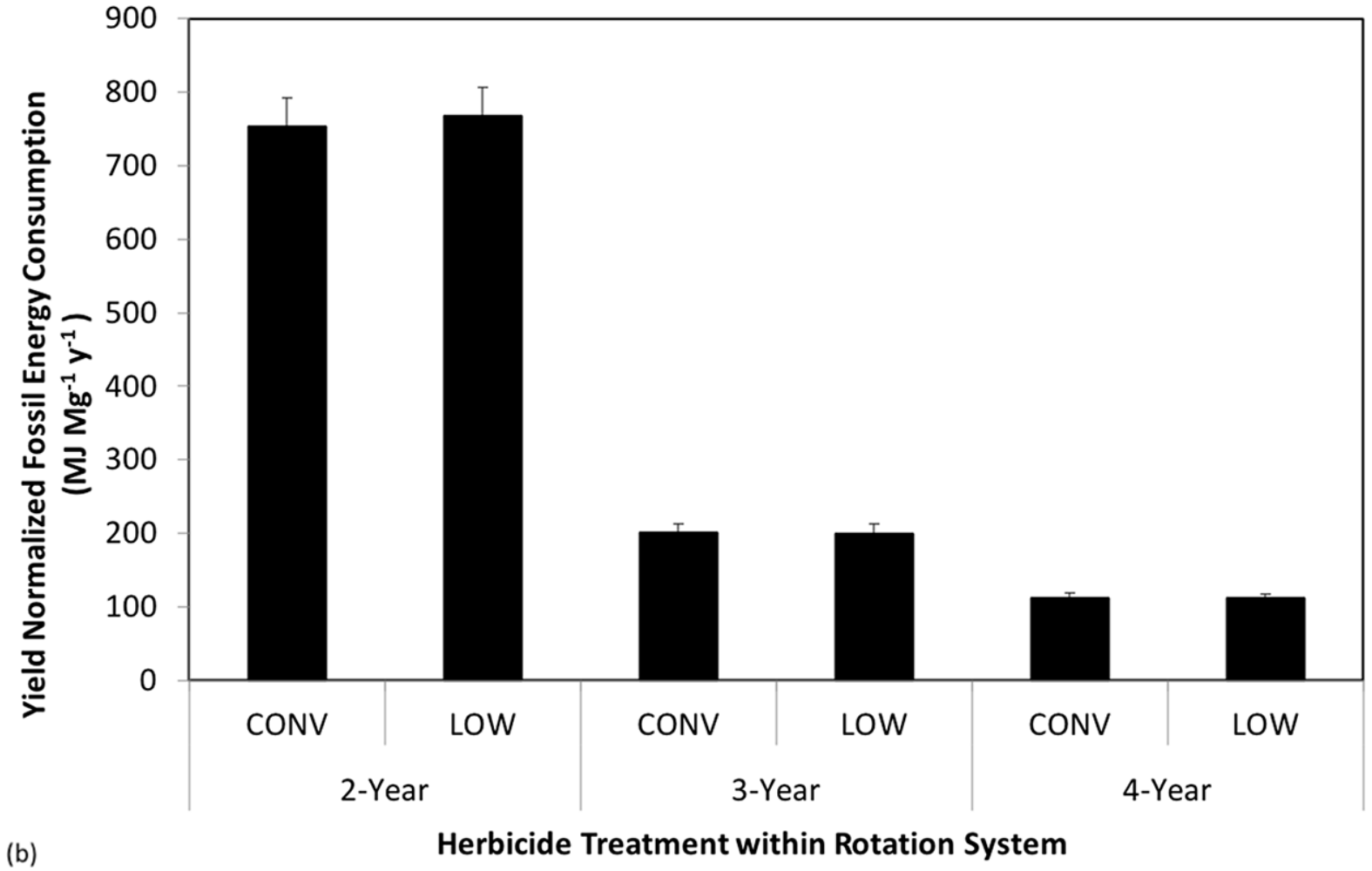
	crop rotation system		
	2 year (kg ha^{-1} yr^{-1})	3 year (kg ha^{-1} yr^{-1})	4 year (kg ha^{-1} yr^{-1})
fertilizer N	89	13	8
fertilizer P	15	0	9
manure N	0	46	34
manure P	0	15	11

- Synthetic N inputs were ~90% lower in the extended rotations
- Net profitability was similar

N rates were determined using the late-spring soil nitrate test

Hunt et al., 2019
Env. Sci. Tech

These diversified crop rotations were also more productive per unit fossil energy input



- Fossil energy consumption was tabulated for all aspects of crop production
- Then, it was divided by the harvest crop yields

Hunt et al., 2020
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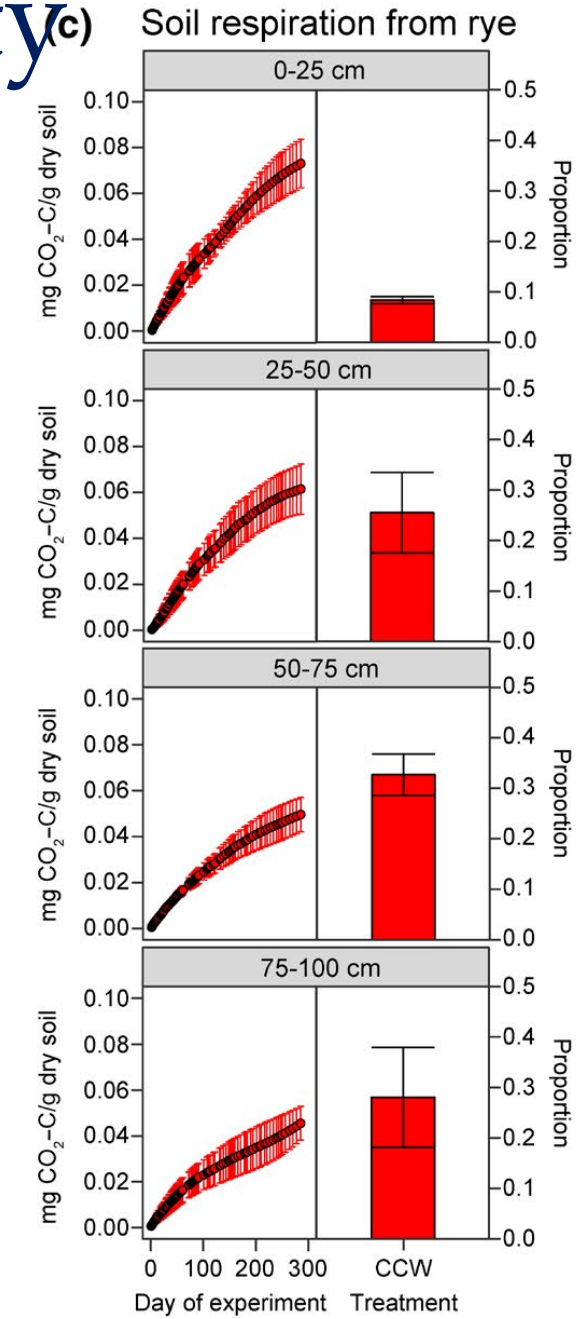

Ye and Hall 2020
GCB-Bioenergy

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- Using isotopes, we found that C from the cover crop accounted for about 10% of respiration at the soil surface
- But, the cover crop supplied ~30% of respiration at a depth of 50 cm to 100 cm
- Increased biological activity may benefit water quality even if SOC doesn't increase:
  - Mean nitrate leaching was 58% lower in the cover-cropped corn (Daigh et al. 2015, J. Environ. Qual.)

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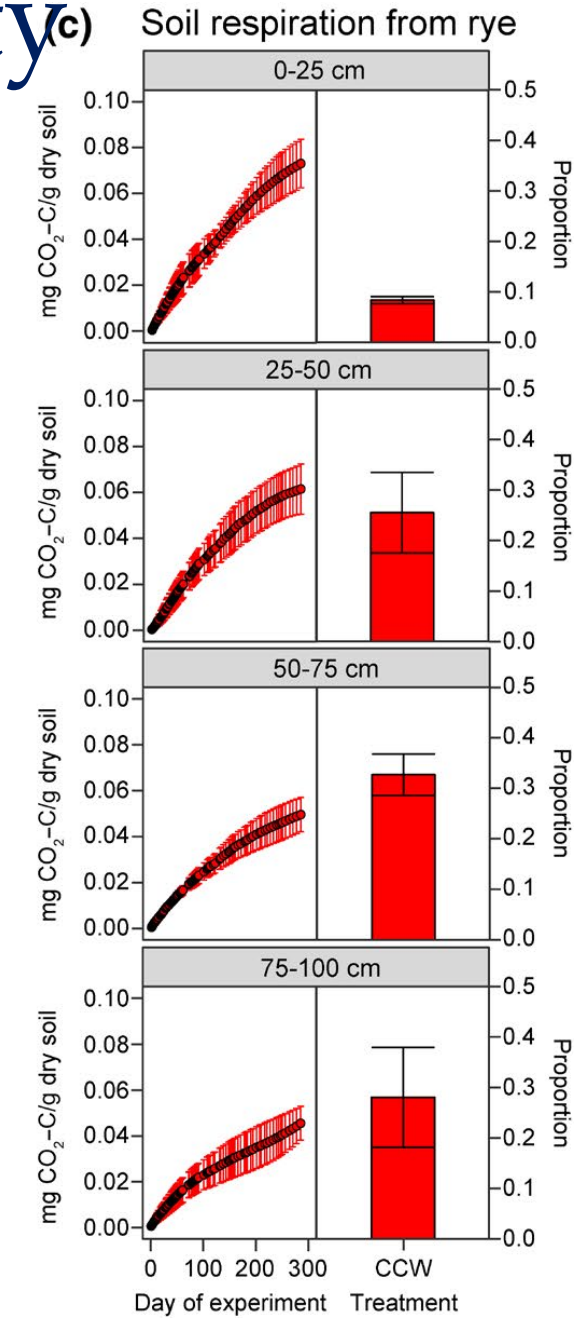

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- Which greenhouse gas is the largest source of current climate warming from typical corn/soybean systems in the US Corn Belt?
  a) Carbon dioxide (CO_2)
  b) Methane (CH_4)
  c) Nitrous oxide (N_2O)

Nitrogen, not carbon, has greater leverage on climate impacts of Corn Belt agriculture

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- Conservative upper bound of soil C gain in the humid Corn Belt:
  - ~ **1600** kg CO_2-eq ha^{-1} y^{-1} (restored prairie; Matamala et al. 2008)
- Estimated C gains from cover crops
  - ~**800 – 1200** kg CO_2-eq ha^{-1} y^{-1} (Poeplau and Don et al. 2015: McClelland et al. 2021)
- Estimated C gain from decreased tillage
  - ~**1,000** kg CO_2-eq ha^{-1} y^{-1} from cool, moist, fine-grained soil (Ogle et al. 2019)

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- Greenhouse gas emissions from synthetic N *production*
  - ~ **350** kg CO_2-eq ha^{-1} y^{-1}(Liu et al. 2020)
- Direct nitrous oxide emissions from central IA corn/soybean soils
  - ~**3,700** kg CO_2-eq ha^{-1} y^{-1} (Lawrence et al., 2021)

How to decrease N_2O emissions?

- Simplest answer: decrease synthetic N fertilizer application.
  - Rough estimate: a 20% decrease in N rate may decrease N_2O by 25%
  - In CO_2 equivalents, this is similar to average SOC gains from cover crops and no-till (about 1000 kg CO_2-eq ha^{-1} y^{-1})

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- More complicated/contentious answers:
  - Precision N management
  - Nitrification inhibitors?
  - Improved drainage?
  - Biochar?
- However, we've already discussed a system that can dramatically decrease synthetic N inputs without sacrificing profitability…

These diversified crop rotations required lower N fertilizer inputs

Table 1. Nutrient N and P Applications via Fertilizer and Composted Manure During 2008–2016 Averaged over All Crop Phases of Each Rotation System

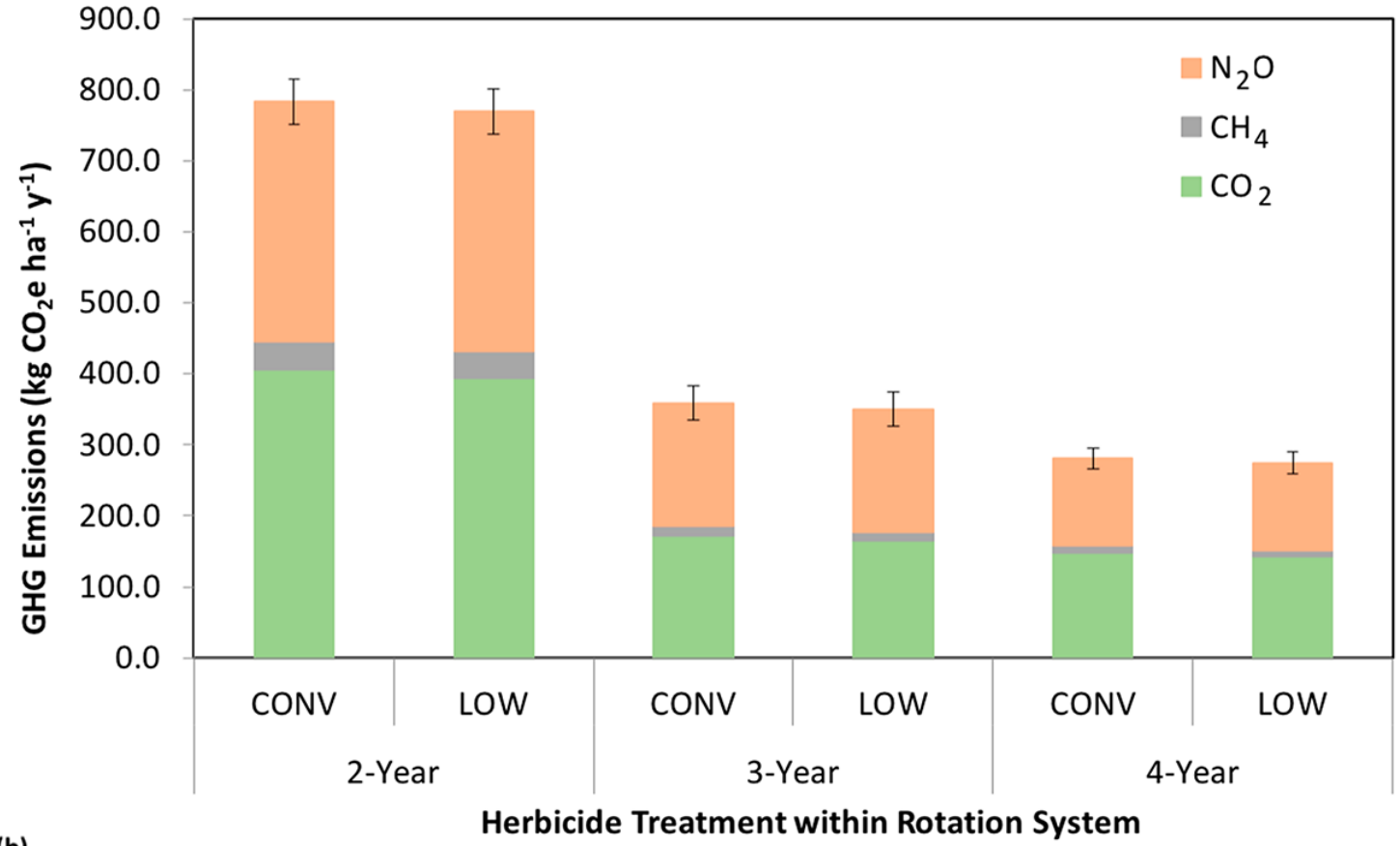
	crop rotation system		
	2 year (kg ha^{-1} yr^{-1})	3 year (kg ha^{-1} yr^{-1})	4 year (kg ha^{-1} yr^{-1})
fertilizer N	89	13	8
fertilizer P	15	0	9
manure N	0	46	34
manure P	0	15	11

- Synthetic N inputs were ~90% lower in the extended rotations
- Net profitability was similar
- See Matt Liebman for further questions about the Marsden experiment

N rates were determined using the late-spring soil nitrate test

Hunt et al., 2019
Env. Sci. Tech

These diversified crop rotations had much lower greenhouse gas emissions



Hunt et al. 2020, ES&T

- Note: the N_2O emissions were estimated from a simple model
- Our measurements from a nearby site indicate that real N_2O fluxes are likely two or three-fold greater! (Lawrence et al. 2021, PNAS)

Implications for carbon markets

- Practices such as no-till and cover crops *can* potentially increase SOC…
- But results are context-dependent, and may not be detectable
- Diversified cropping systems may have little effect on SOC but may have large effects on soil biological processes
- Cropping systems that decrease synthetic N inputs may have greatest climate benefit (decreased N_2O emissions) even if they do not store additional SOC
- The same logic likely holds true for water quality improvement

Acknowledgements

- **Dr. Matt Liebman**, ISU faculty emeritus, for initiating and providing access to the Marsden and COBS experiments (now managed by **Dr. Michael Thompson** and **Dr. Marshall McDaniel**)
- **Drs. Wenjuan Huang and Chenglong Ye**, who led several of the soil carbon studies mentioned above
- Numerous other staff and students, especially **Matt Woods** and **Carlos Tenesaca**
- Funding from USDA, NSF, the Iowa Nutrient Research Center, and GRER (U. of Iowa), Leopold Center for Sustainable Agriculture

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Question: where in this field is the soil "healthiest"?

~1 km

a) In the dark green areas (uplands)

b) In the light green areas (slopes)

c) In the purple areas (depressions)

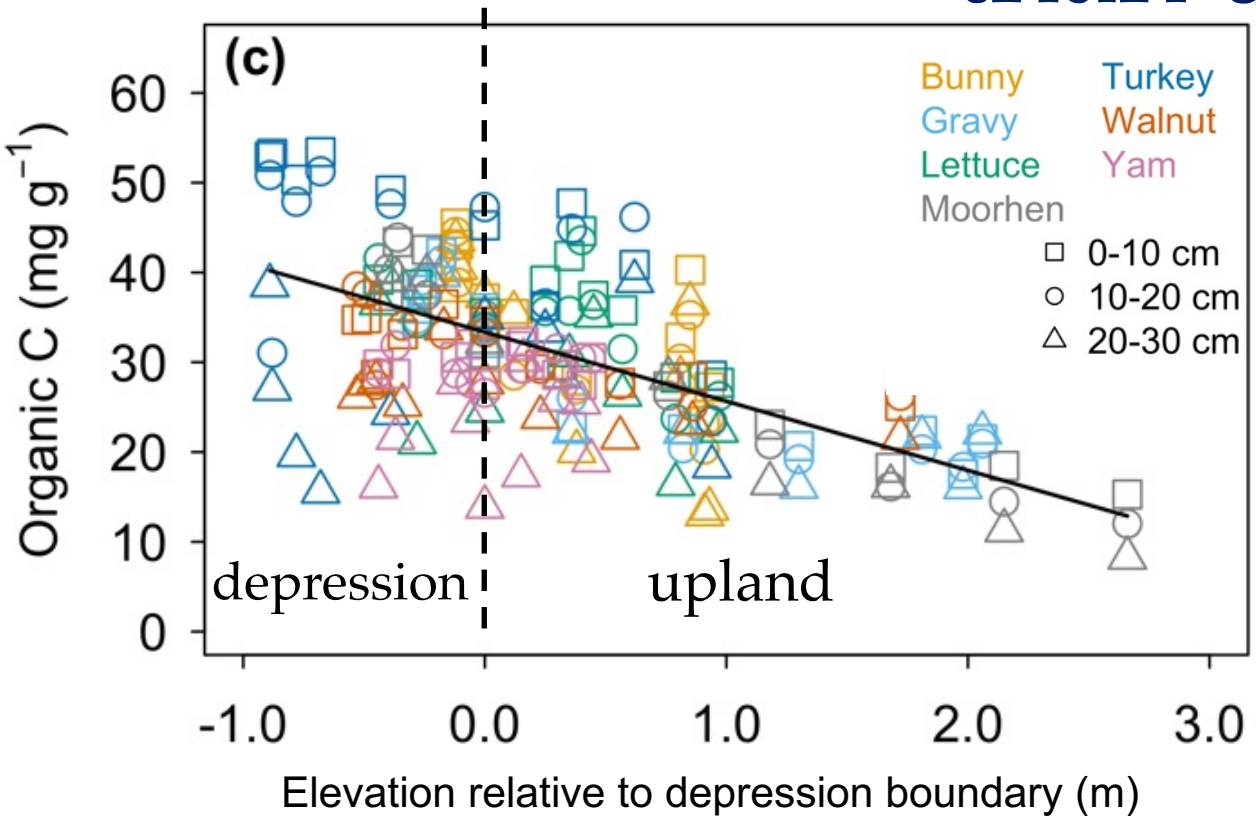
McDeid et al. 2018, Wetlands

Is this a “healthy” soil?

Image: the bottom of a farmed pothole depression near Ames, IA in June 2018

Huang et al., in review

SOC was much greater in depressions than uplands



- Systematic increase in SOC (0 – 30 cm) in depressions
- Threshold change in isotope composition of SOC at depression boundaries

Huang et al, in review

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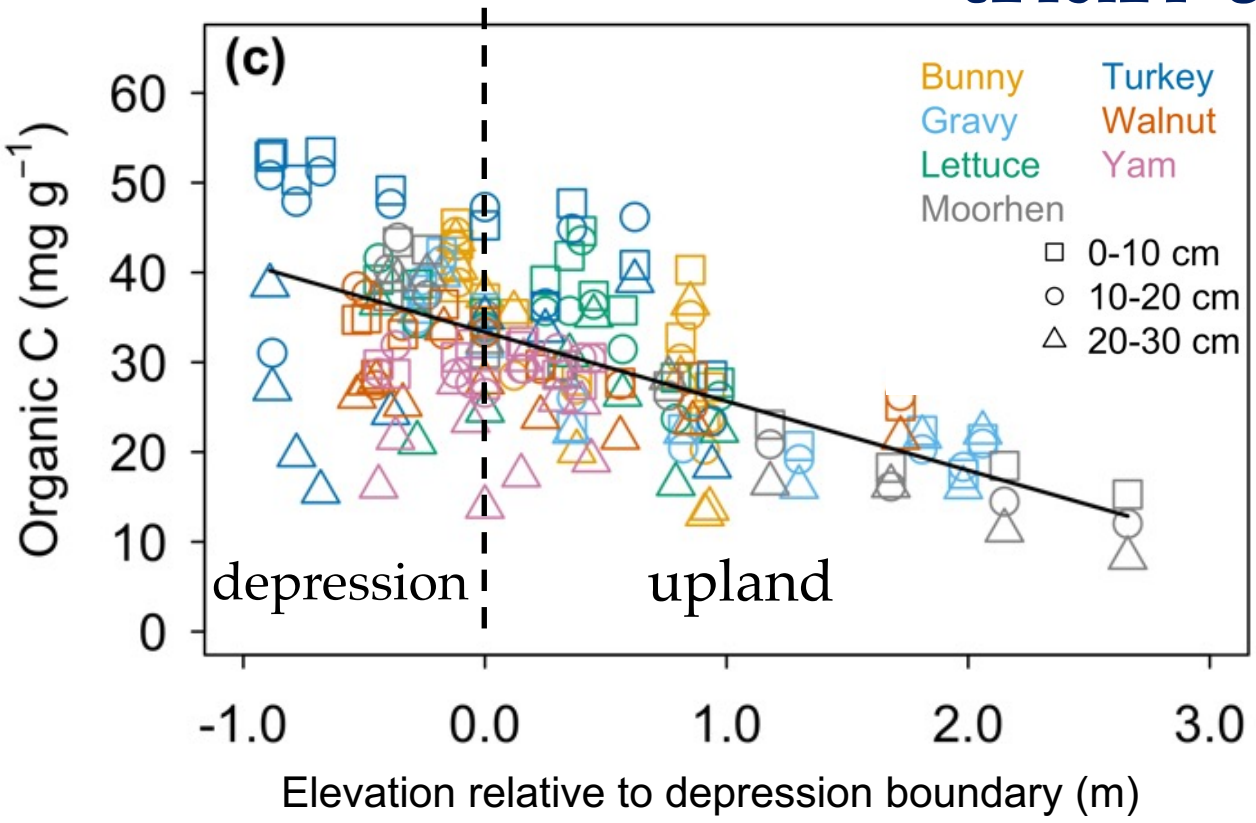

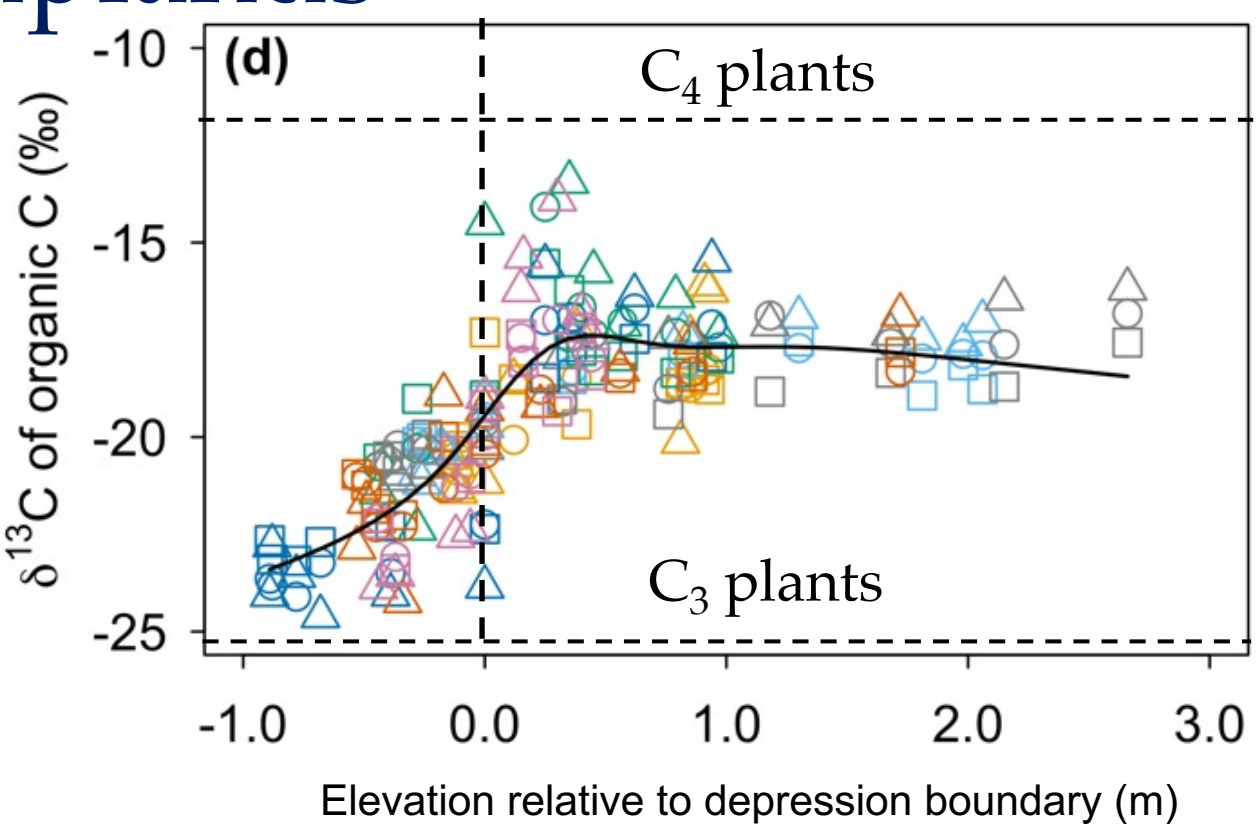

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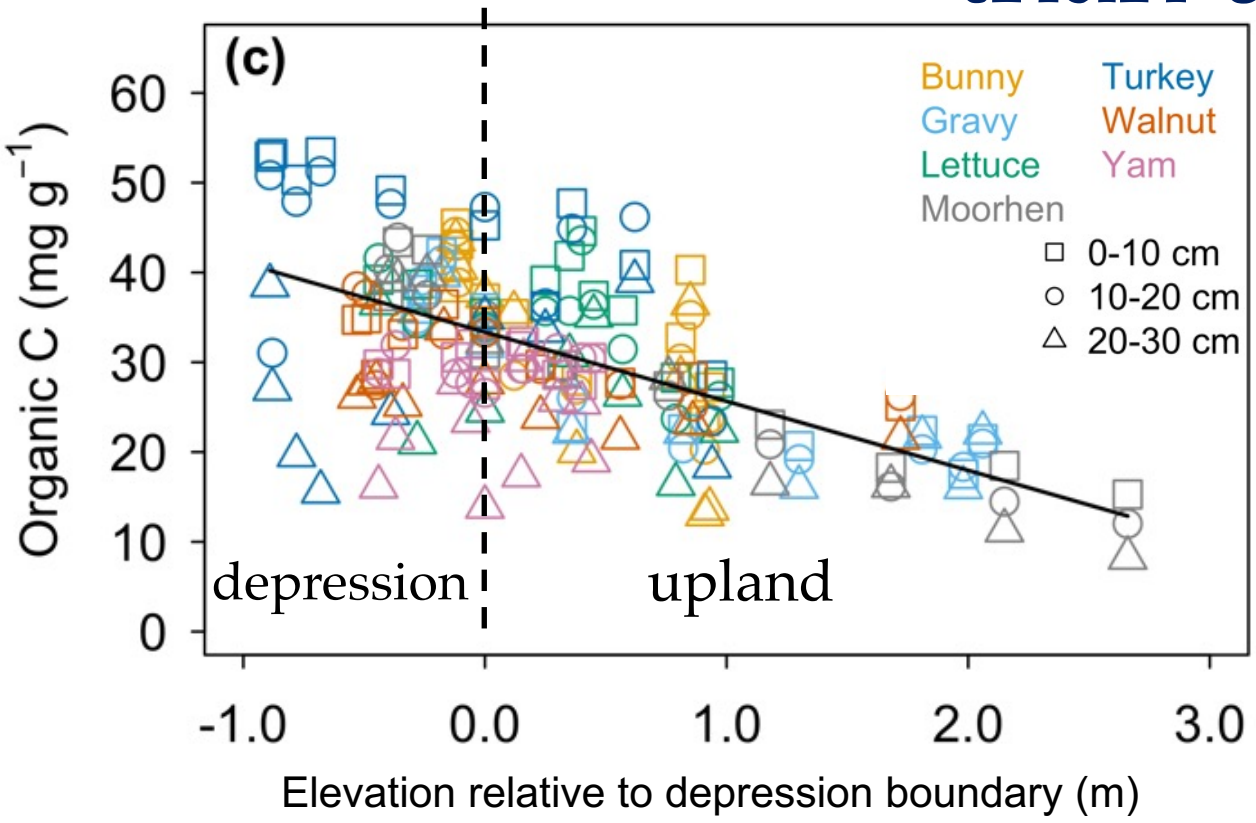
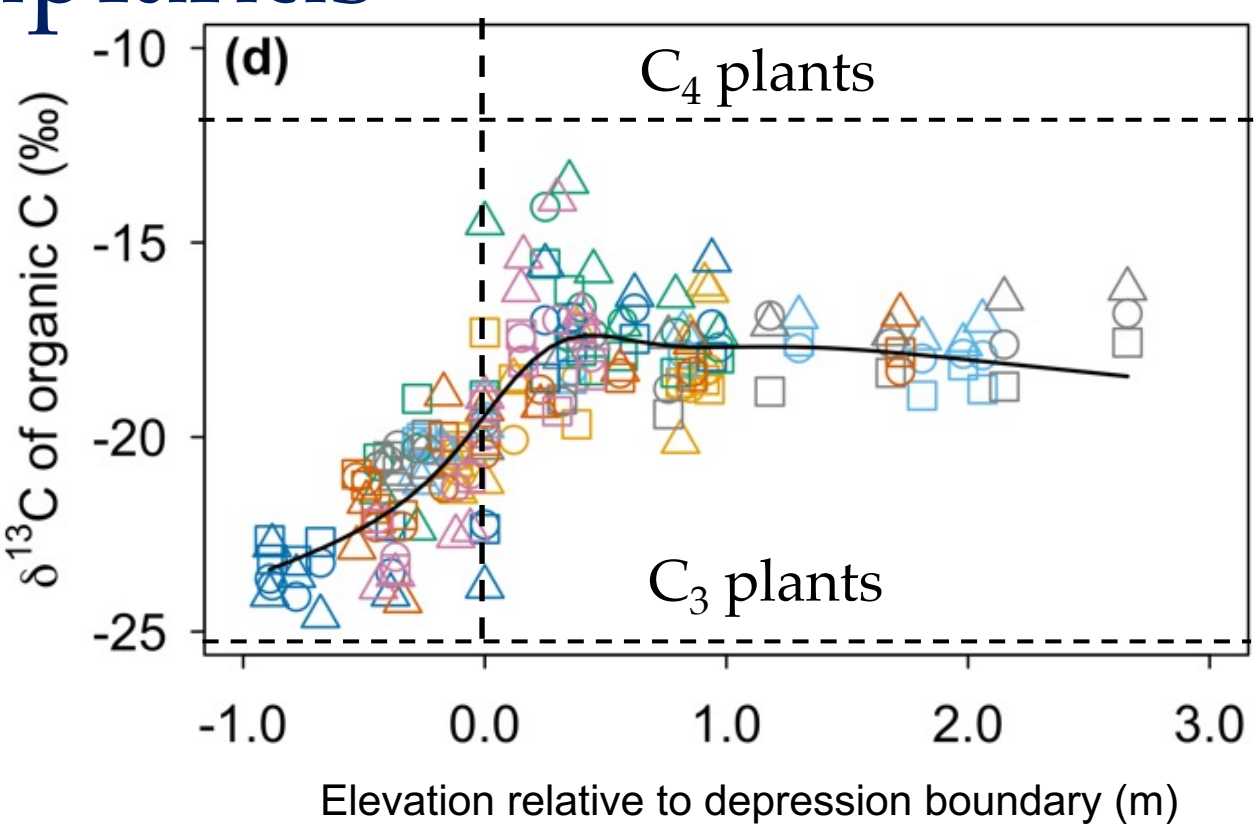
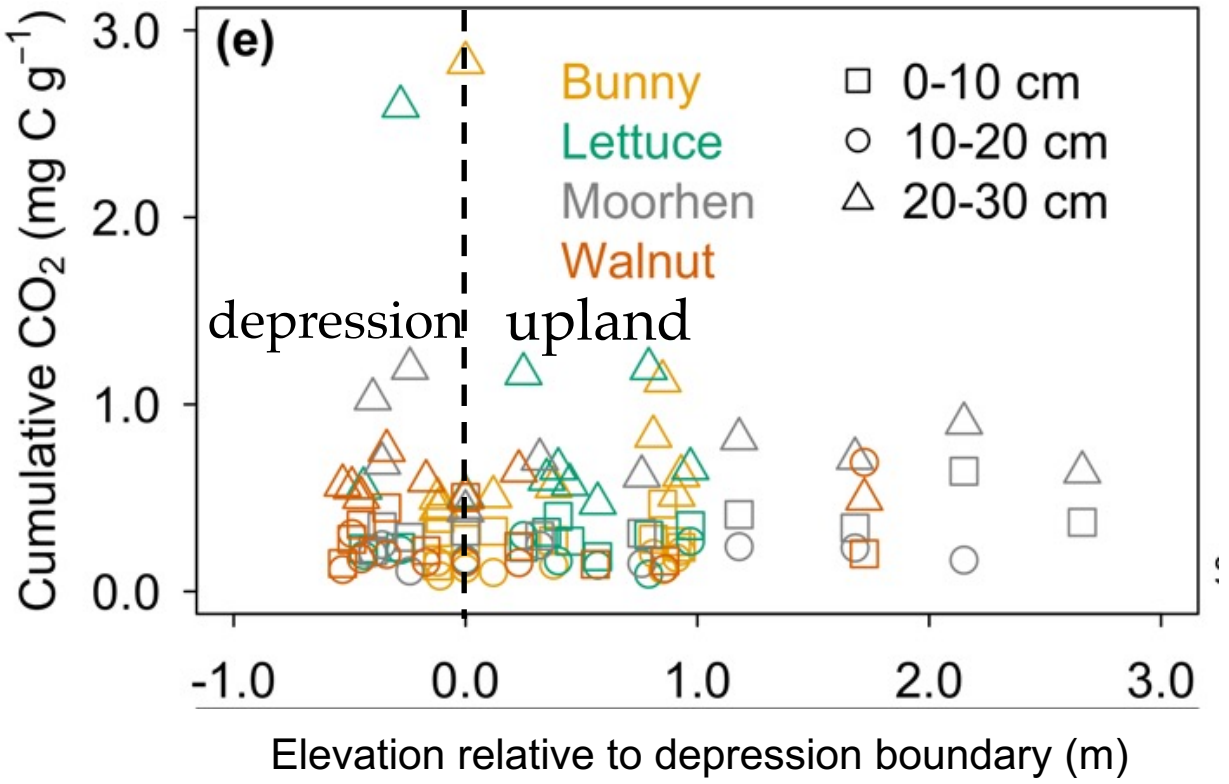




- Variation in SOC among samples was best explained by silt and clay
- Erosion has led to accumulation of pre-agricultural SOC in depressions

Huang et al, in review

Soil respiration and its sources did not vary between depressions and uplands



- Perhaps soil respiration is a better metric of soil health in this case?

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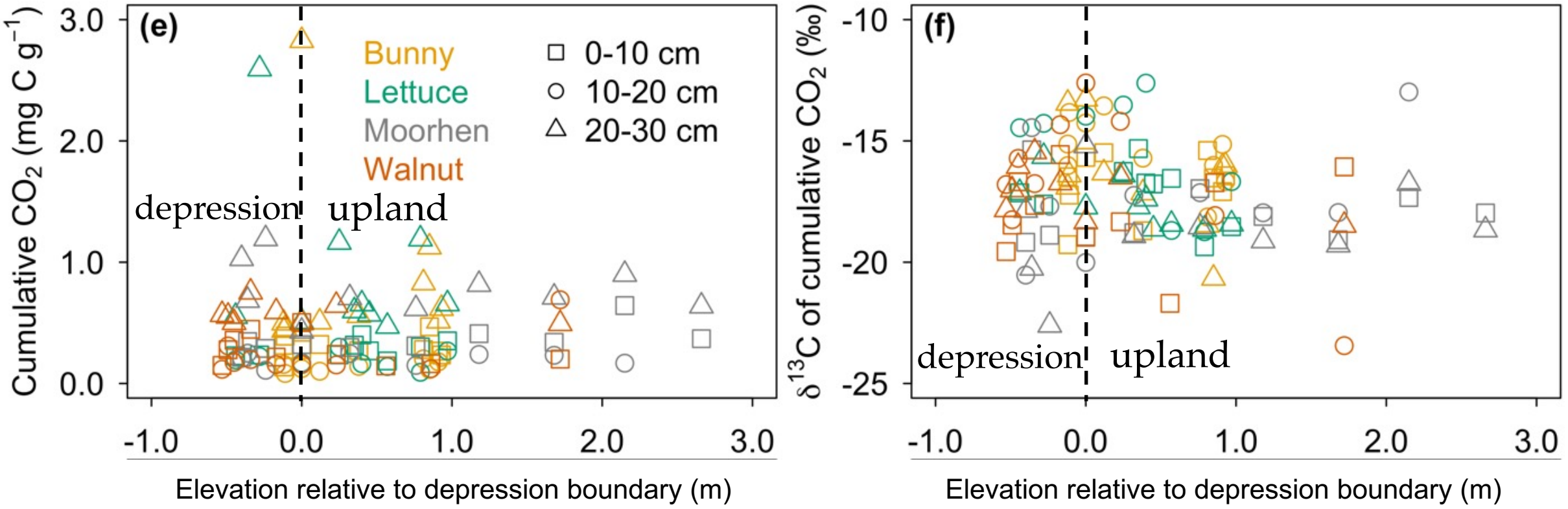

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Key point:
SOC is a legacy of the landscape

~1 km

- Glaciers and more than a century of erosion have shaped the distribution of SOC in our region
- SOC content changes slowly
- Assessing impacts of practice changes on SOC is a four-dimensional problem!
- Other measures of soil health (e.g. soil respiration) may be more sensitive

McDeid et al. 2018, Wetlands

The “soil carbon dilemma”:

Attempting to hoard as much organic matter as possible in the soil, like a miser hoarding gold, is not the correct answer. Organic matter functions mainly as it is decayed and destroyed. Its value lies in its dynamic nature.

- Quote from William Albrecht, 1938 USDA yearbook of agriculture (**as cited in Janzen 2006, Soil Biol Biochem**)
- From a modern perspective, we now know that it is difficult to “hoard” soil carbon, even if we wanted to
- All carbon decomposes, it is simply a matter of how fast or slow!