Dynamics of soil organic C and soil GHG emissions in agriculture

Environmental and management drivers

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The Keck Institute for Space Studies

Soil management/climate mitigation short course

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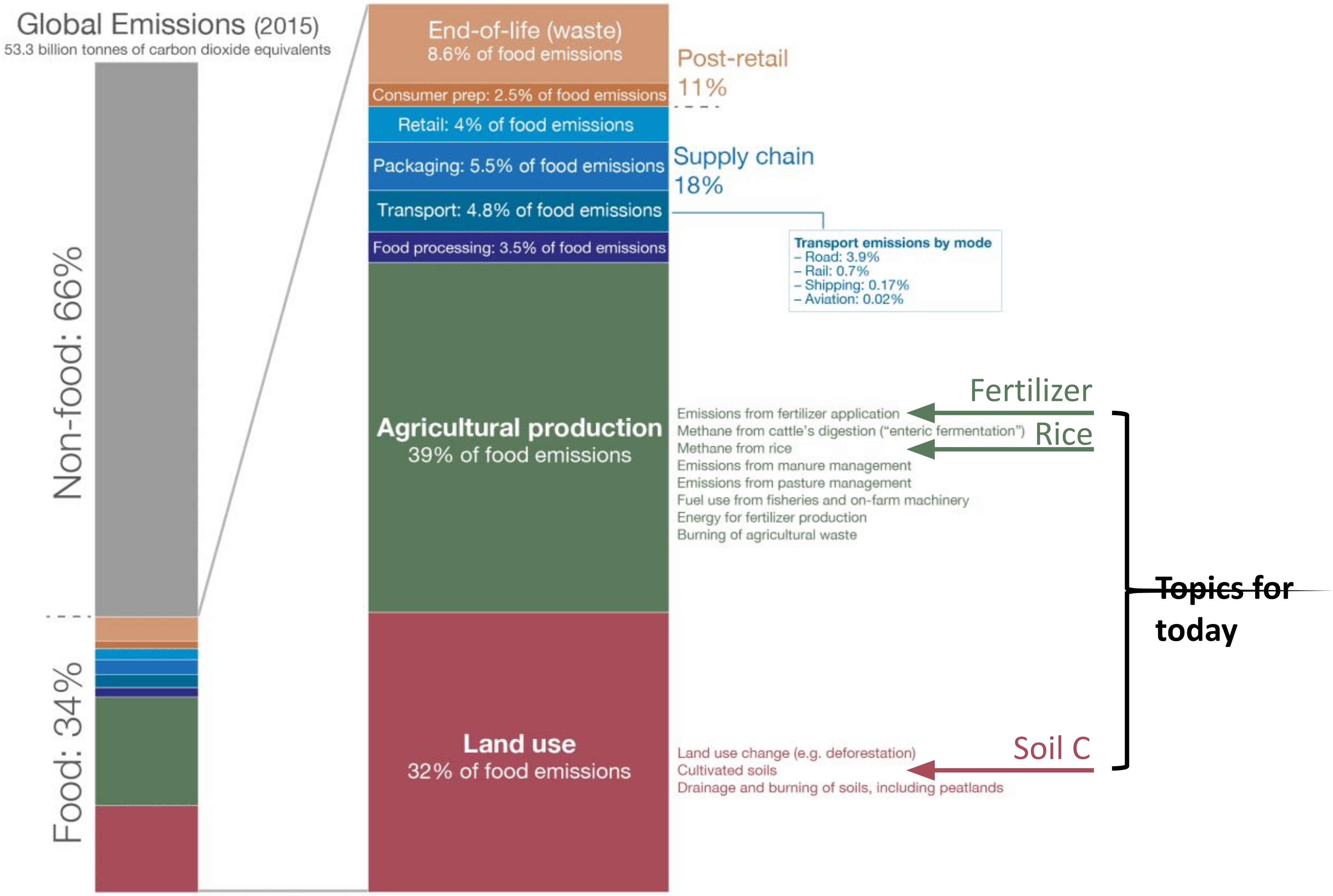
University of Kentucky



Data source: Crippa, M., et al. (2021) Food systems are responsible for a third of global anthropogenic GHG emissions. *Nature Food*.

OurWorldinData.org – Research and data to make progress against the world's largest problems.

Soil organic C makes up a small percentage of the soil mass but has a big impact on soil properties.

Photos by Ray Weil

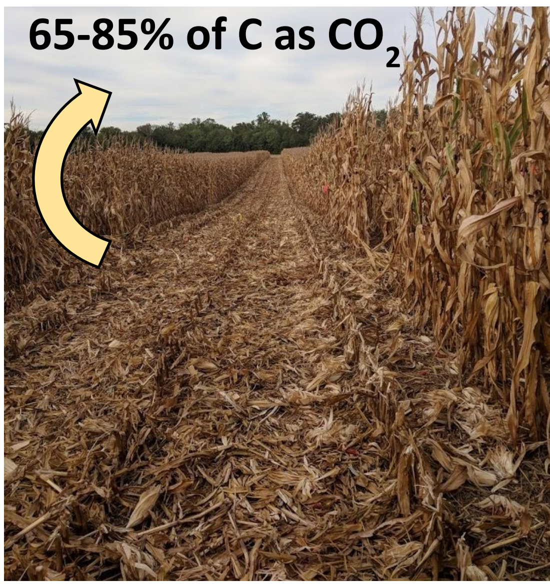
Soil organic matter is the portion of soil material that is derived from living organisms.

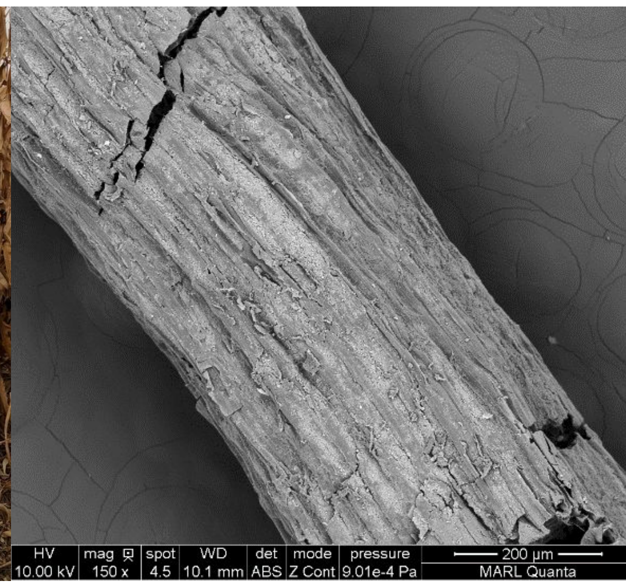
Soil organic matter

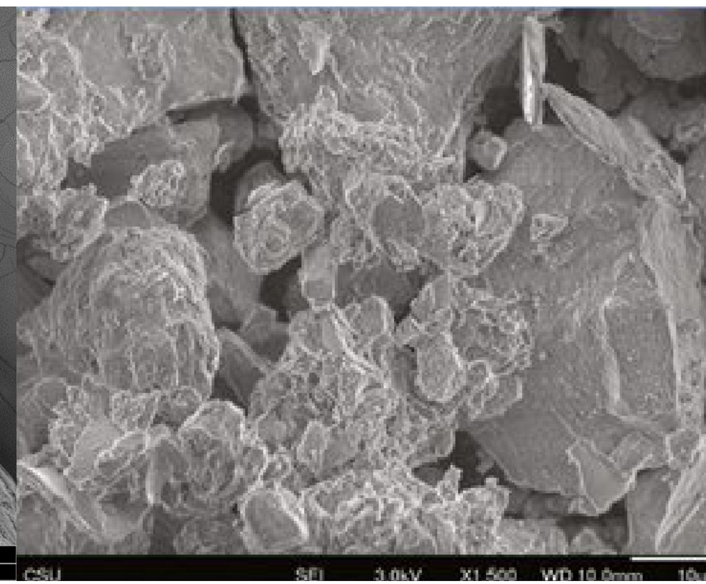
Plant litter/crop residue

Fragmented plant tissue
(Particulate organic matter)

Single molecules or microscopic fragments
(Mineral-associated organic matter)

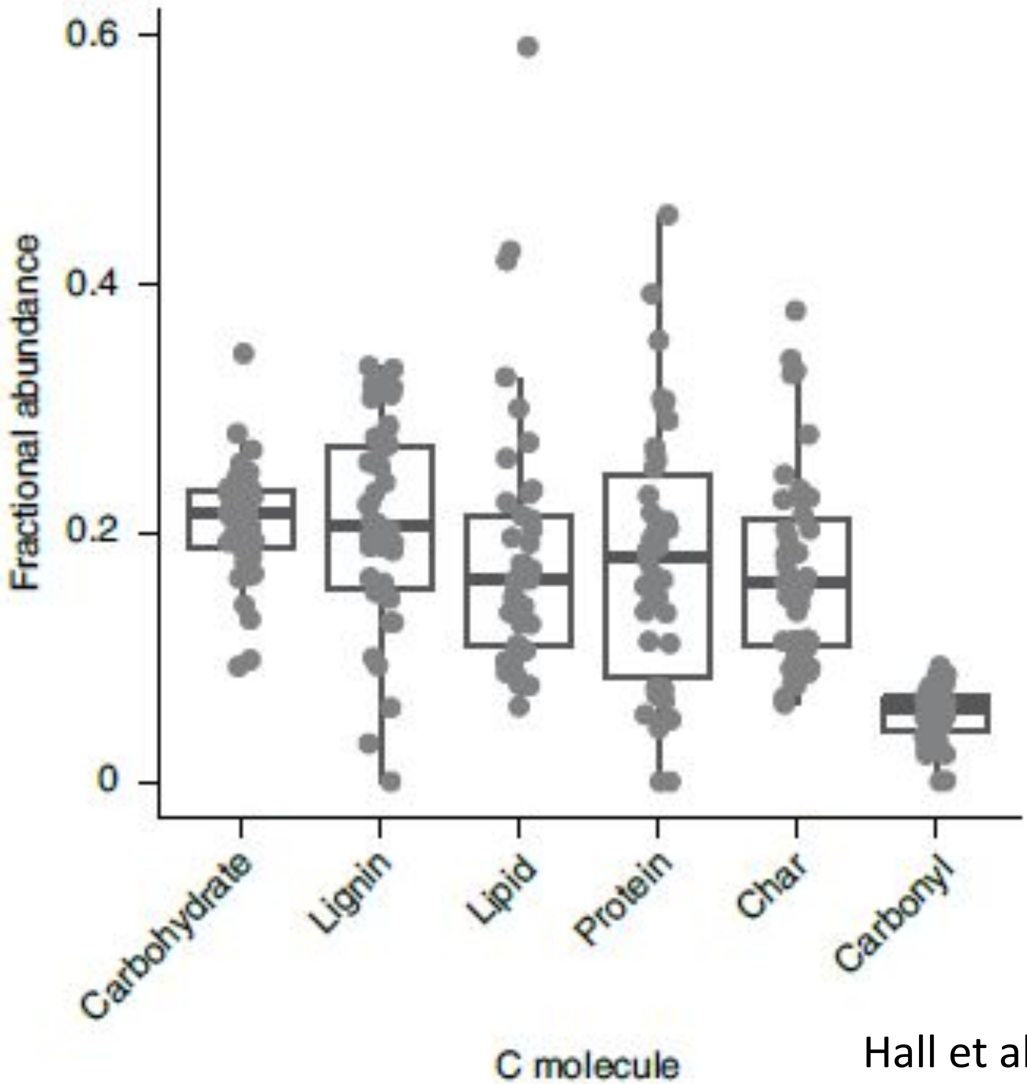




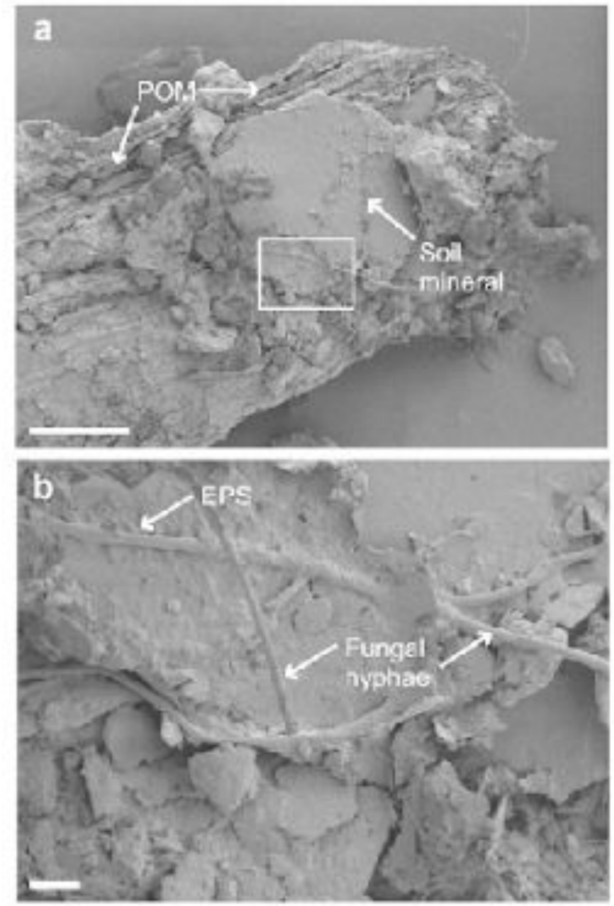


Decreasing size, increasing density, increasing persistence

Soil organic matter consists of plant and microbially derived compounds.



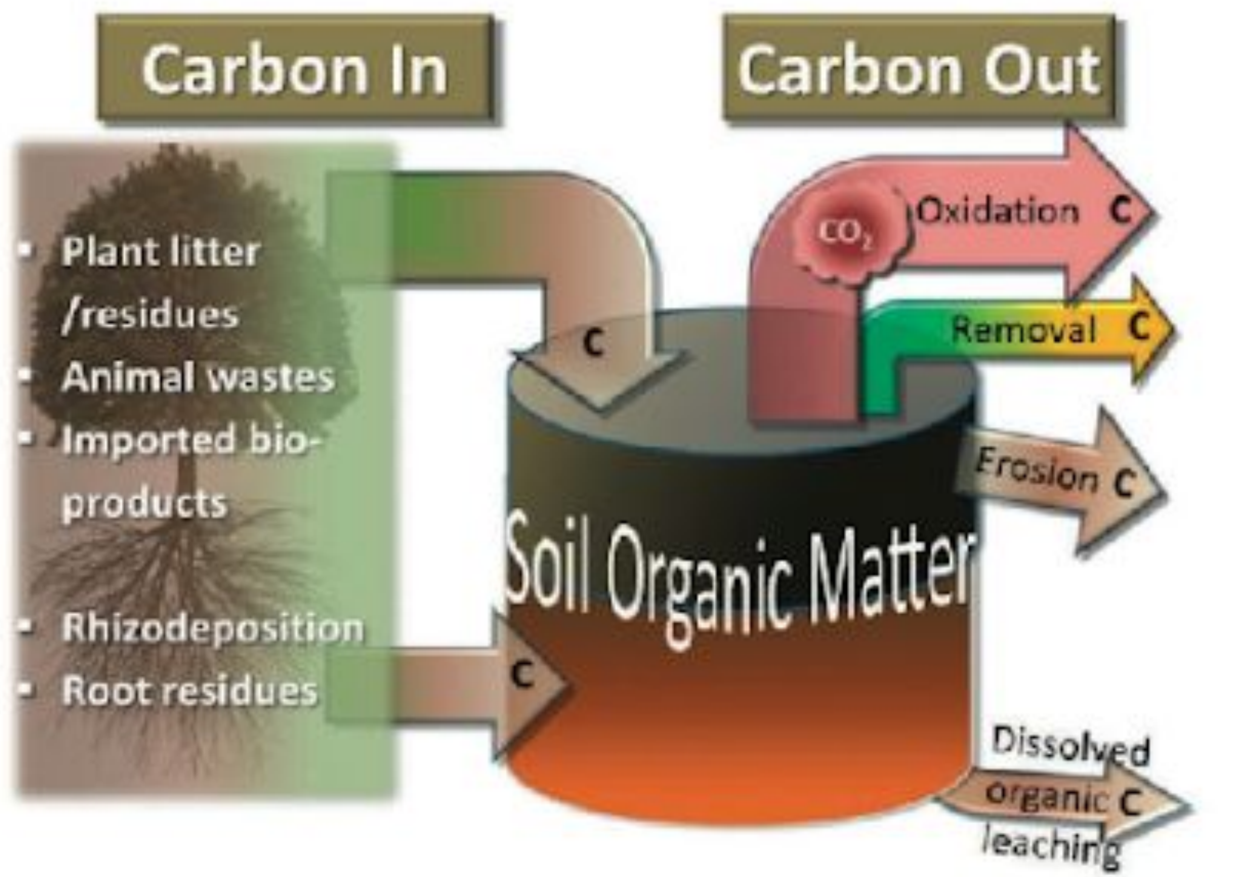
Hall et al. 2020



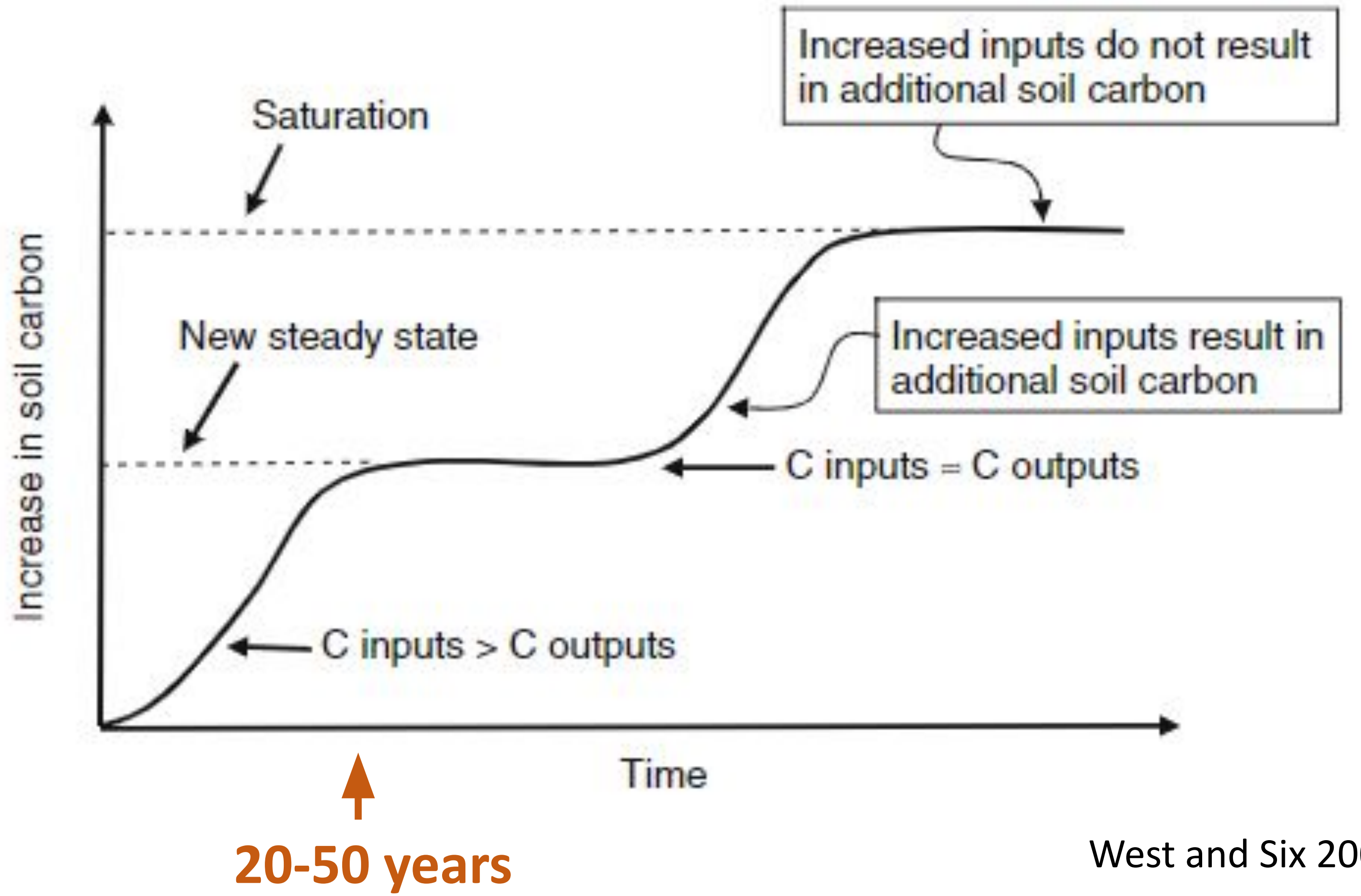
10 µm

Witzgall et al. 2021

Soil organic C stocks represent a balance of inputs and outputs.



Soil carbon sequestration has a limited duration.



West and Six 2007

Factors that affect C inputs and outputs in agricultural systems

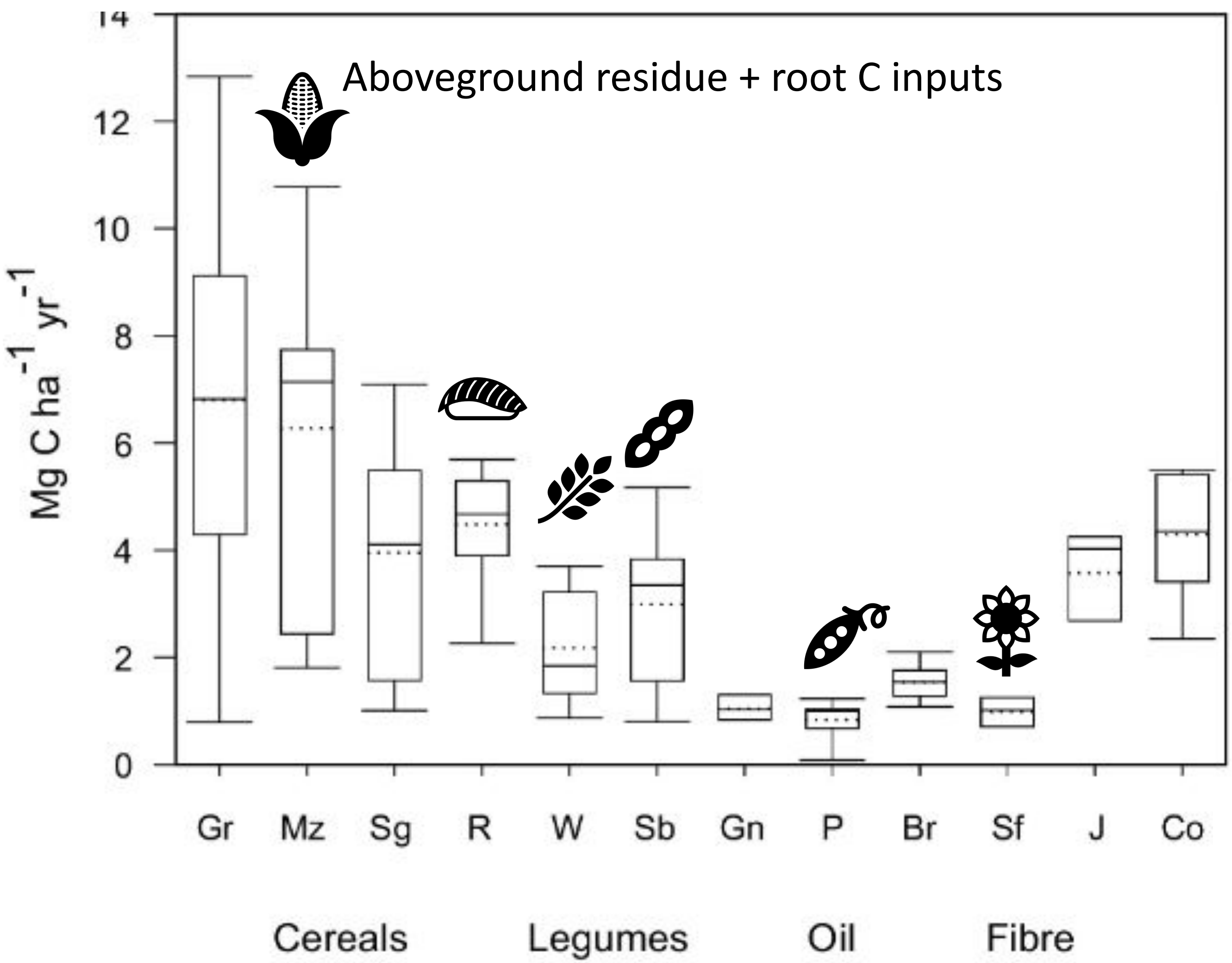
Inputs

- Species of crops in rotation
- Crop productivity
  - Genotype x environment x management
- Fraction of the crop that is harvested
- Cropping intensity
- Use of biomaterials

Outputs

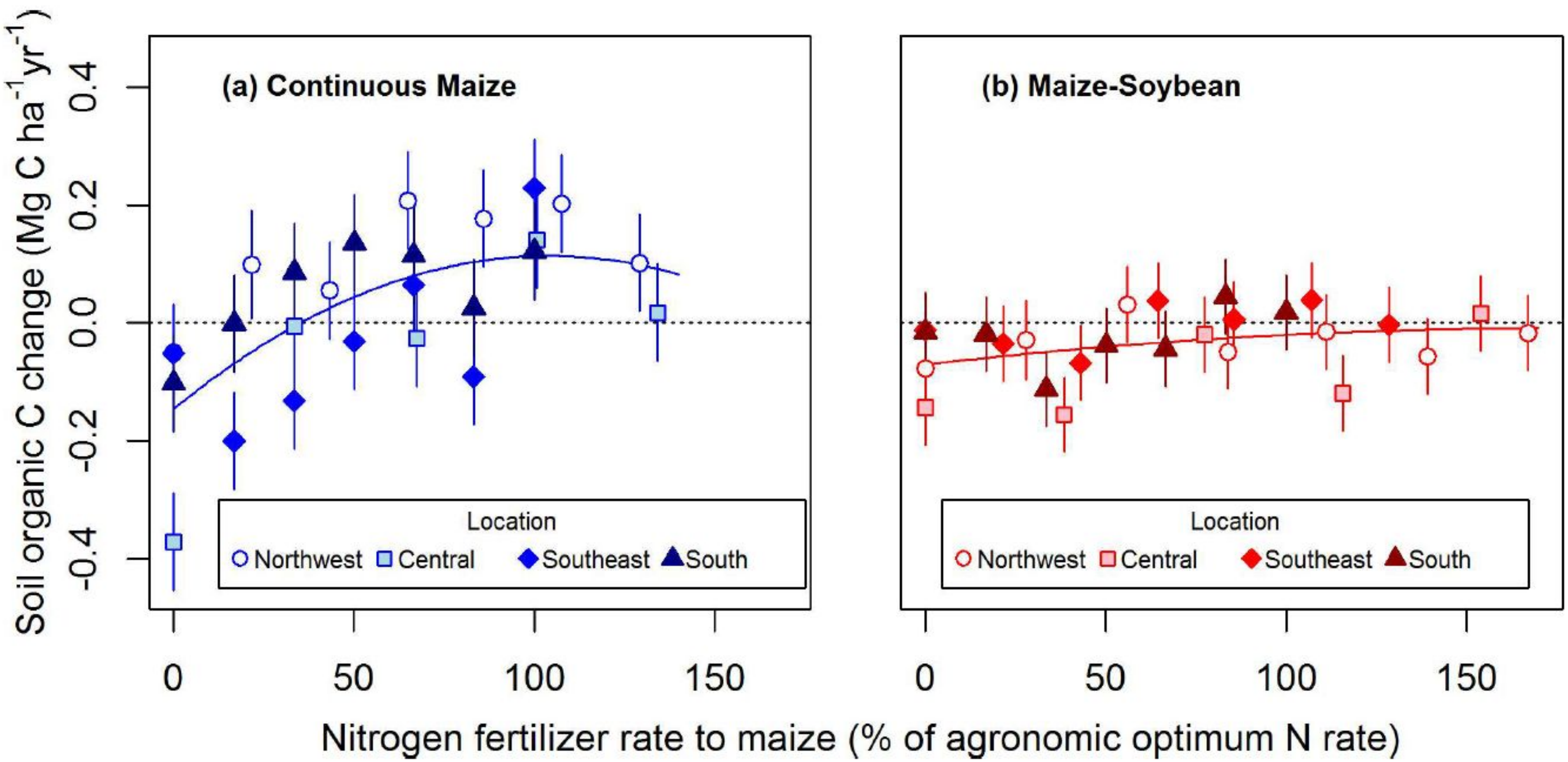
- Temperature
- Soil aeration status
- Soil texture
- Soil disturbance
- Quality of inputs
- Placement of inputs
- Use of pyrolysis

Crop species provide different amounts of C to the soil



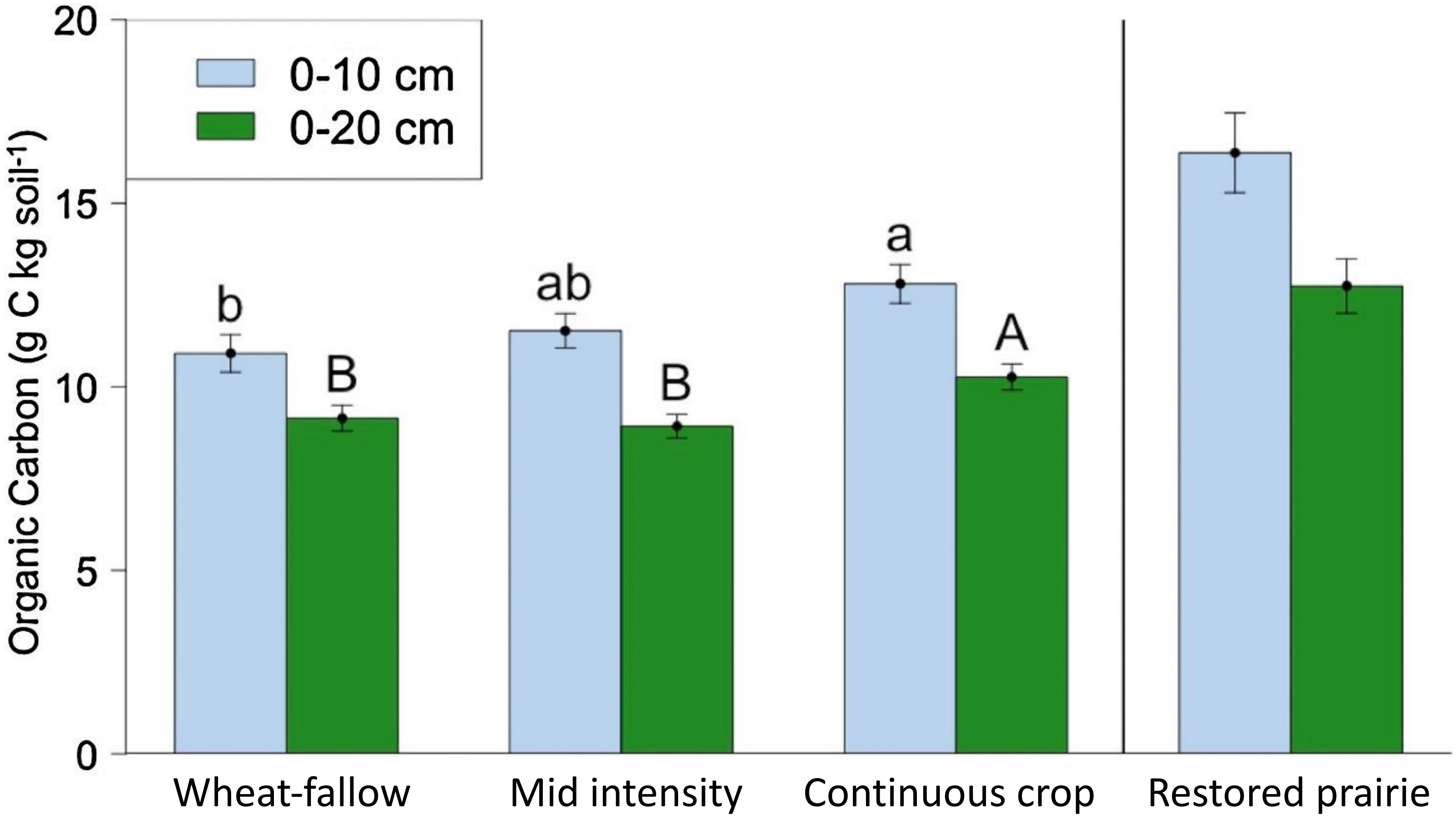
Mathew et al. 2017

Fertilization increases soil organic C by increasing C inputs



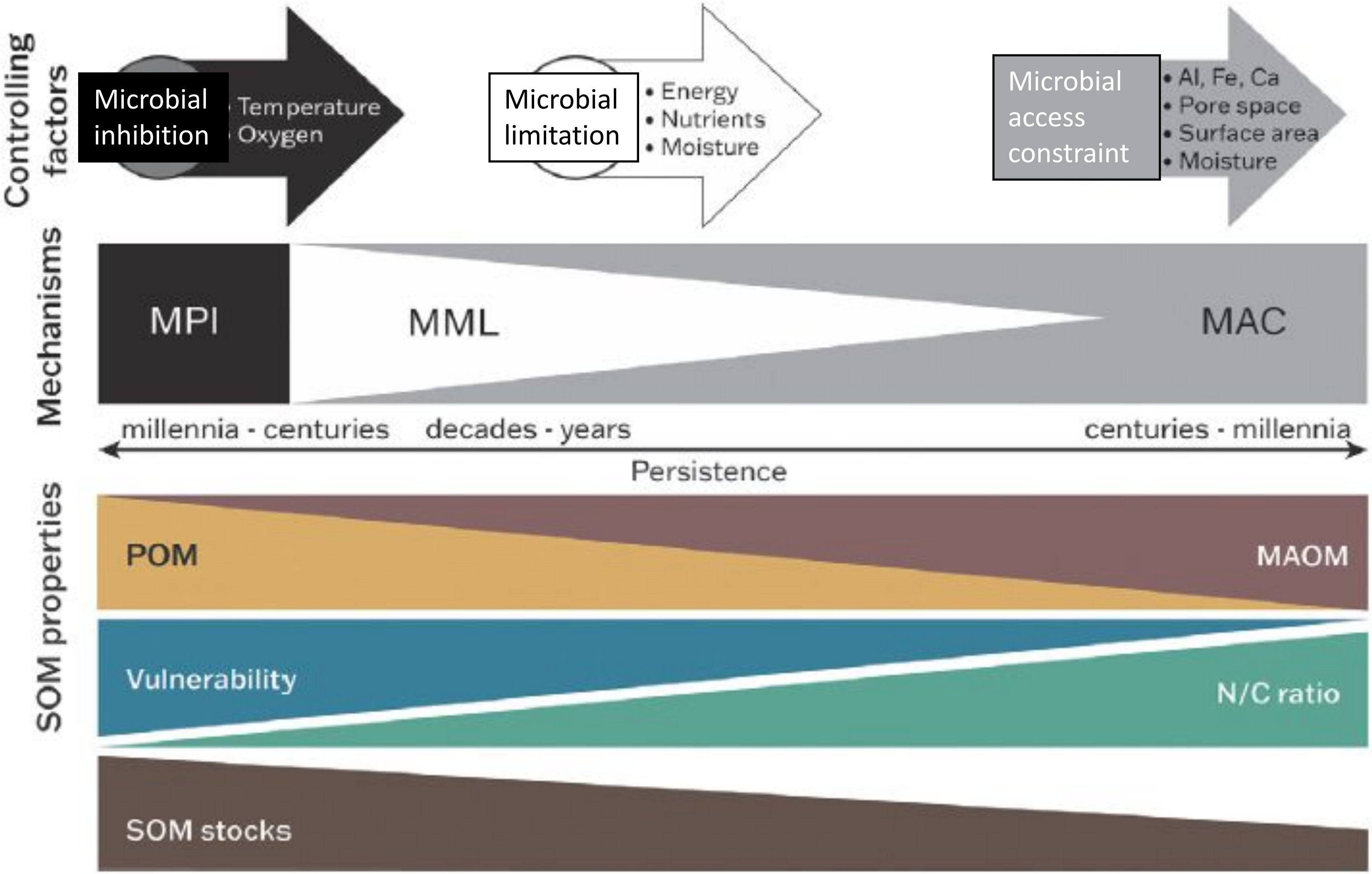
Poffenbarger et al. 2017

Cropping system intensification increases soil organic C by increasing C inputs



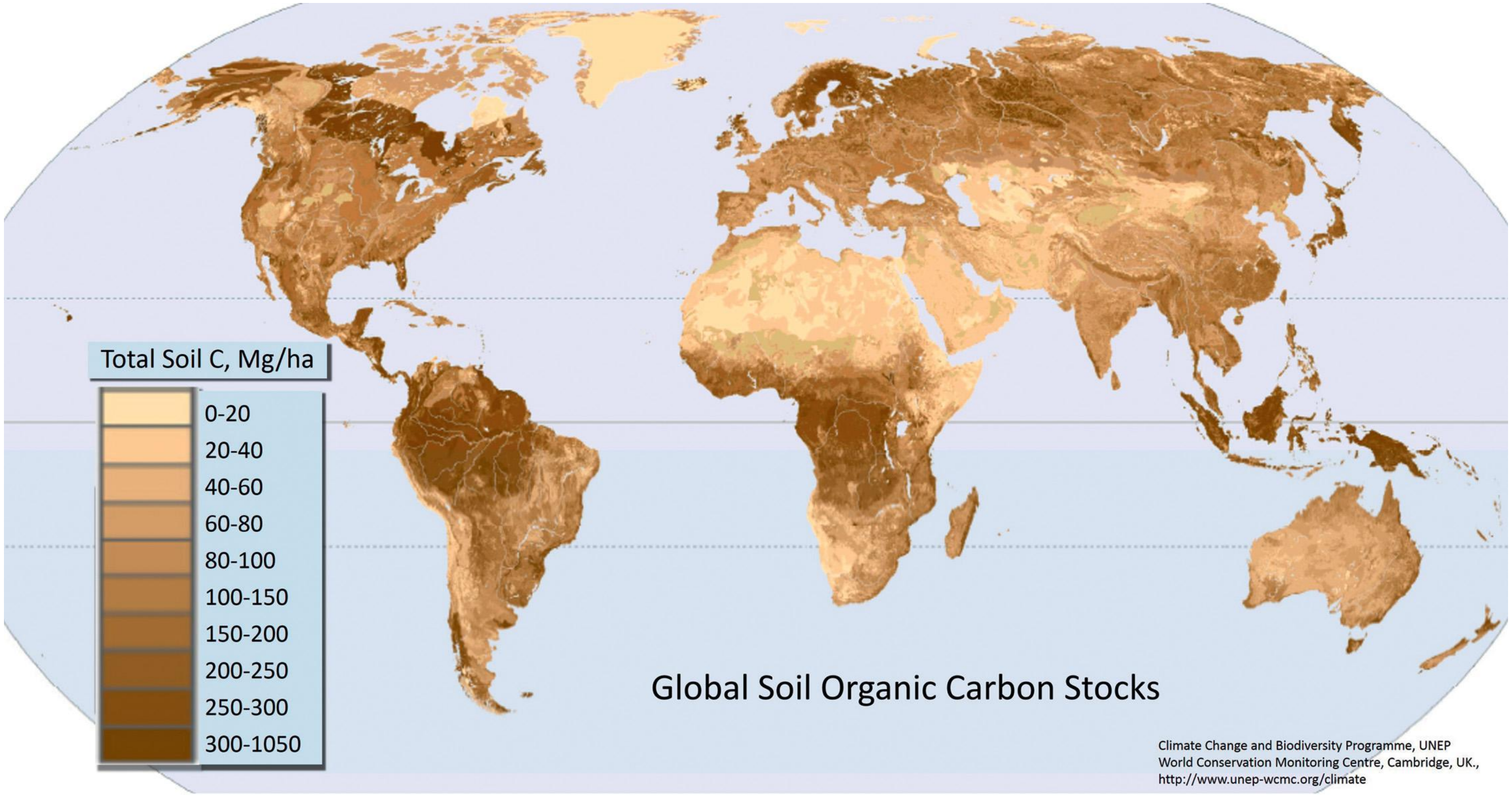
Rosenzweig et al. 2018

Mechanisms of soil organic matter protection



Cotrufo and Lavallee 2022

Global distribution of soil organic carbon (0-1 m)



- Low mean annual temperatures slow decomposition more than productivity -> highest SOM levels are found in cold regions.
- High rainfall increases plant growth more than it does decomposition -> high SOM levels found in humid regions.

Weil and Brady 2017, adapted from Scharlemann et al. 2010

Management controls on C outputs – drainage

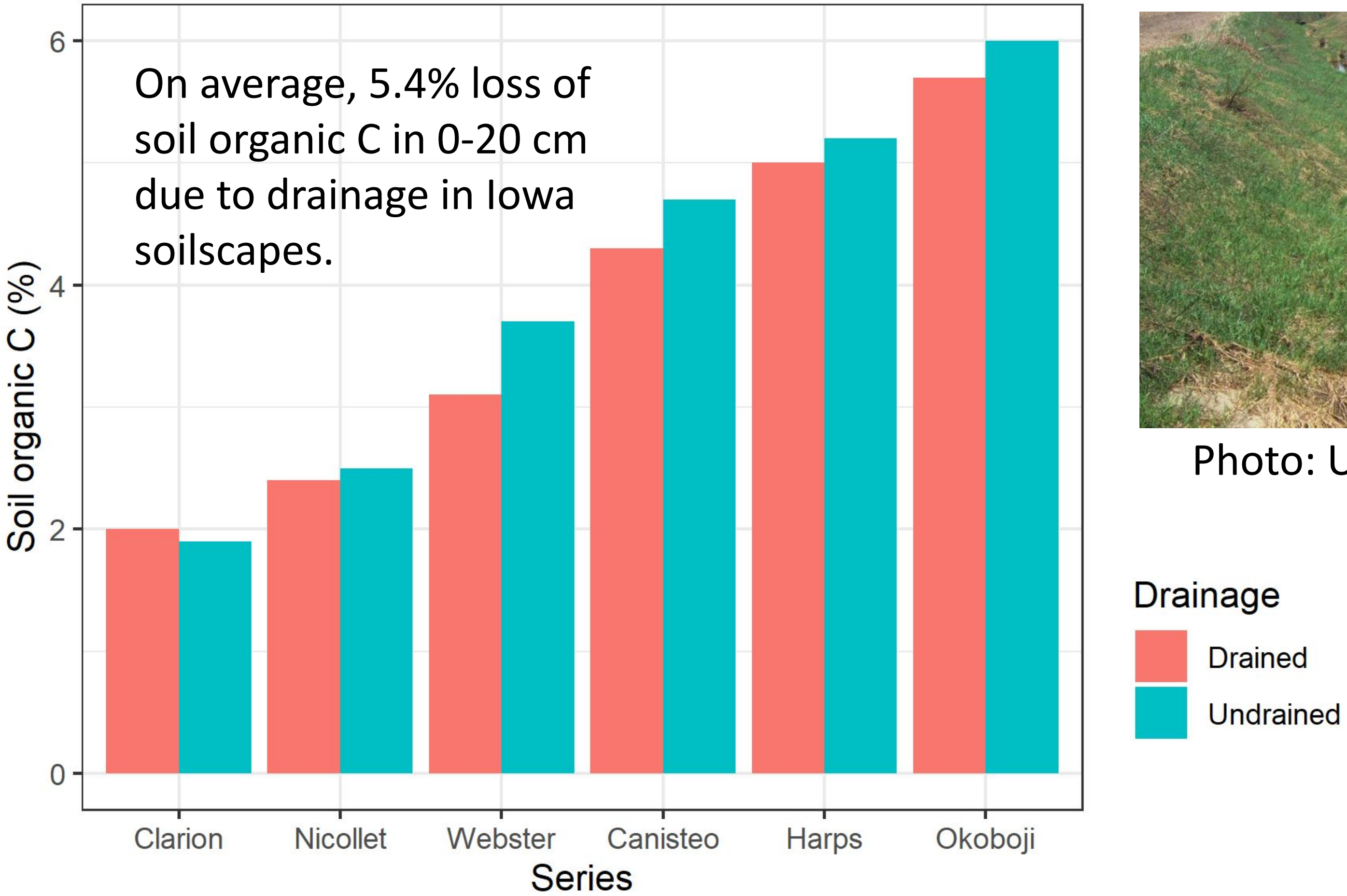
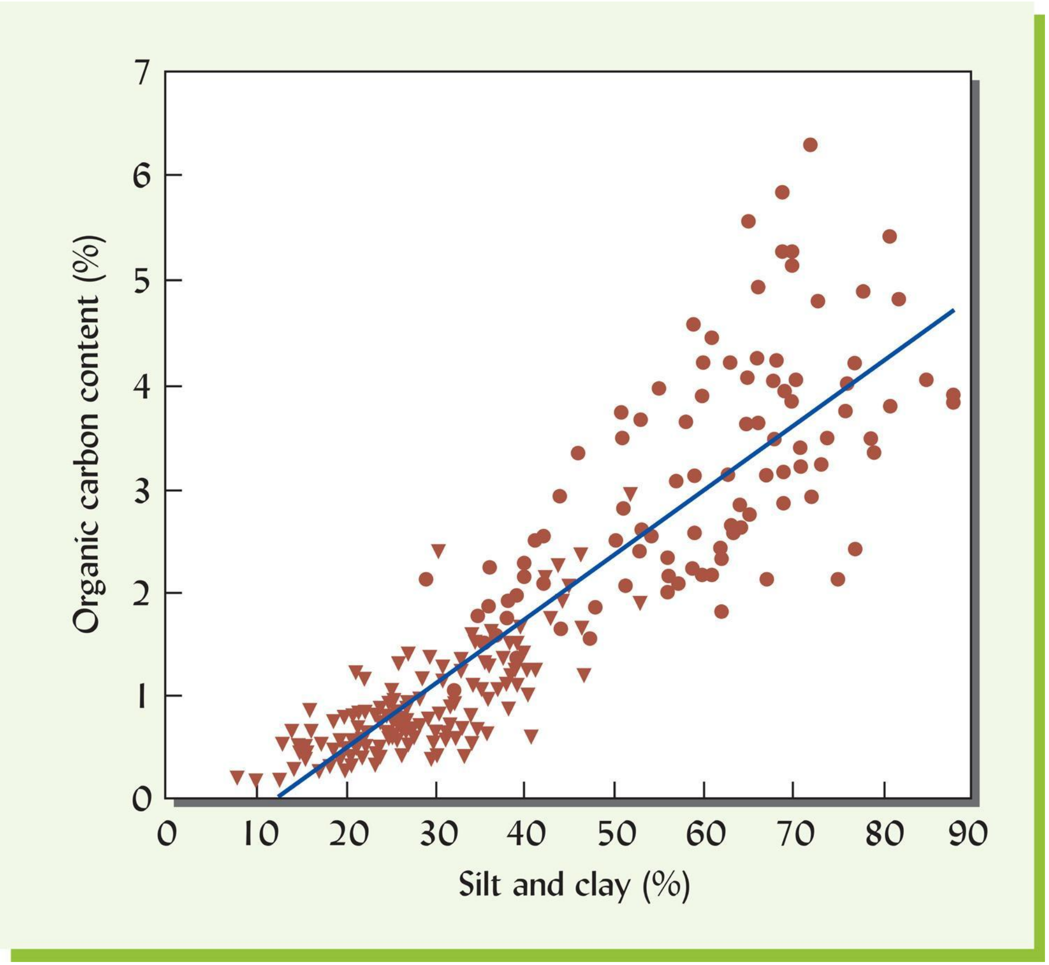


Photo: University of Minnesota

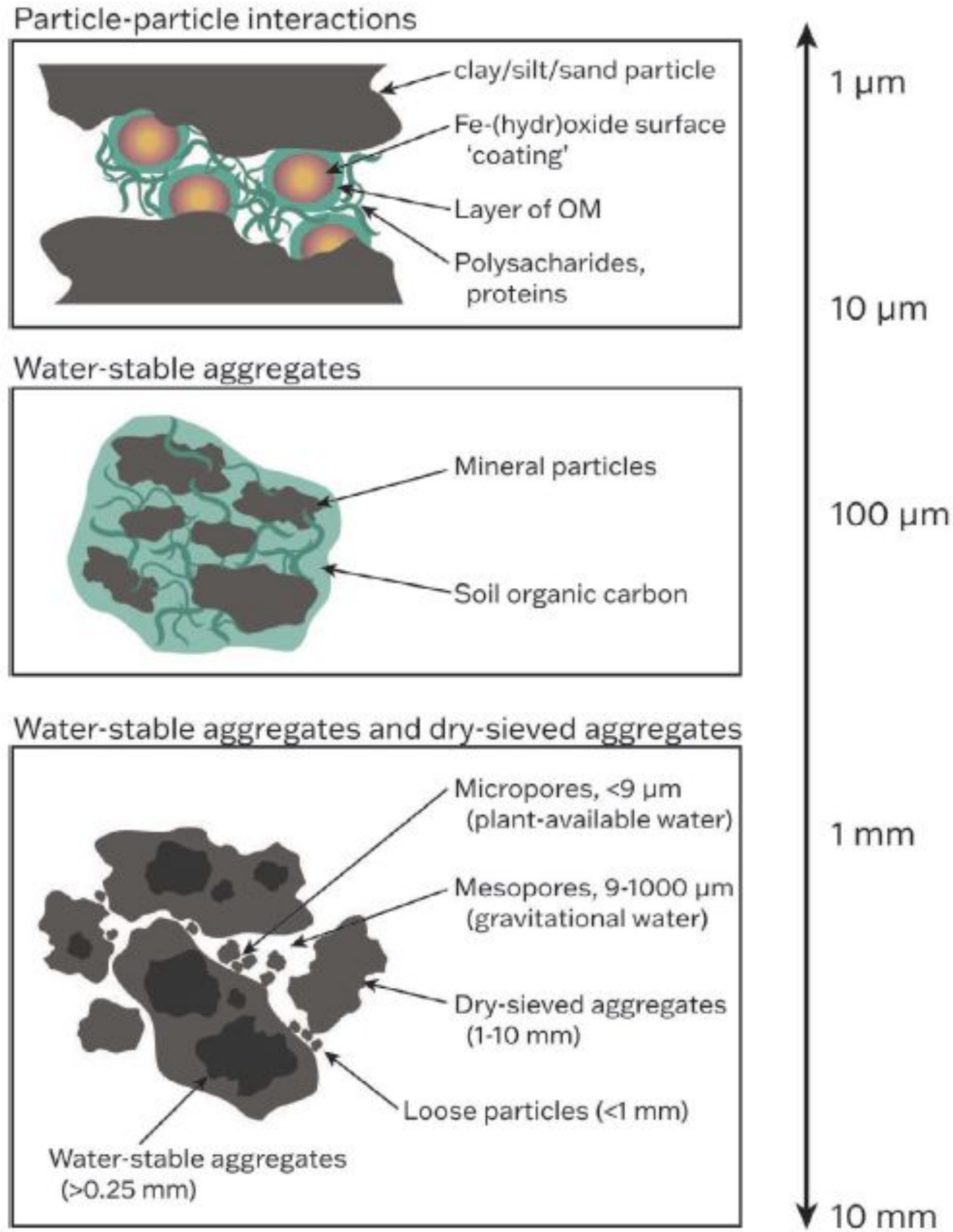
Fenton and James 1993

Soils with higher silt and clay tend to have higher soil organic C.



Weil, Stine, Mughogho 2017

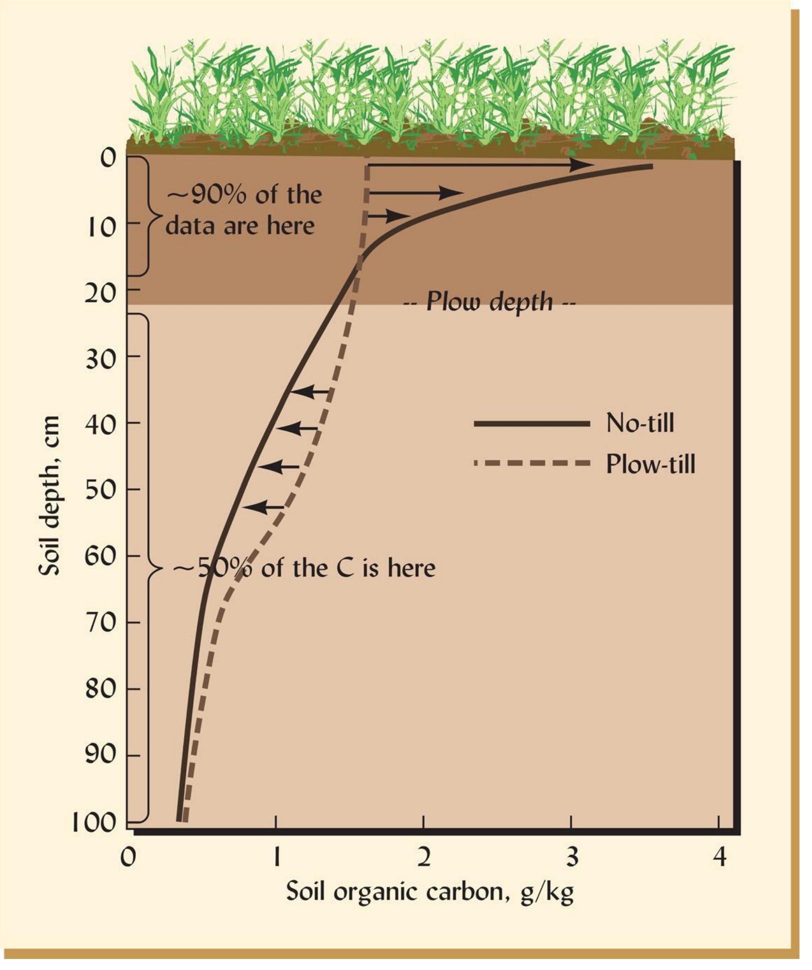
Organo-mineral interactions at different scales



Cotrufo and Lavallee 2022 adapted from Regelink et al. 2015

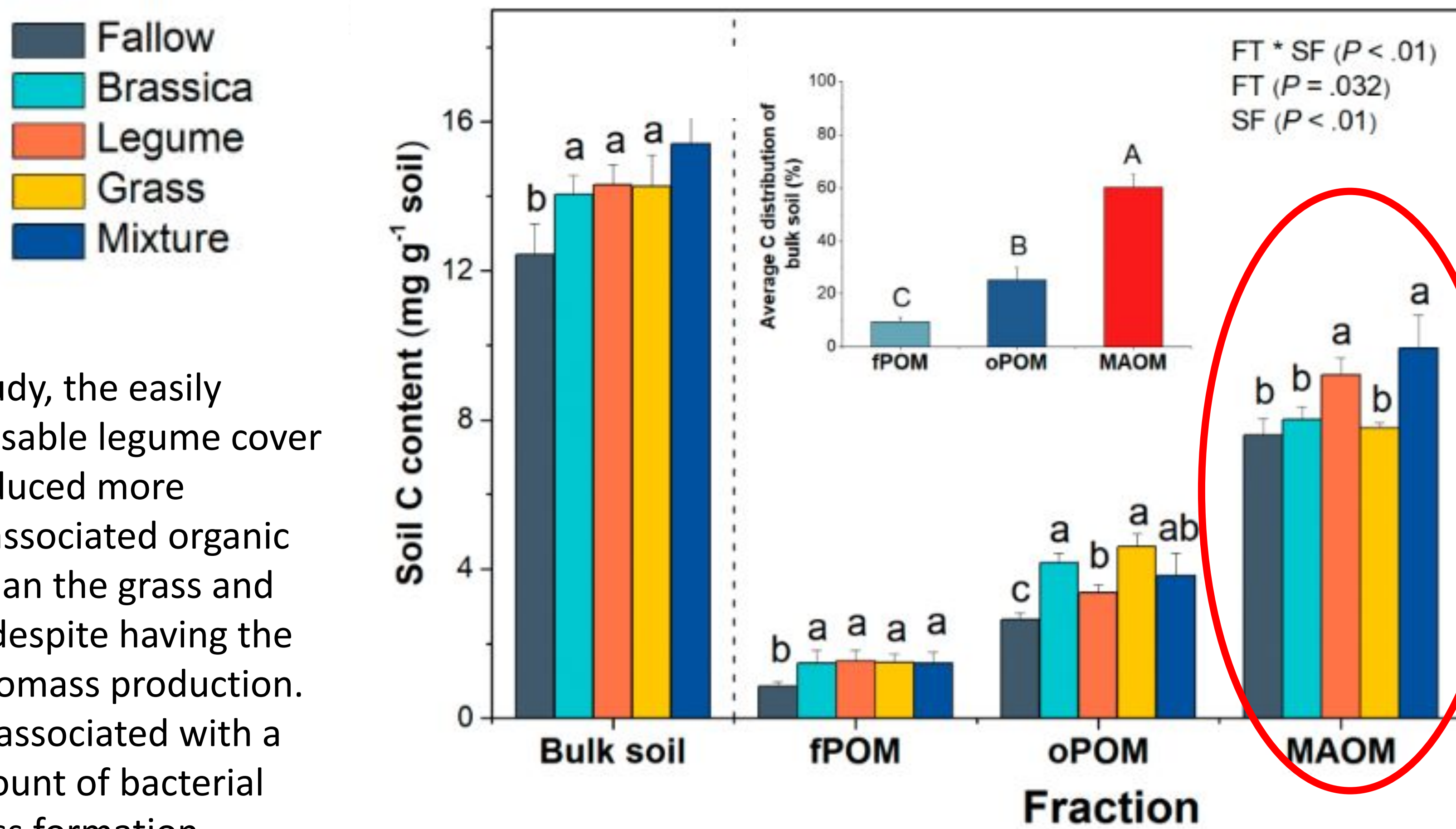
Management controls on C outputs – no-till

- No-till provides greater protection of particulate organic matter through aggregation (Six et al. 1999).
- Increased soil organic C levels in no-till soils are most pronounced at the surface.
- In some environments, there is no increase in whole-profile soil organic C under no-till (Ogle et al. 2019).



Weil and Brady 2017

Management controls on C outputs – quality

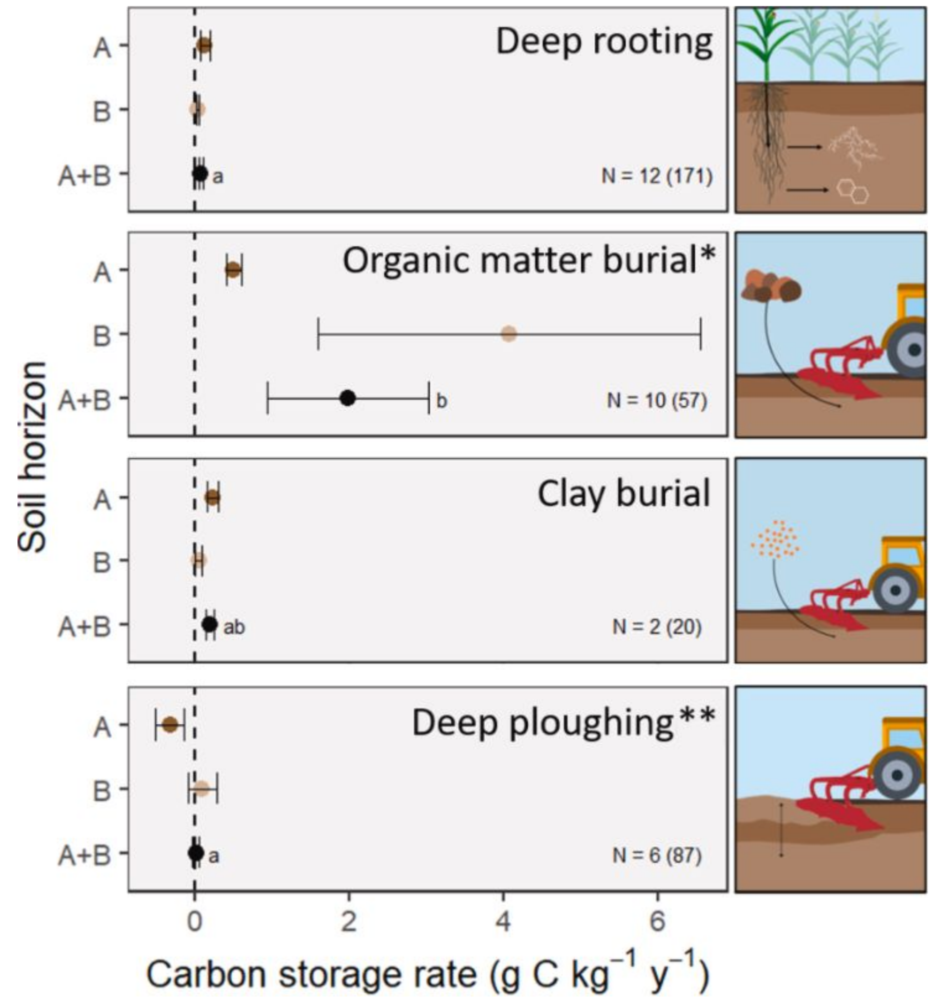


In this study, the easily decomposable legume cover crop produced more mineral-associated organic matter than the grass and brassica despite having the lowest biomass production. This was associated with a large amount of bacterial necromass formation.

Zhang et al. 2022

Management controls on C outputs – deep placement

- Carbon has a longer residence time in the subsoil.
  - Less disturbance
  - Physical inaccessibility of microbes to C substrates
  - High abundance of available mineral surfaces
  - Unfavorable conditions for microbial activity



Button et al. 2022

Management controls on C outputs – biochar

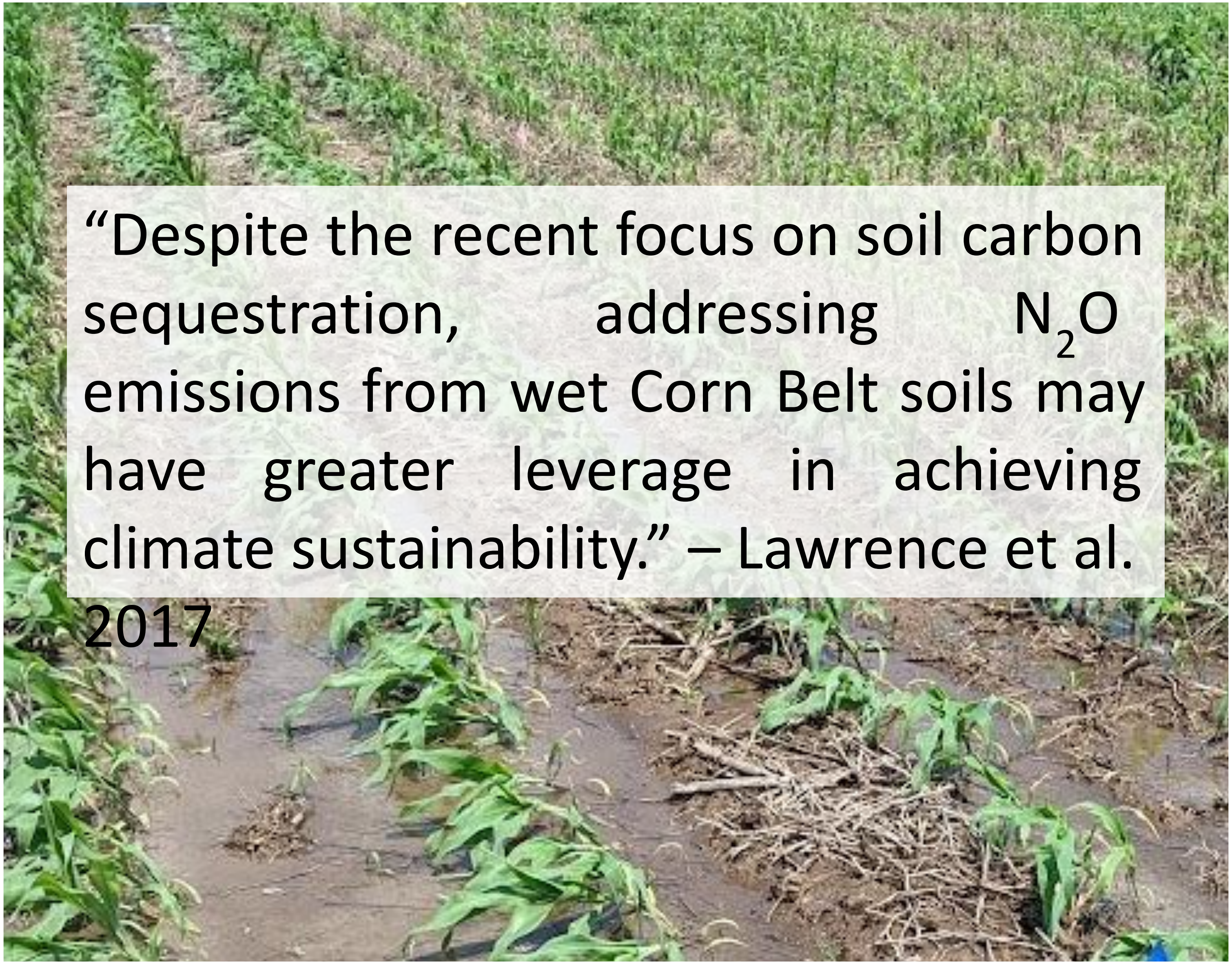
- Biochar is produced from thermal treatment of organic matter under reduced or zero oxygen.
- Mineralized 10-100x more slowly than uncharred residues (Lehmann et al. 2015).
- Potential to confer greater stability of other organic matter, improve water and nutrient retention (reviewed in Powlson et al. 2011).

Photo by Sanjai Parikh

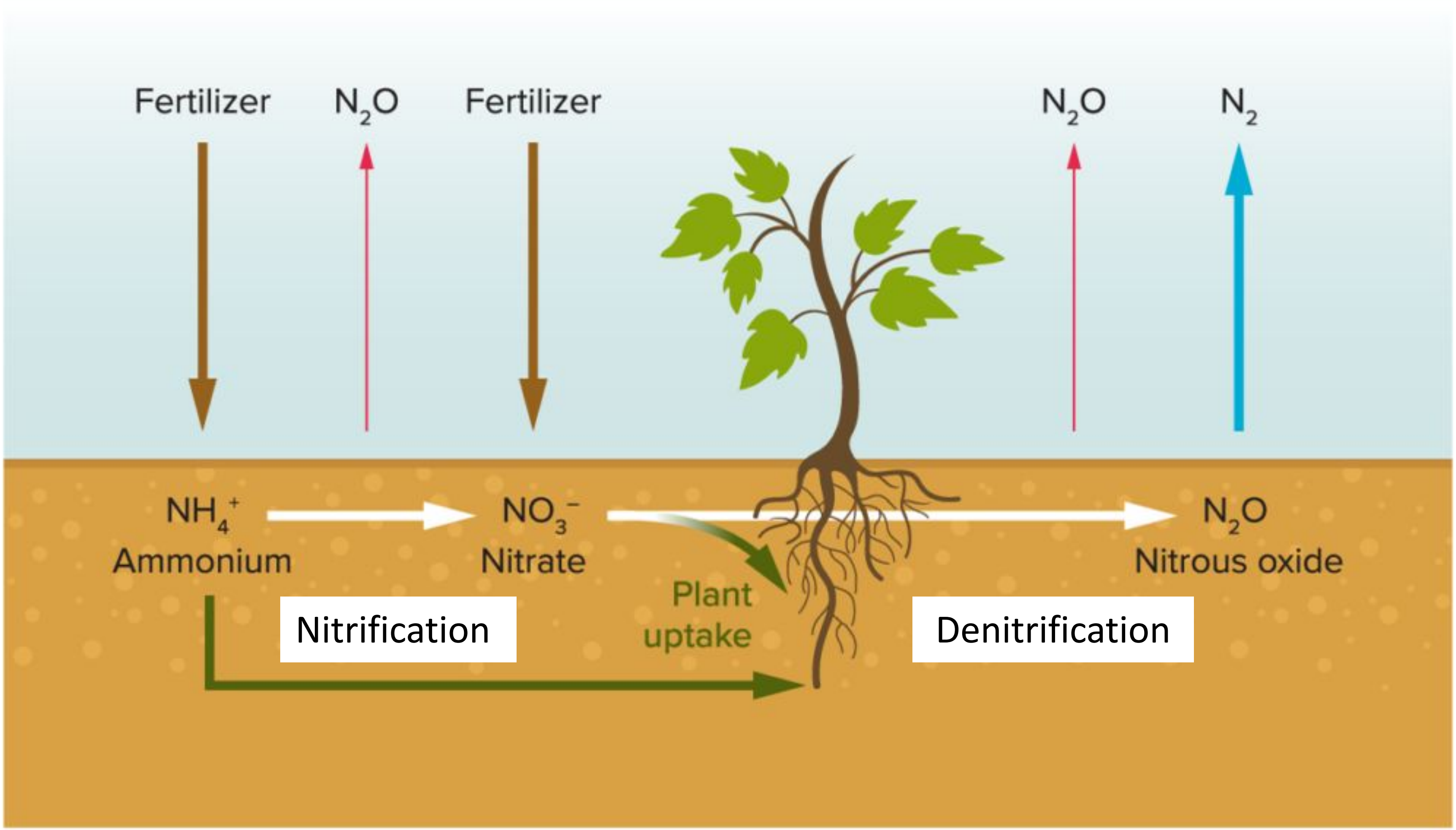
Not all practices that increase soil organic matter lead to CO_2 drawdown

Practice for increasing soil organic matter	Ancillary effects
Irrigation	CO_2 generated from pumping of irrigation water
Fertilization	CO_2 generated from off-site manufacture of fertilizer; N_2O generated from soil application
Manure application	Manuring redistributes carbon from another location, must consider other potential fates of the C.
Biochar	Rate of carbon storage is uncertain relative to emissions associated with collecting and pyrolyzing materials.
Reduced tillage	Reduces emissions from agricultural machinery but does not necessarily increase carbon storage for the whole profile.
Perennial vegetation	Potential for leakage (i.e., land-use change impact)

Schlesinger 2000, 2022, Paustian et al. 2016


"Despite the recent focus on soil carbon sequestration, addressing N_2O emissions from wet Corn Belt soils may have greater leverage in achieving climate sustainability." – Lawrence et al. 2017

How excess fertilizer causes nitrous oxide emissions



SOURCE: E. VERHOEVEN *ET AL / CALIFORNIA AGRICULTURE* 2017

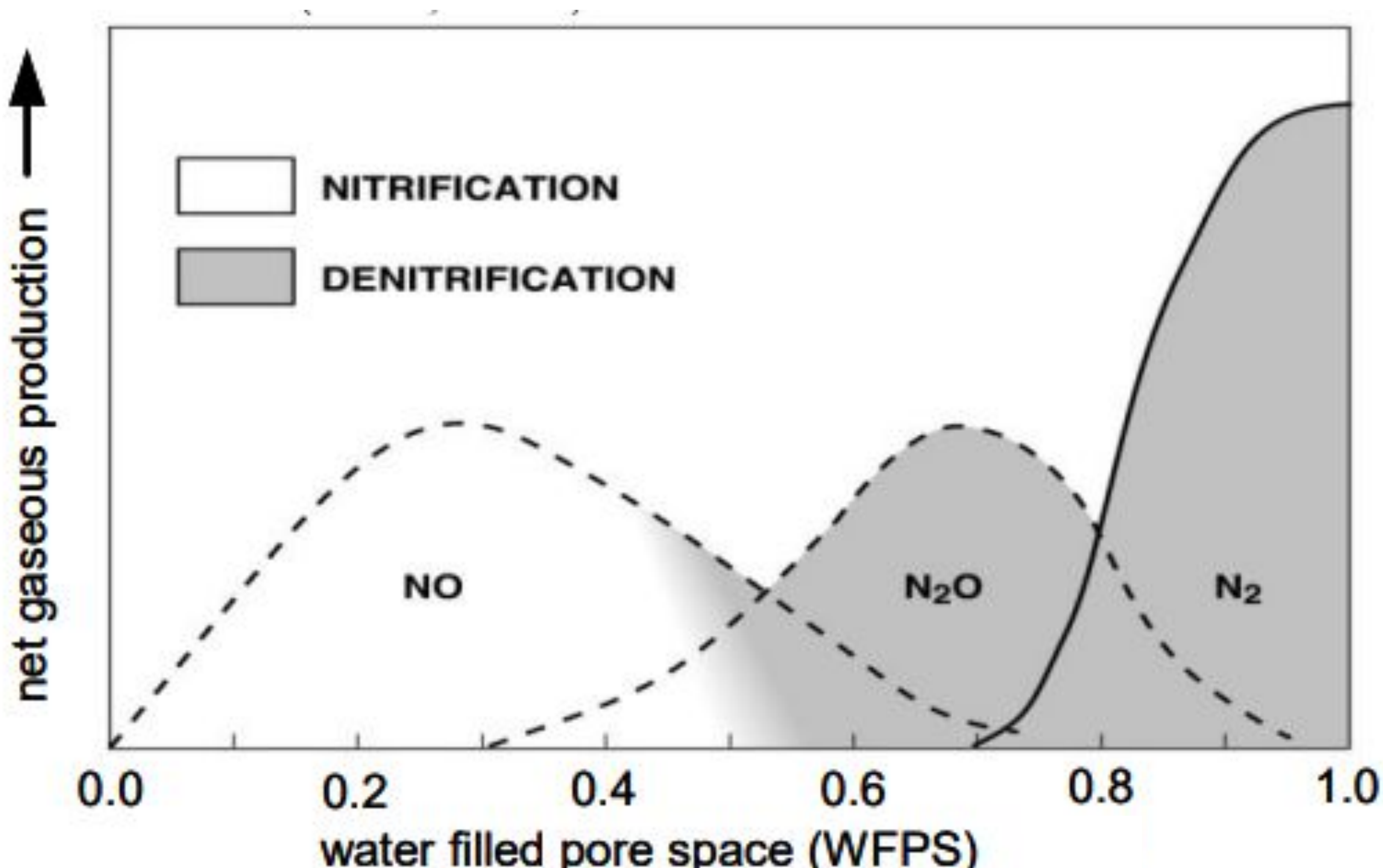
KNOWABLE MAGAZINE

Requirements for nitrification

- ✔ Supply of NH_4^+
- ✔ Nitrifier population
  - Abundant in most soils, but may take weeks to build up in sterile or subsoils
- ✔ Oxygen supply (>0.5 mg O_2/L in soil water)
- ✔ pH between 5 and 9 (optimum: 8)
- ✔ Soil moisture (optimum: field capacity)
- ✔ Temperature >5^0 C (optimum: 25-35^0 C).

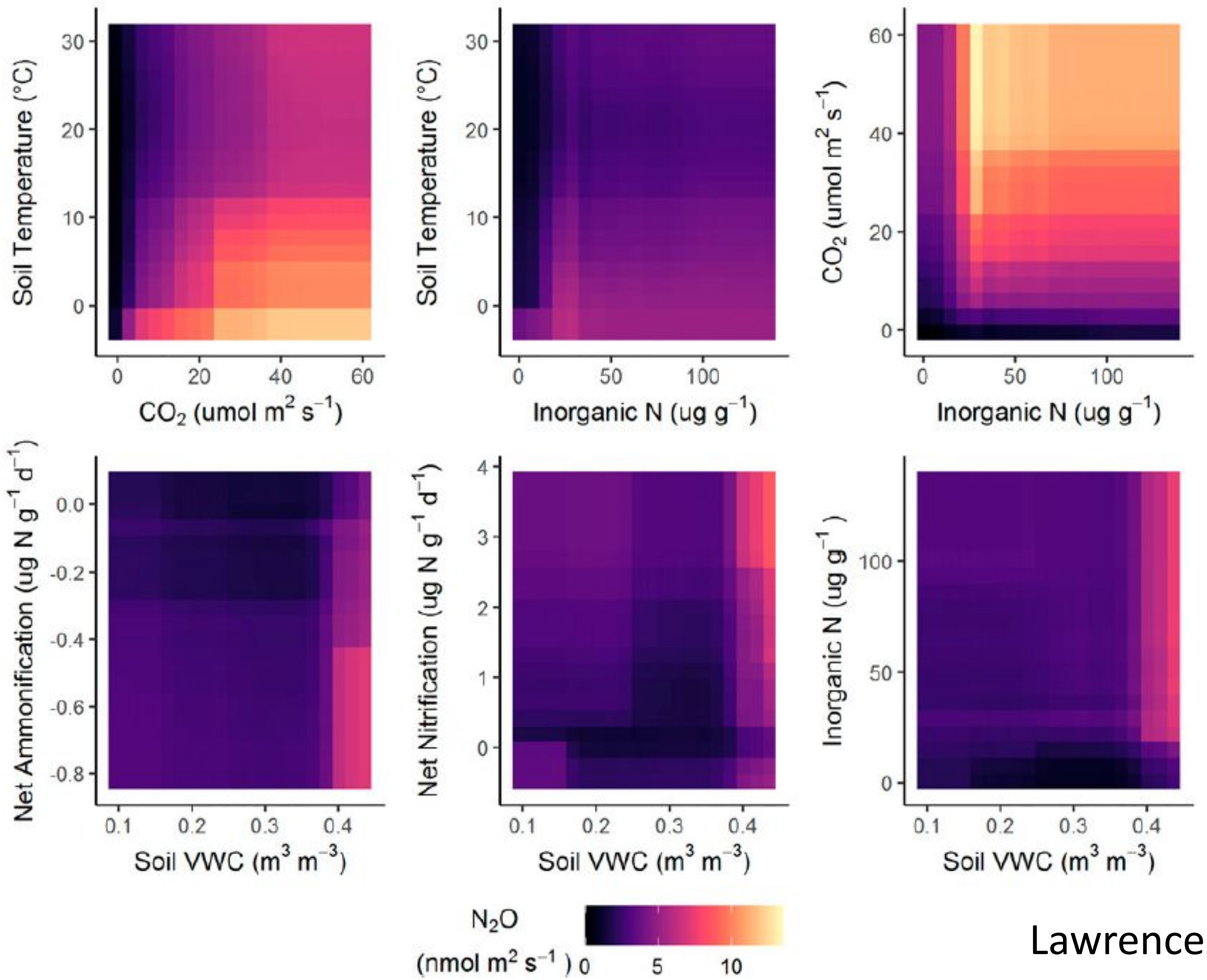
Requirements for denitrification

- ✔ Locally anaerobic conditions (<0.2 mg O_2/L in soil water)
  - ✔ Influenced by soil moisture, texture, compaction, biological activity
- ✔ Decomposable organic matter
- ✔ Source of NO_3^-
- ✔ Temperature >2-5^{0}C (optimum 25-35^{0}C)



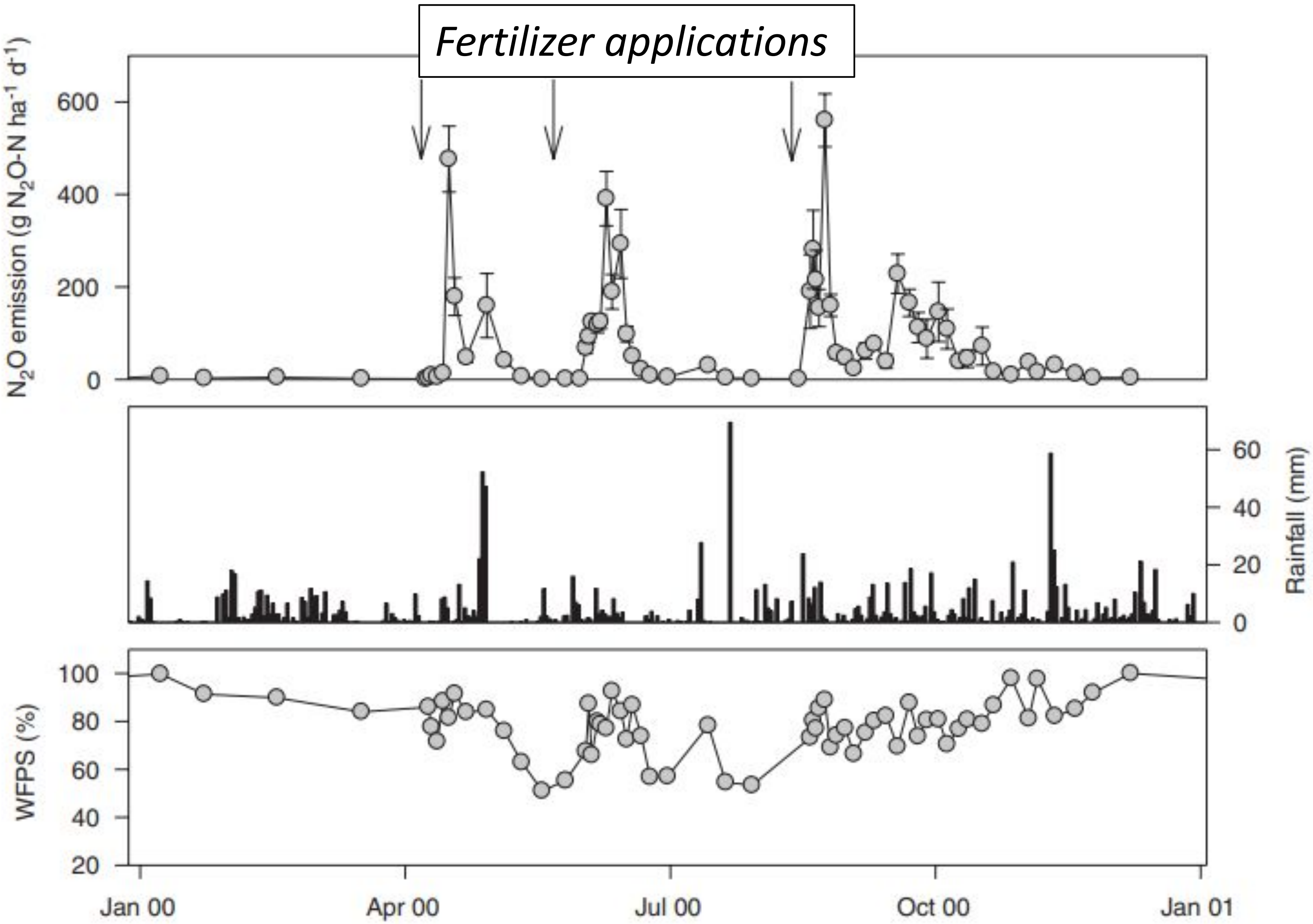
Davidson 1991

Soil moisture, temperature, N supply, and microbial activity interactively affect N_2O emissions in the US Corn Belt.



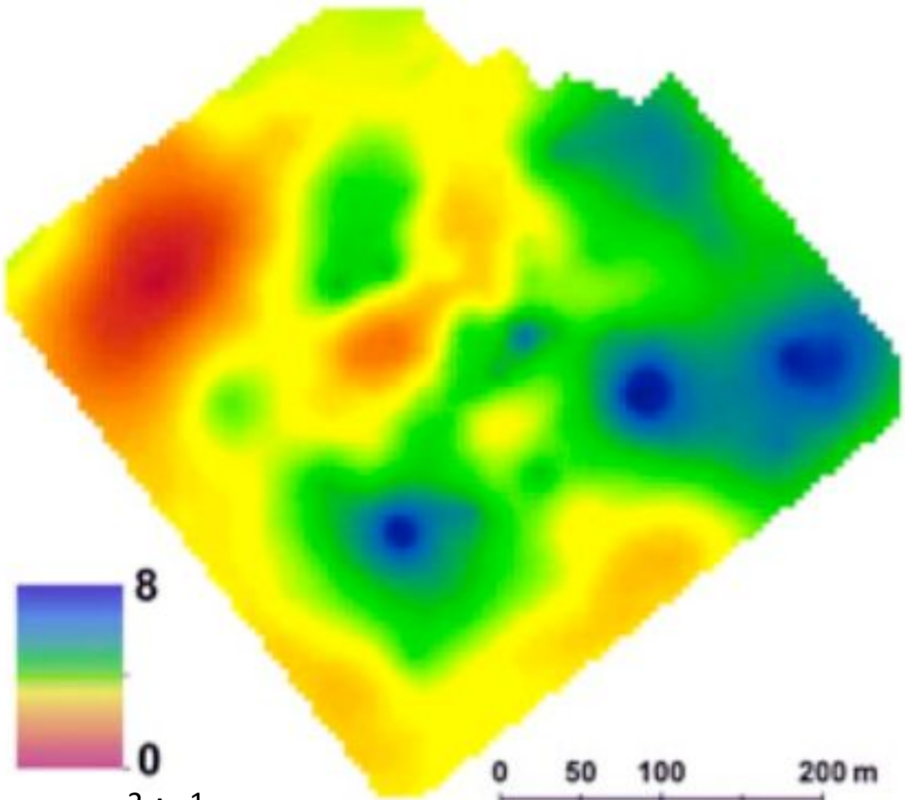
Lawrence et al. 2021

High temporal variation in N_2O emissions



Dobbie and Smith 2003

High spatial variation in N_2O emissions

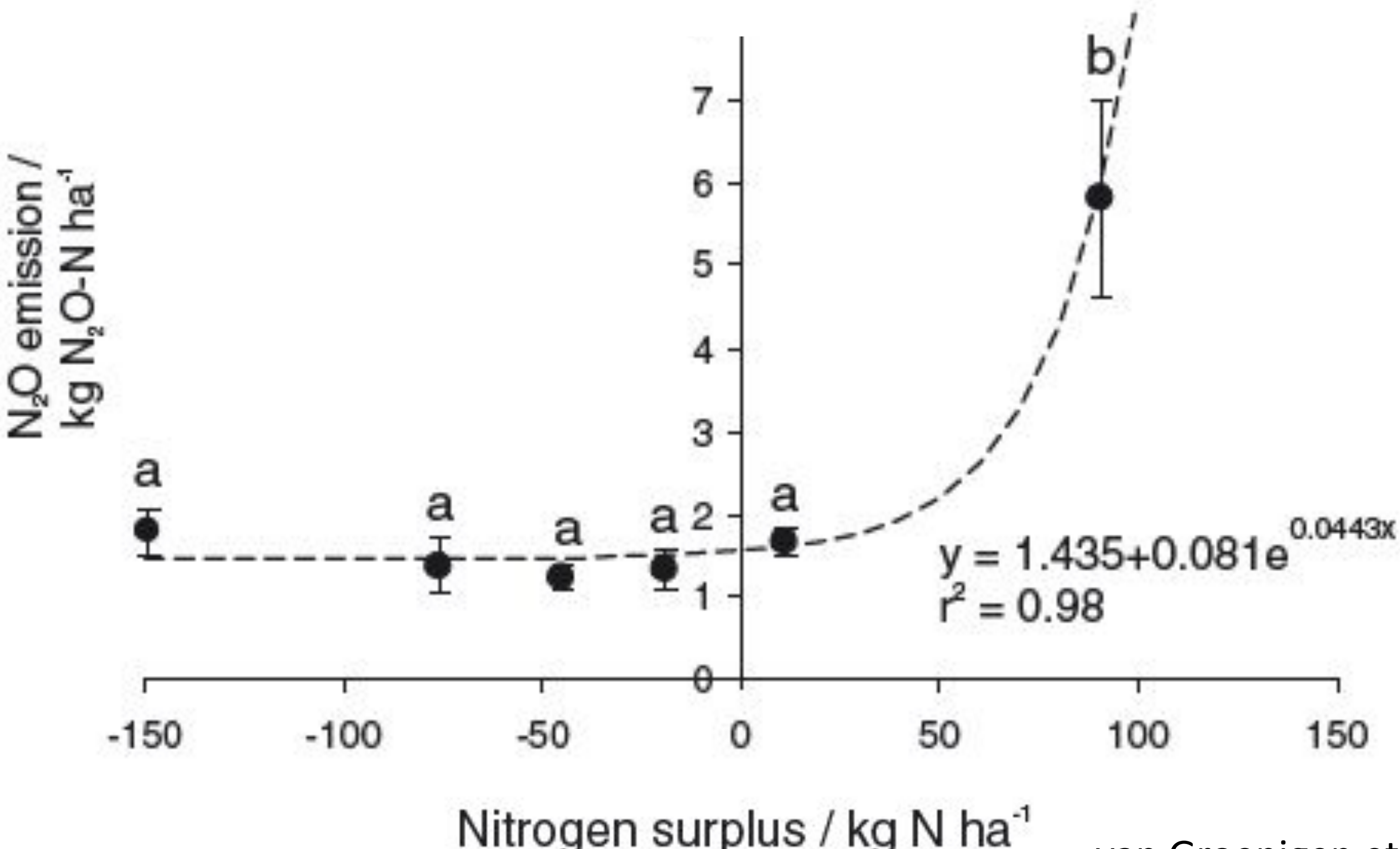


µg N_2O m^{-2} h^{-1}

McDaniel et al. 2017

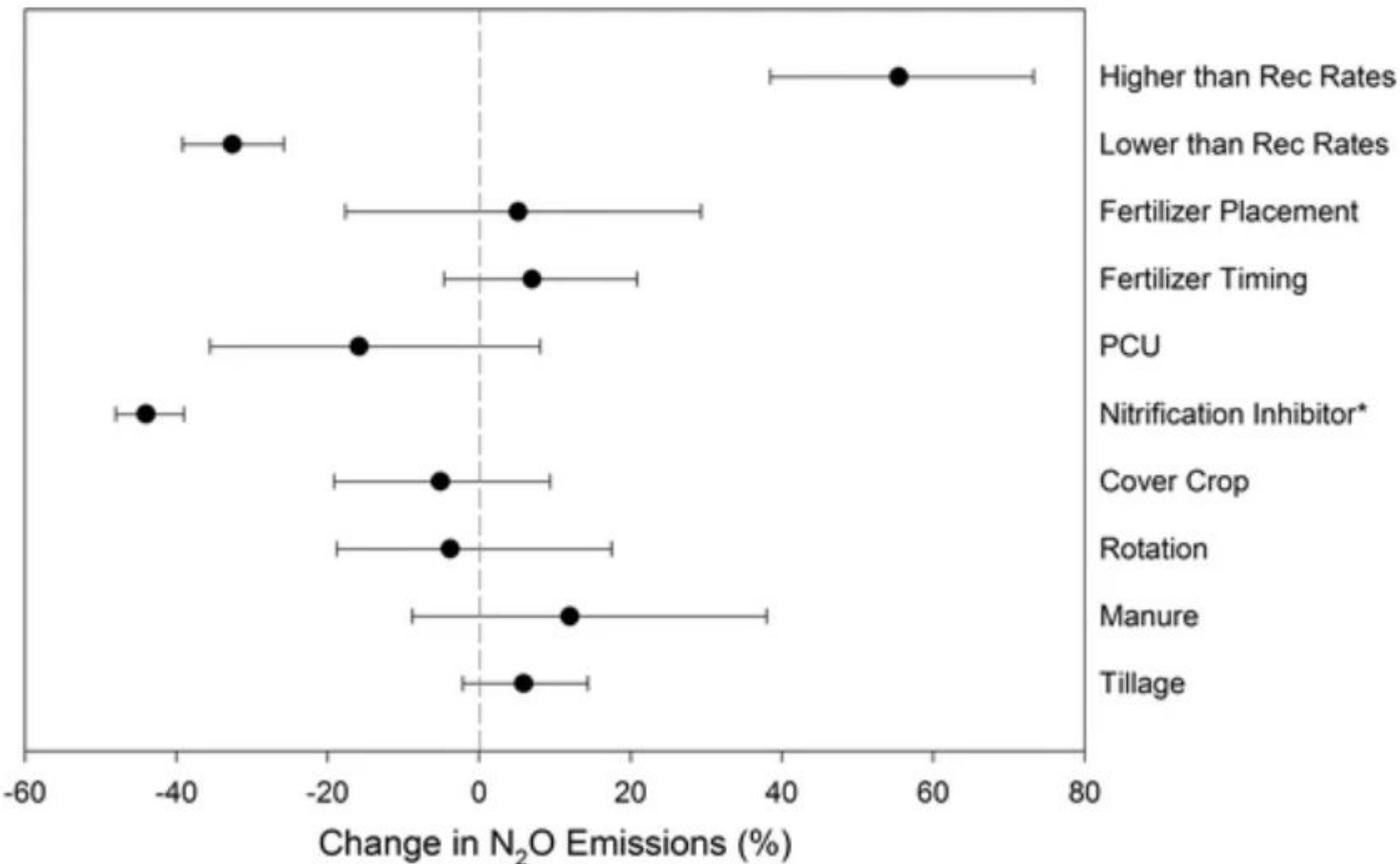
- 24% of emissions came from just 1% of the area
- Hotspots corresponded with areas of higher inorganic N, dissolved organic C

Nitrous oxide emissions increase with surplus nitrogen fertilizer inputs.

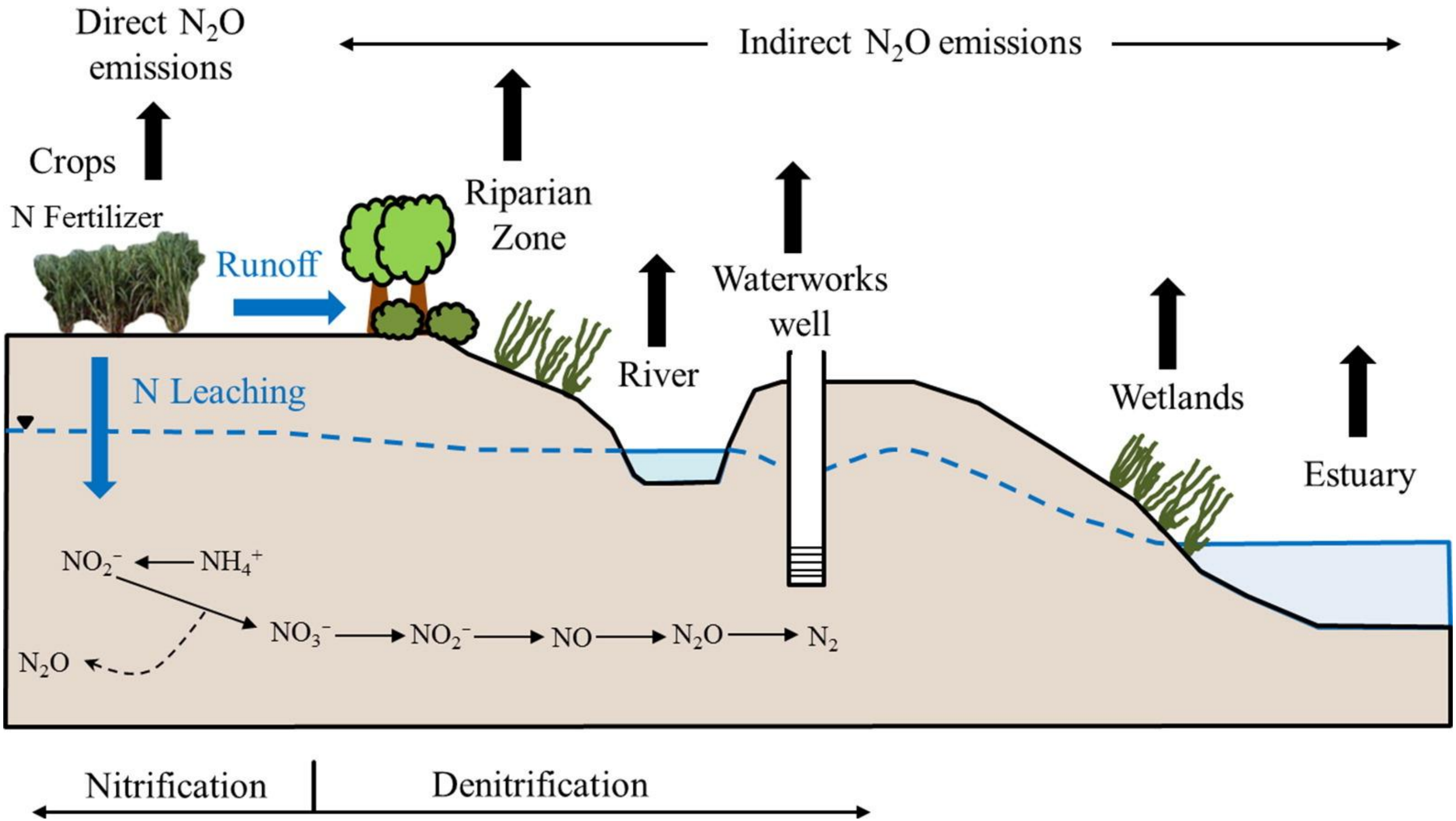


van Groenigen et al. 2010

Nitrous oxide management strategies

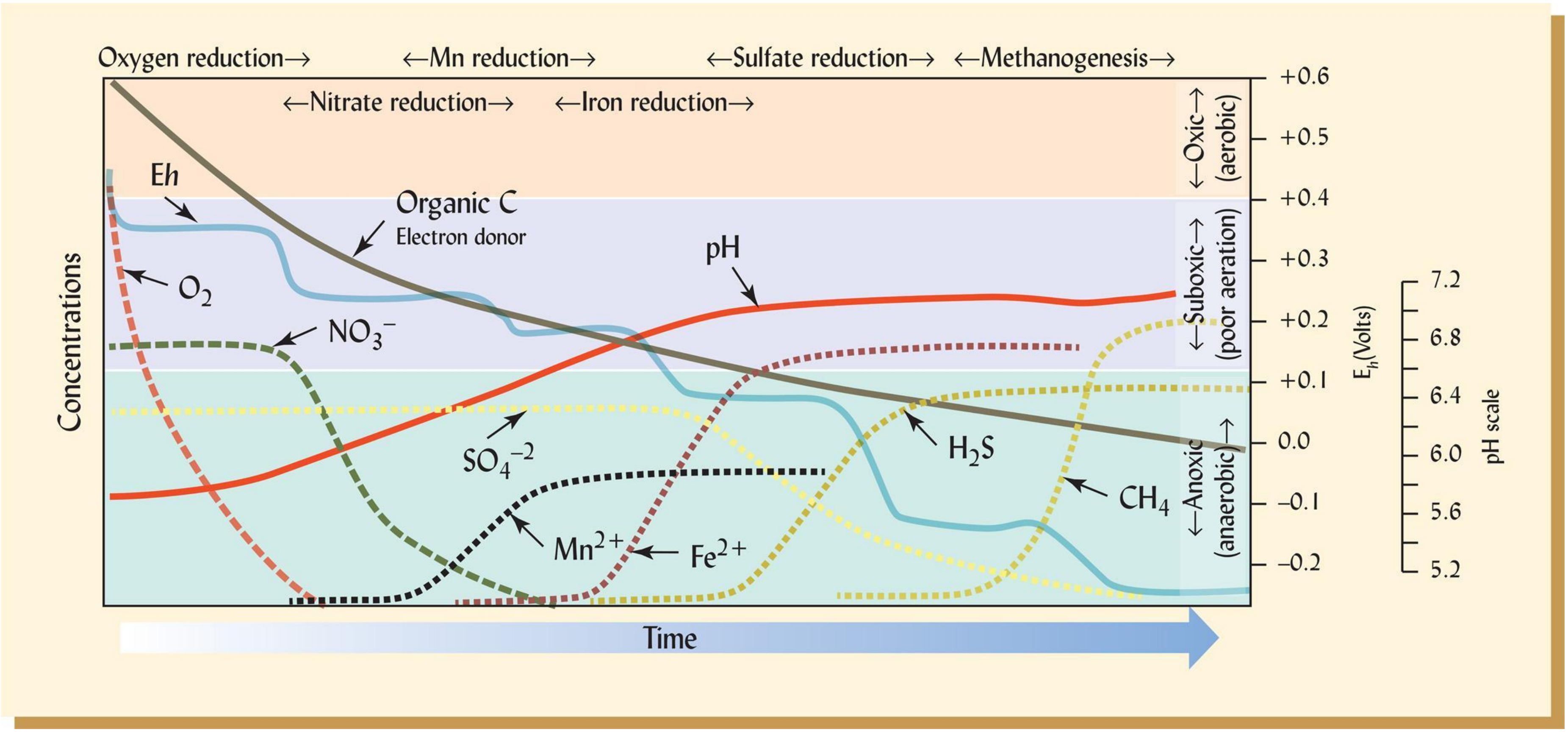


Han et al. 2017

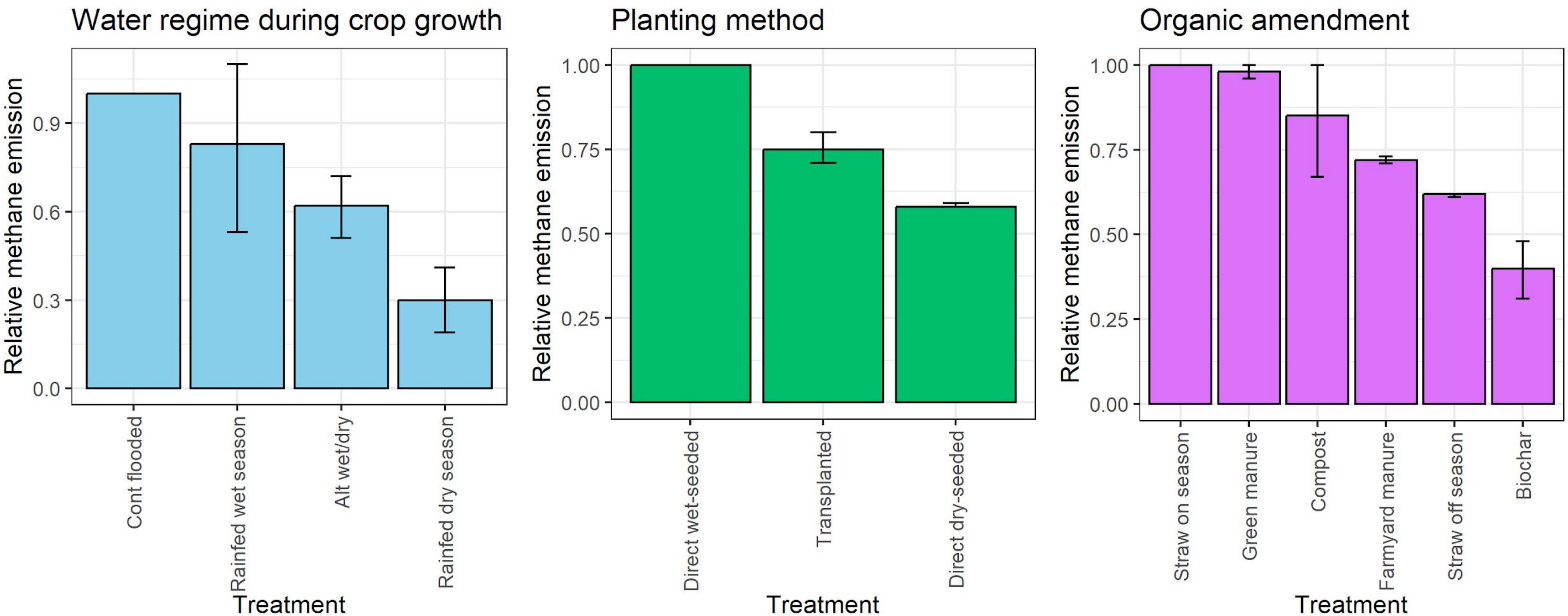


Jurado et al. 2017

Methane production occurs in the absence of oxygen (i.e., rice paddies)

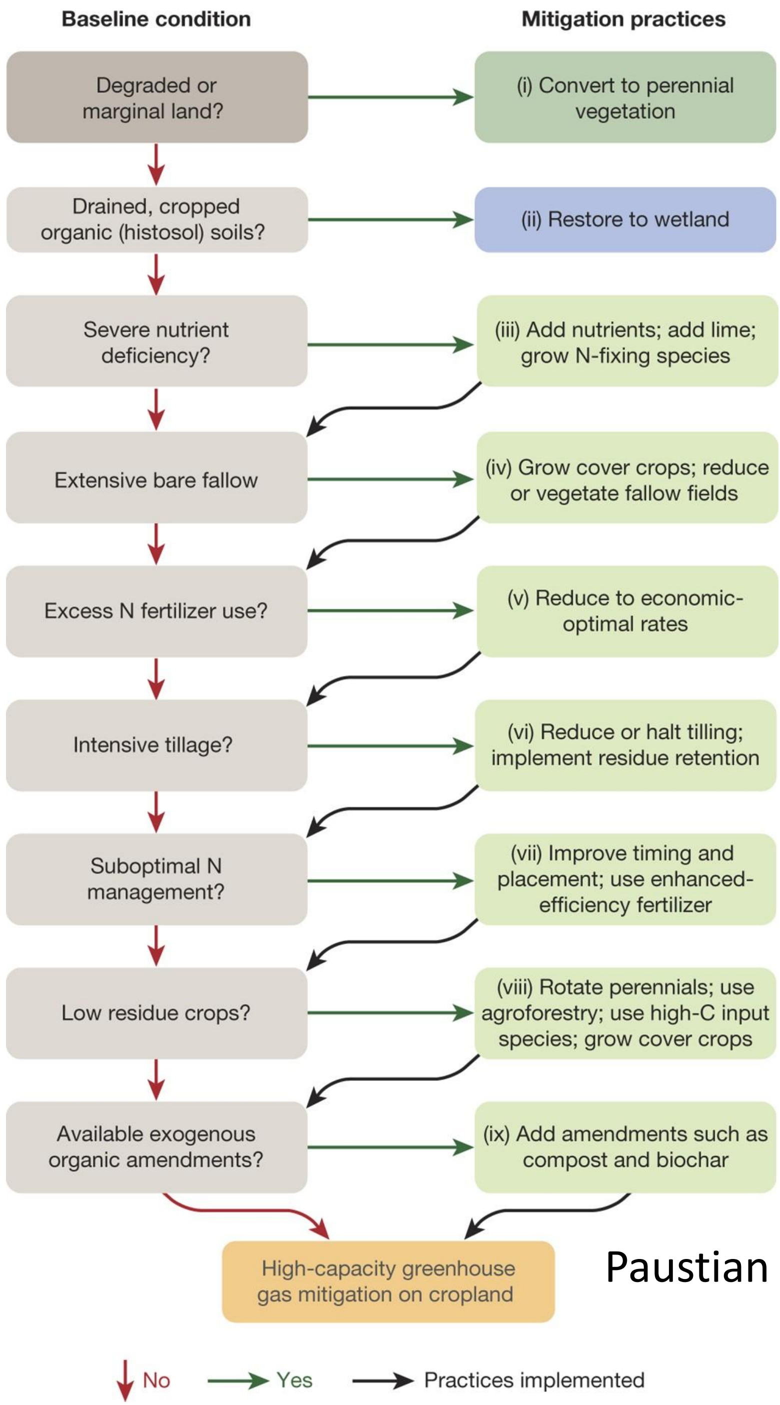


Quantitative review reveals management practices to reduce methane from rice production



Nikolaisen et al. 2023

Putting it all together: Climate-smart soil management practices differ depending on the context.



Paustian et al. 2016

Thank you

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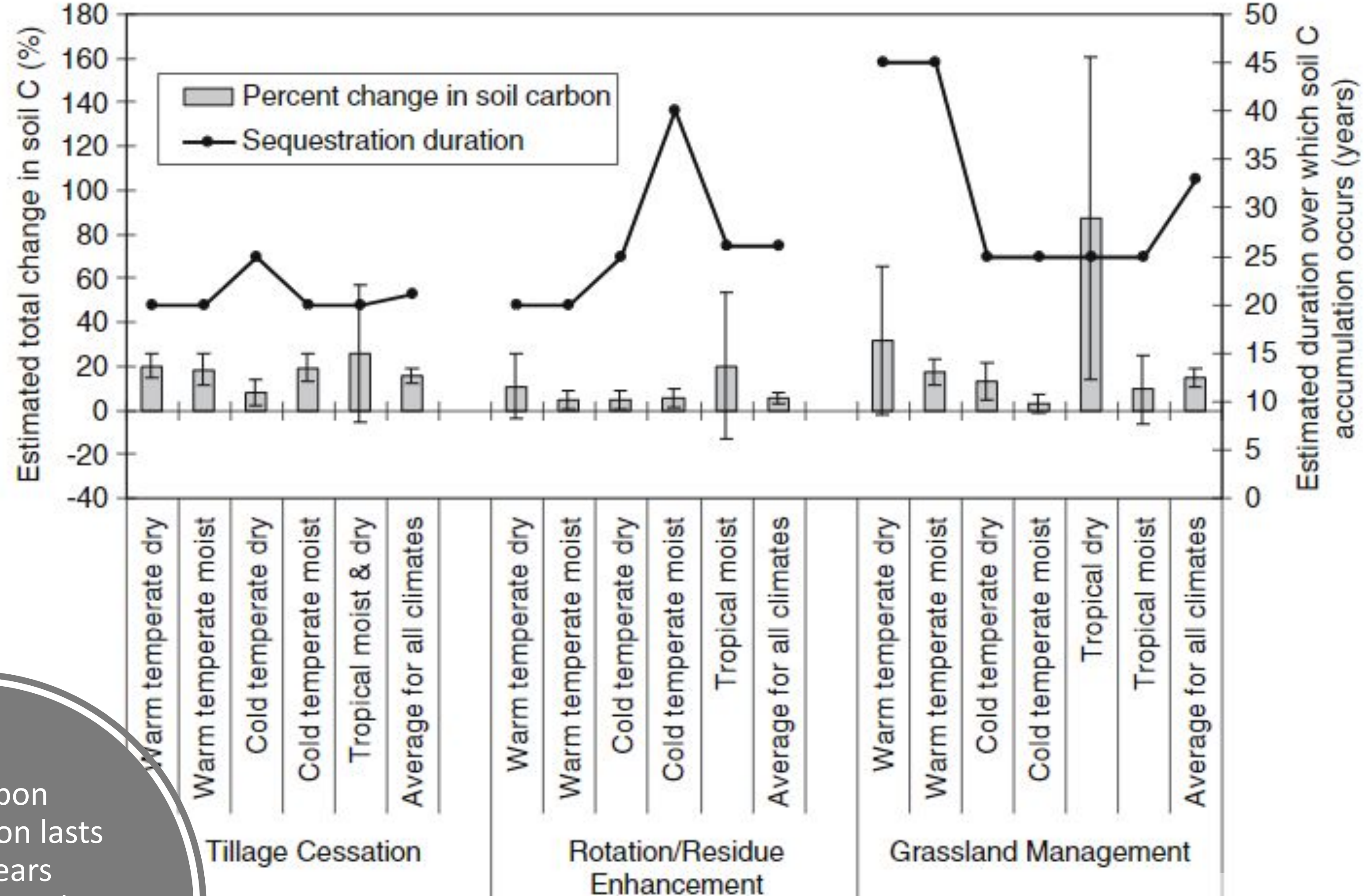
https://www.poffenbargerlab.com/



West and Six 2007

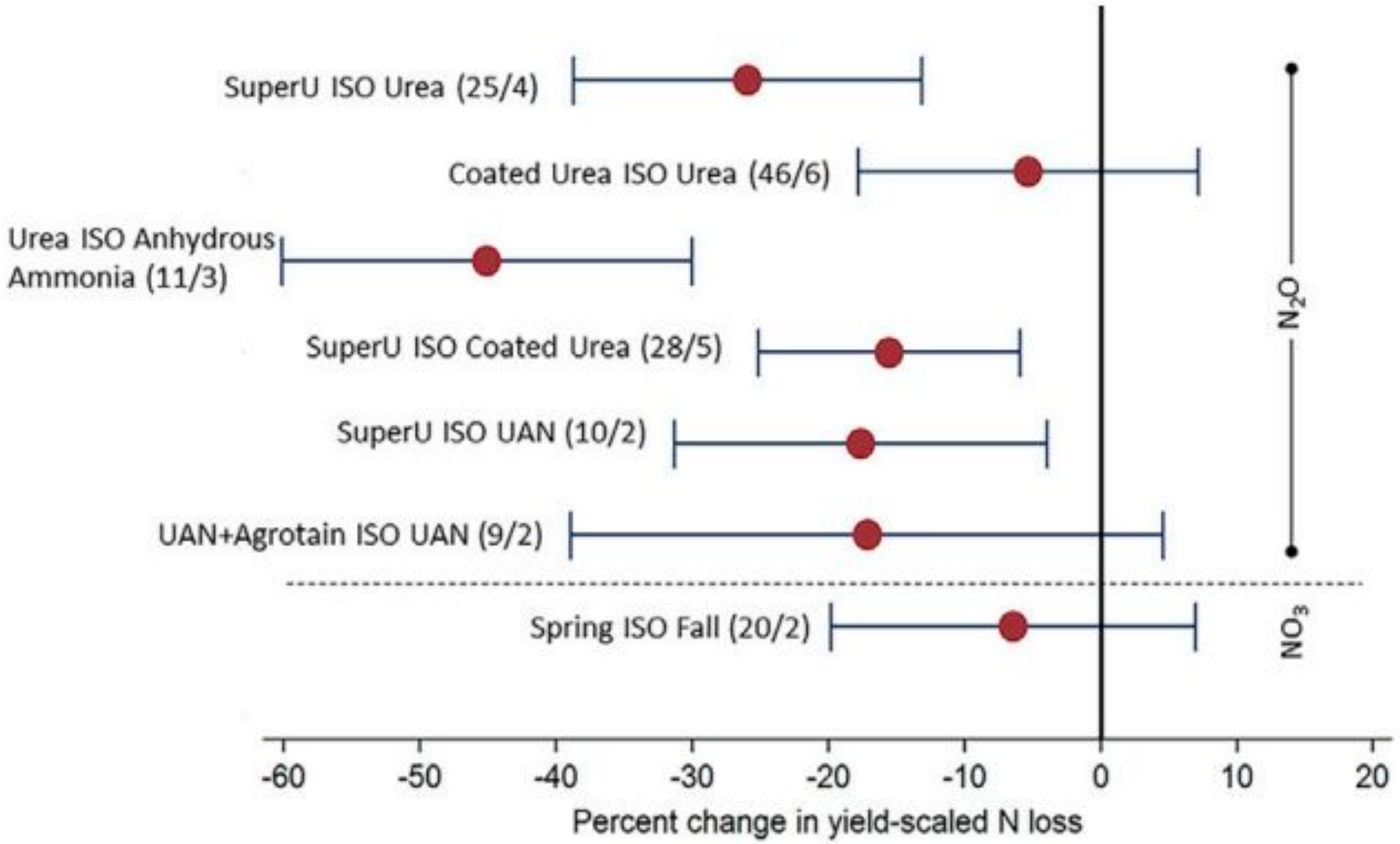
Soil carbon sequestration lasts 20-50 years depending on the environment and management change.

Denitrification is most pronounced in poorly-drained soils with high organic matter content.

Soil organic matter (%)	Excessively well drained	Well drained	Moderately well drained	Somewhat poorly drained	Poorly drained
	% inorganic soil N denitrified				
<2	2-4	3-9	4-14	6-20	10-30
2-5	3-9	4-16	6-20	10-25	15-45
>5	4-12	6-20	10-25	15-35	25-55

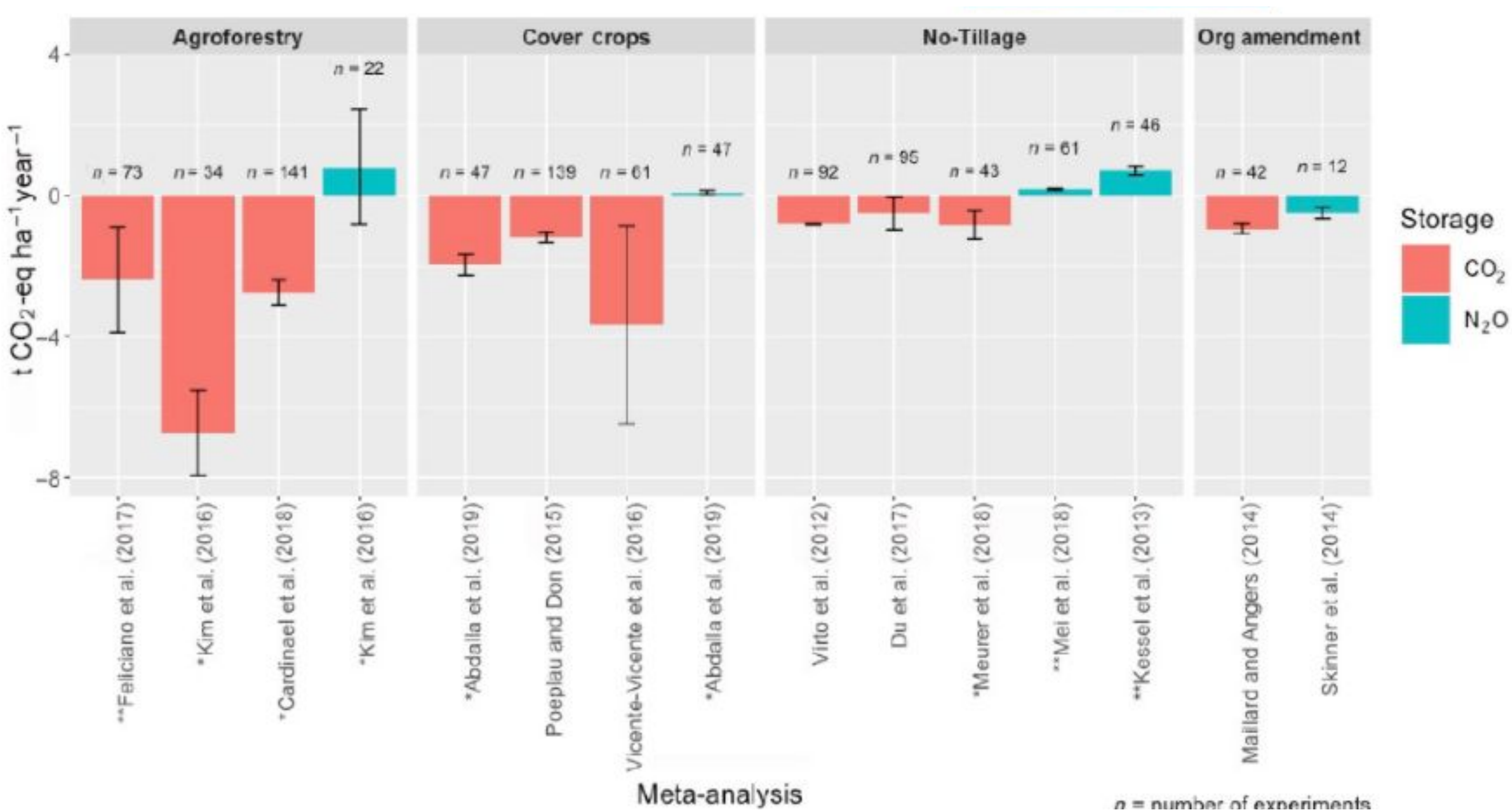
Meisinger and Randall 1991

Nitrous oxide management strategies



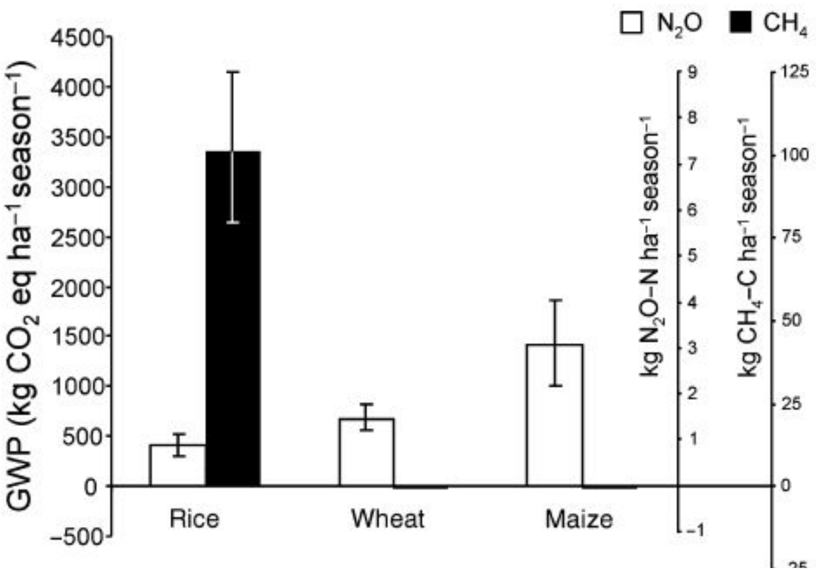
Eagle et al. 2017

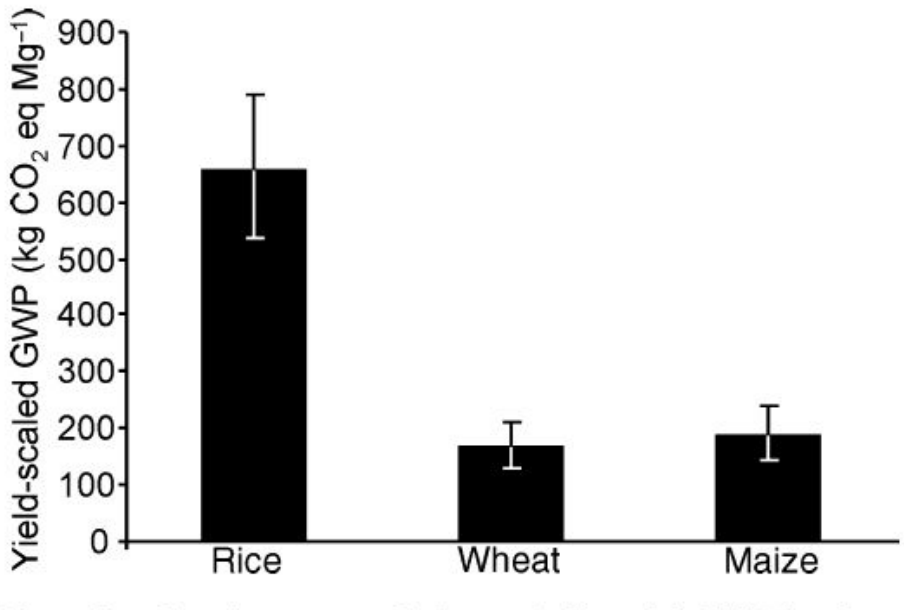
Can N_2O emissions offset C storage?



Guenet et al. 2021

Nitrous oxide and methane emissions by major crop





Linquist et al. 2012