Regenerating soil organic matter for the benefit of climate and food production:
A systemic multifaceted approach

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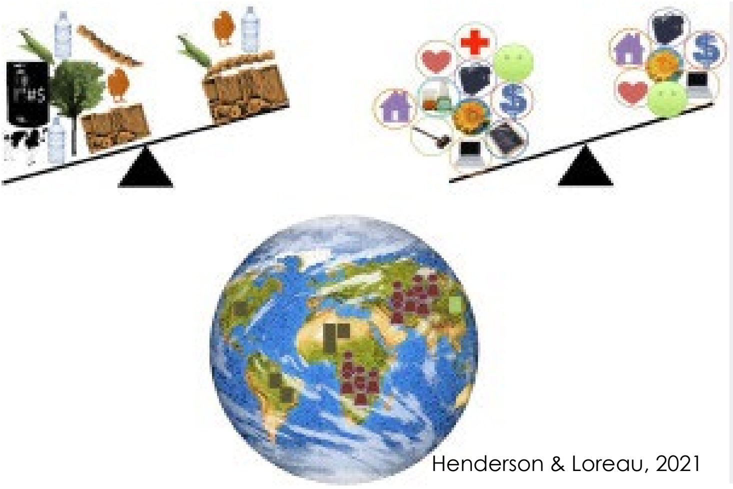
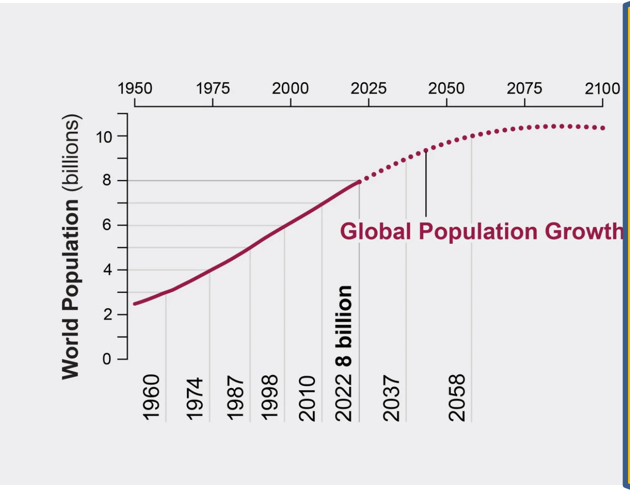
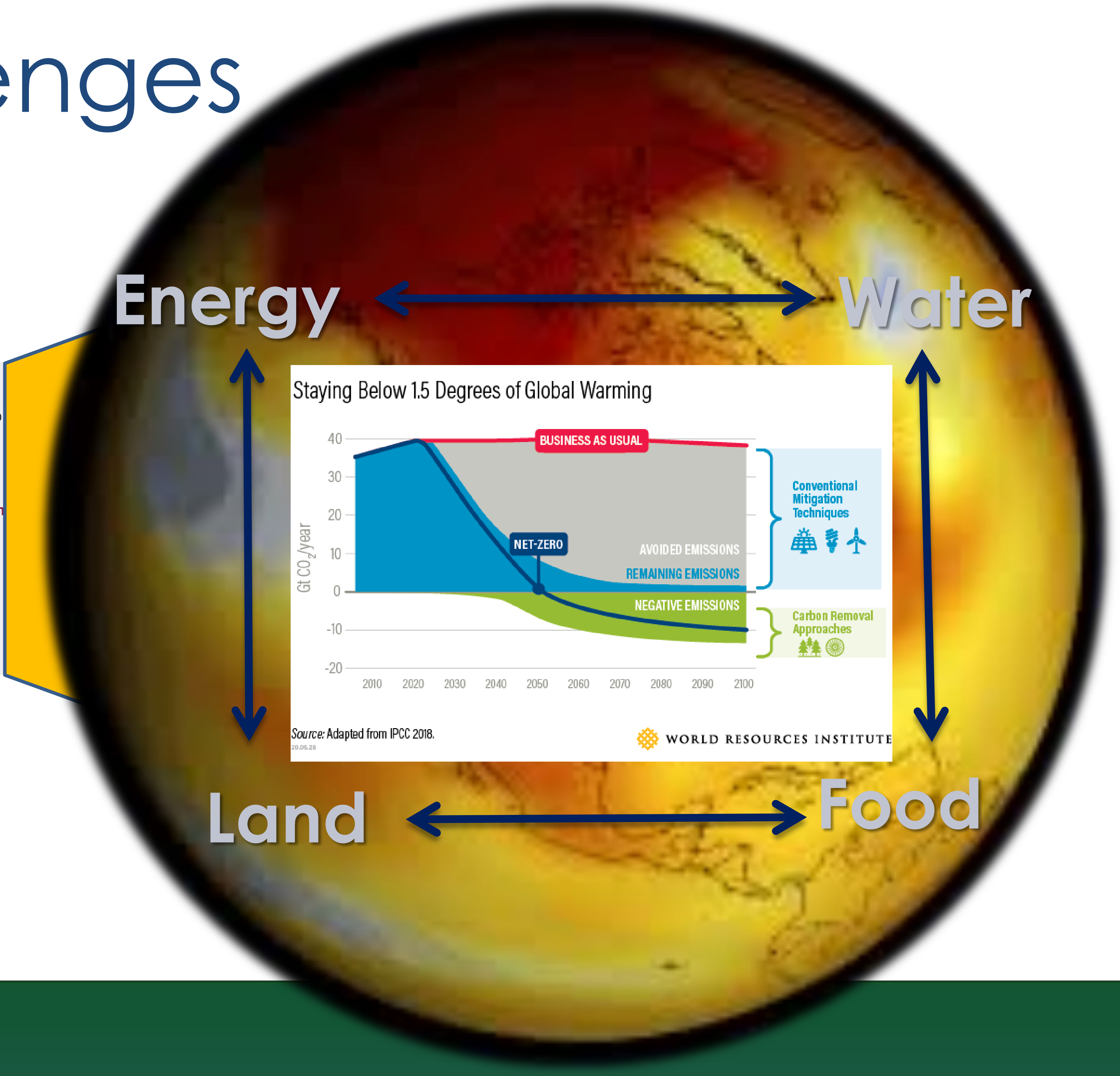
COLLEGE OF AGRICULTURAL SCIENCES
COLORADO STATE UNIVERSITY

Our wicked challenges

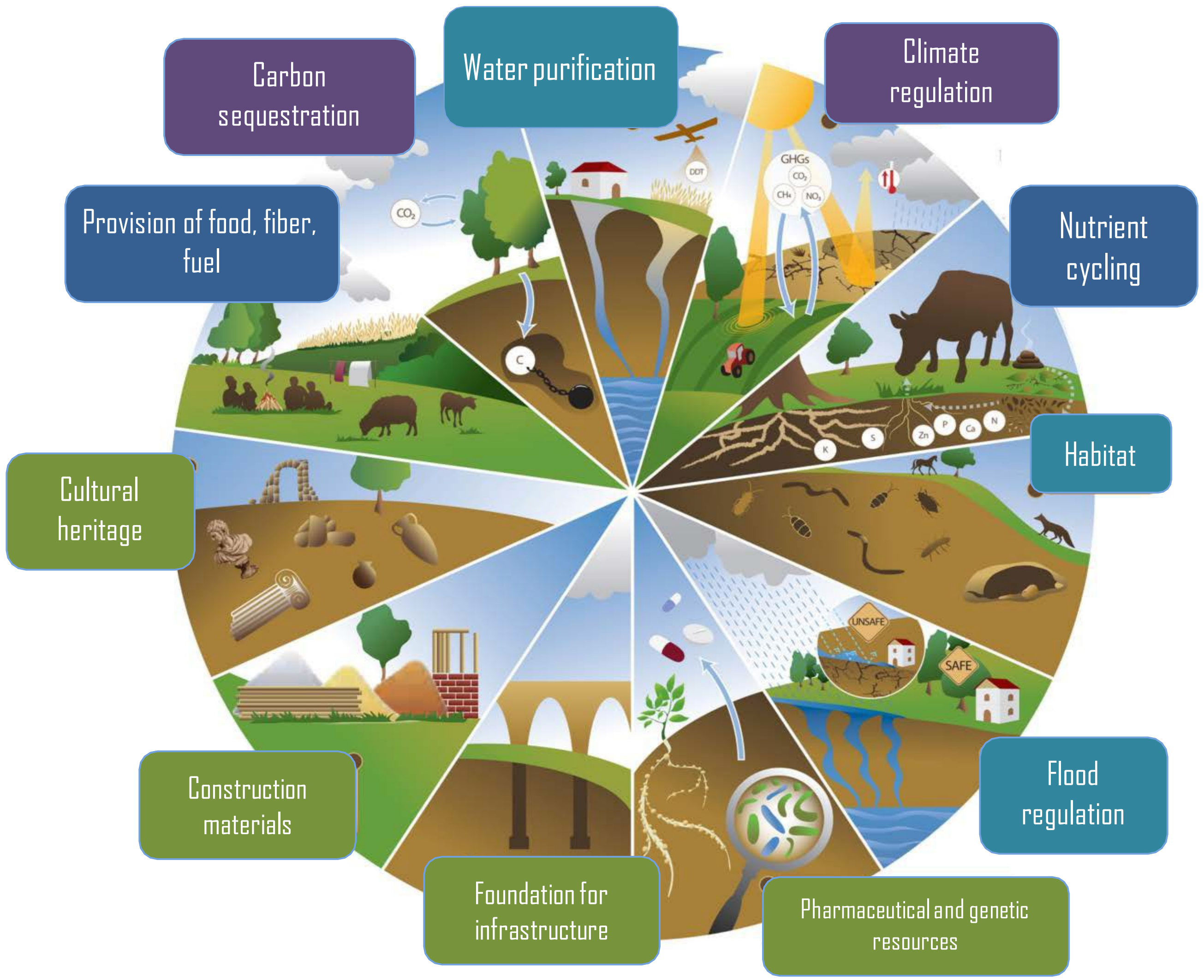


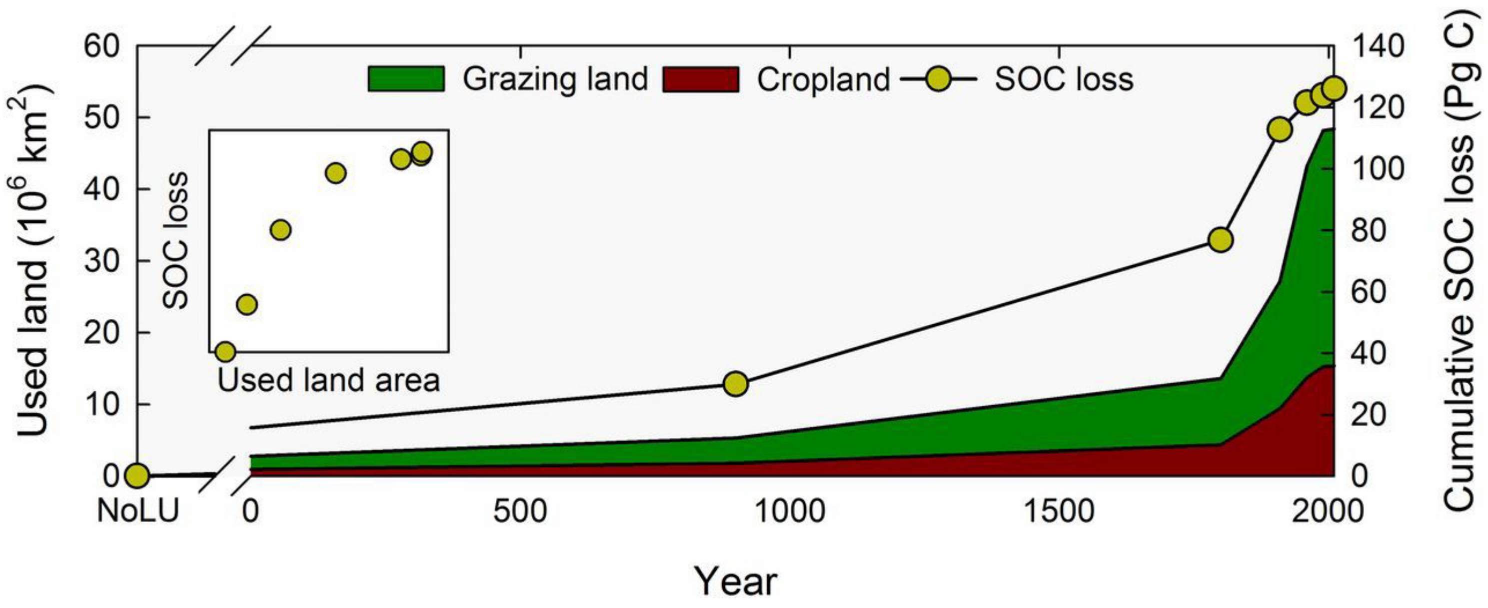
Henderson & Loreau, 2021





Soil is at the nexus of our challenges underpinning many ecosystem services including supporting yields and mitigating climate warming

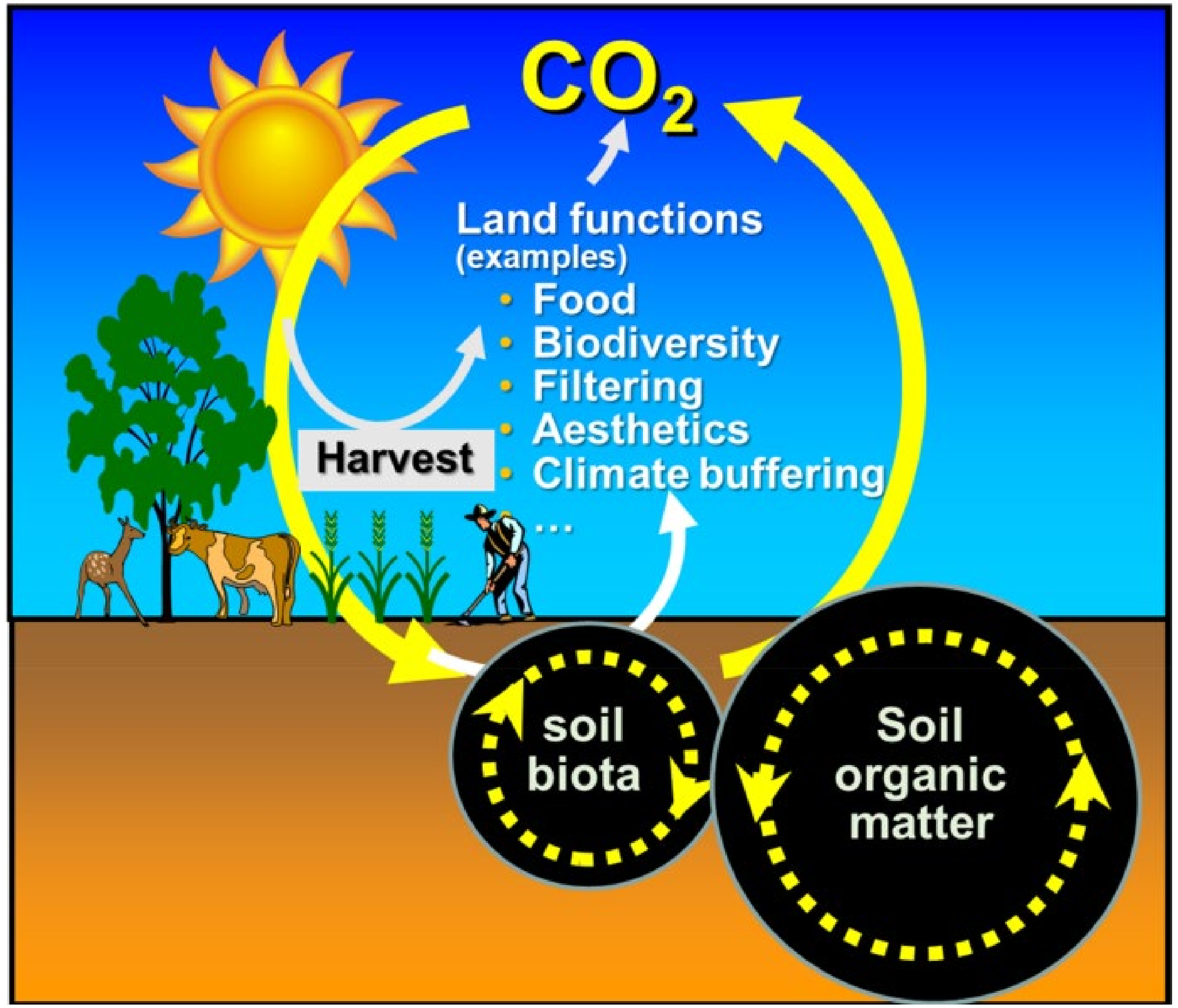




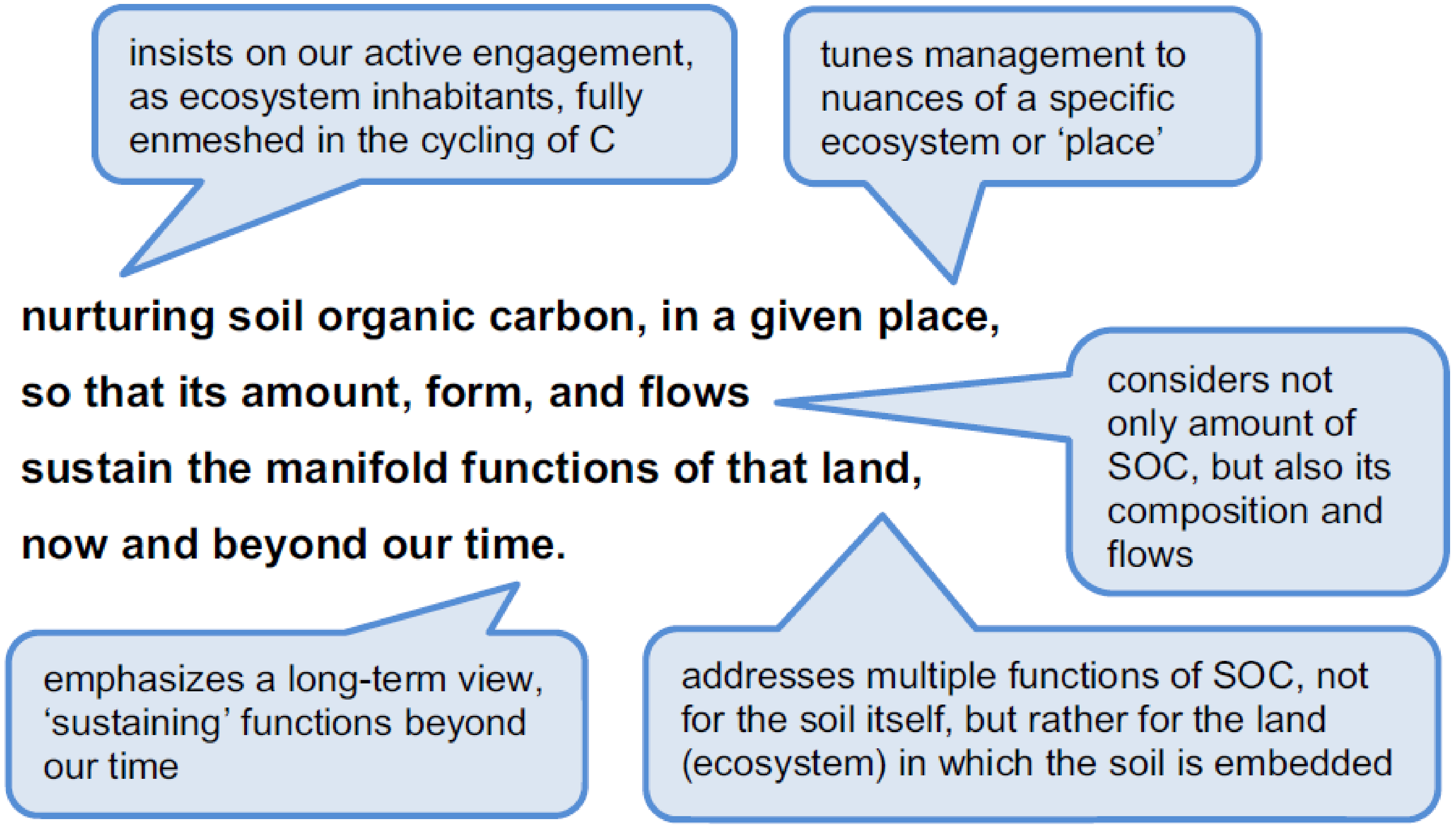
The carbon debt of 12,000 years of human land use

From Soil C “sequestration” to soil C stewardship

Janzen, 2024

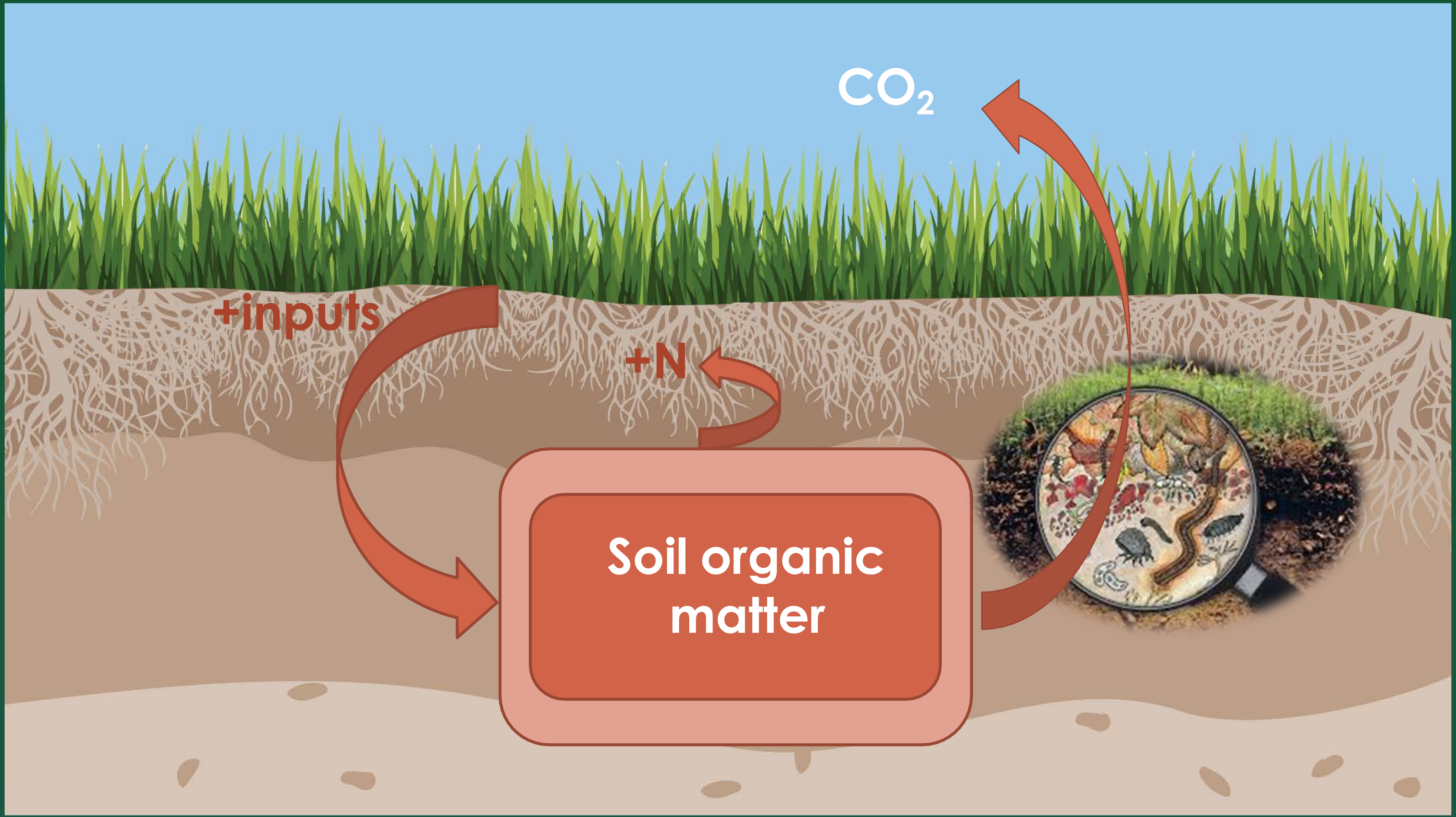


A proposed definition of ‘soil carbon stewardship’, showing noteworthy emphases



Addressing the soil C dilemma:

Promoting accrual and turnover to regenerate fertility



Can we increase soil carbon storage while also increasing nutrient mineralization and natural provision of fertility?

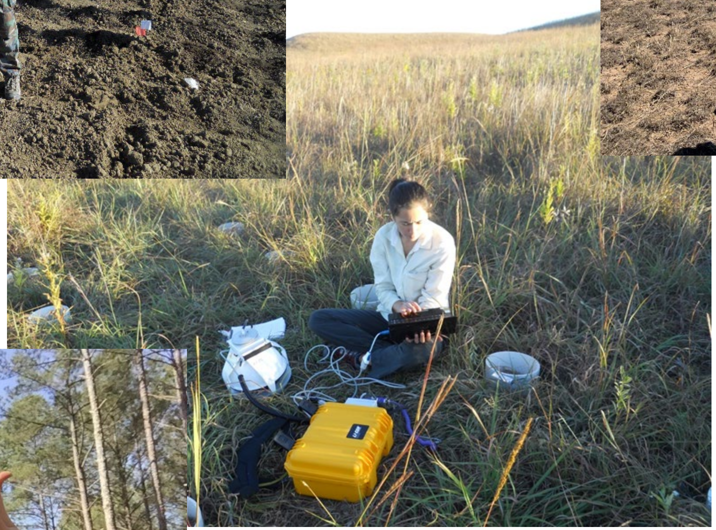
Janzen, 2006

Soil C sequestration and soil health goals need to merge!

How does soil organic matter form, turn over and persist?

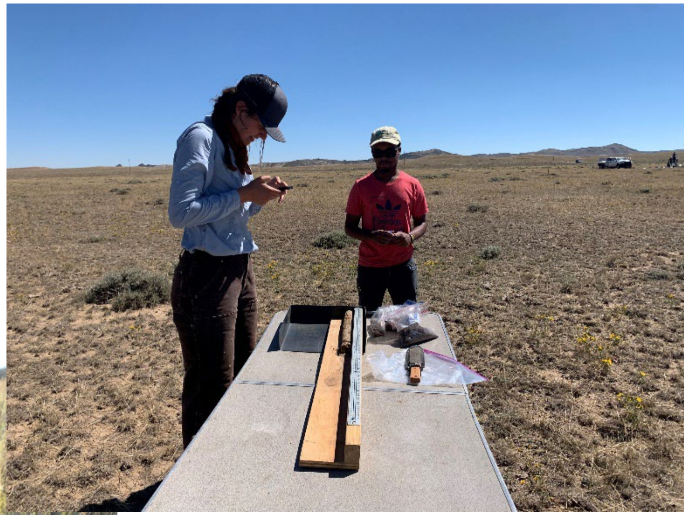
From the Arctic
to the Tropics

In croplands

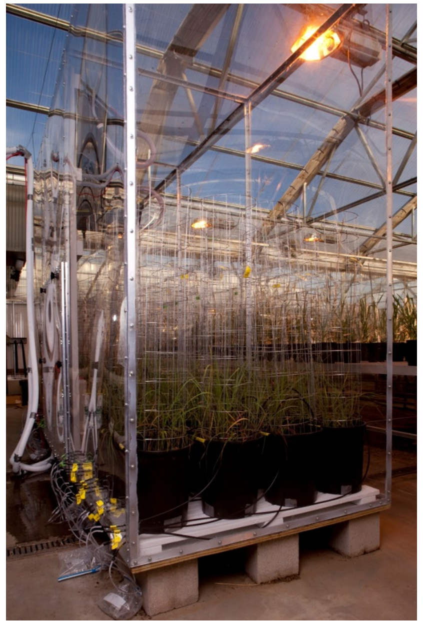


grasslands

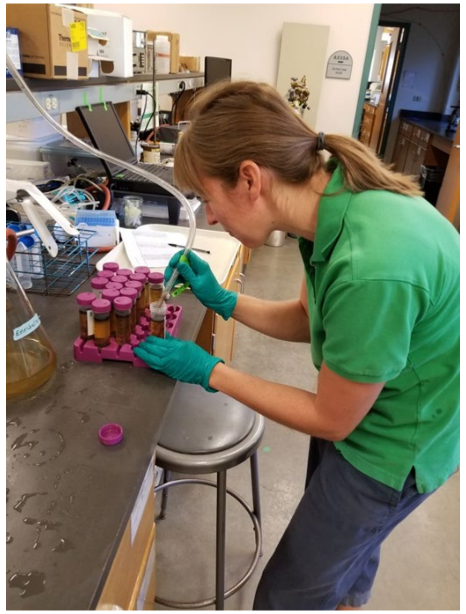
forests



Quantifying
natural stocks



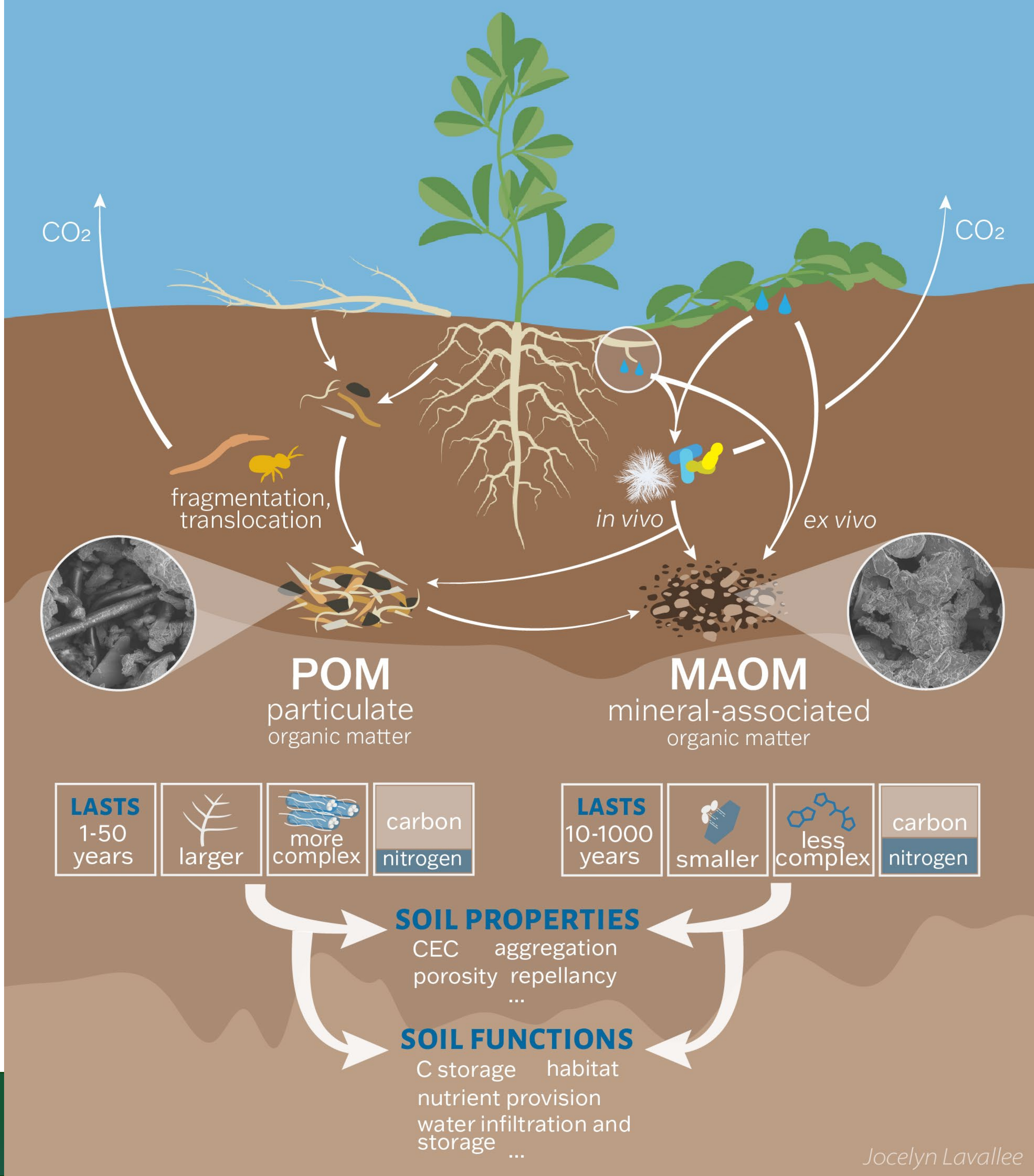
Using isotope
labeling



Processing
thousands of soil
samples!

Not all soil organic matter is made equal: We developed and apply the POM *versus* MAOM study framework

Cotrufo & Lavallee, 2022



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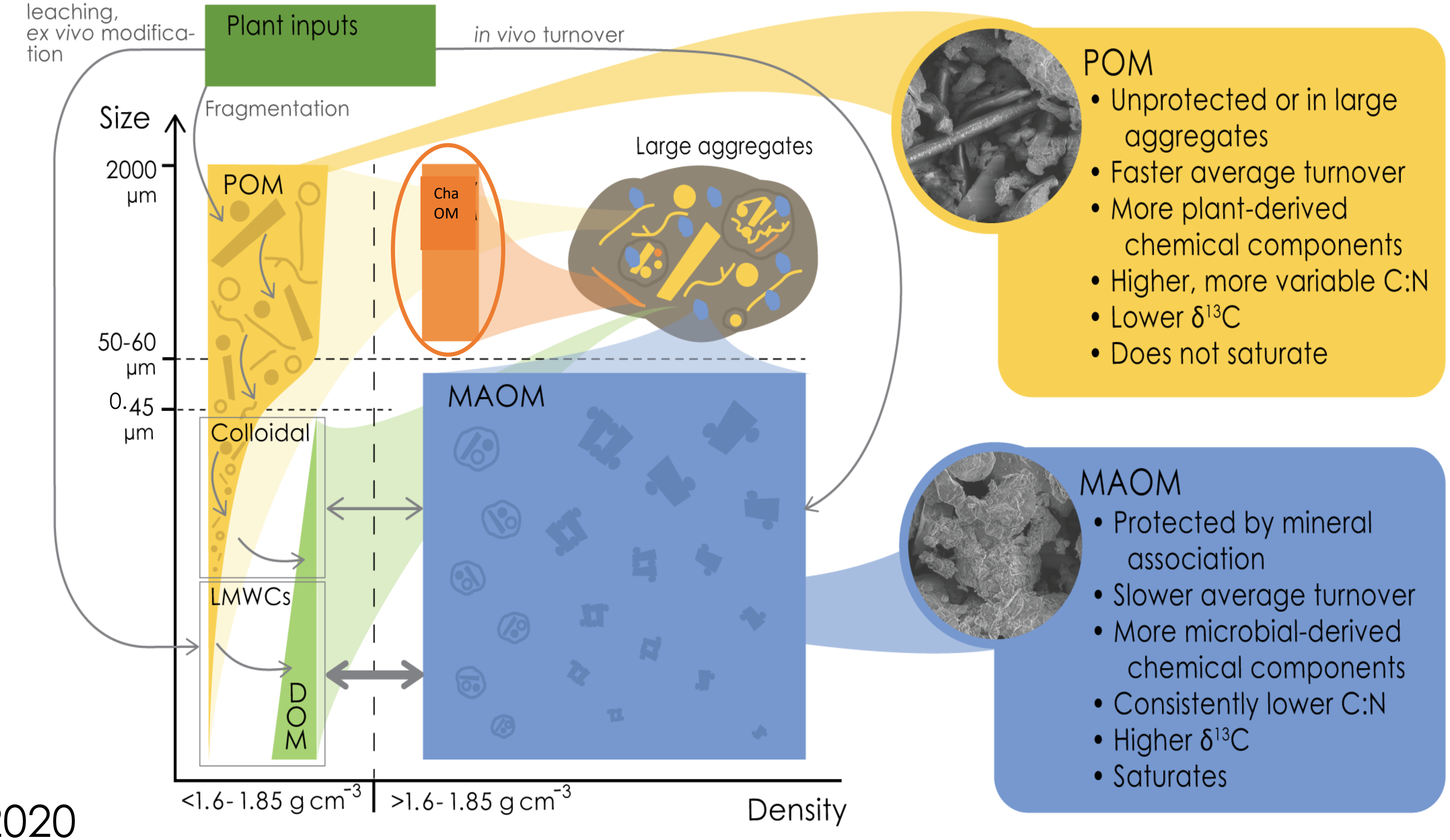
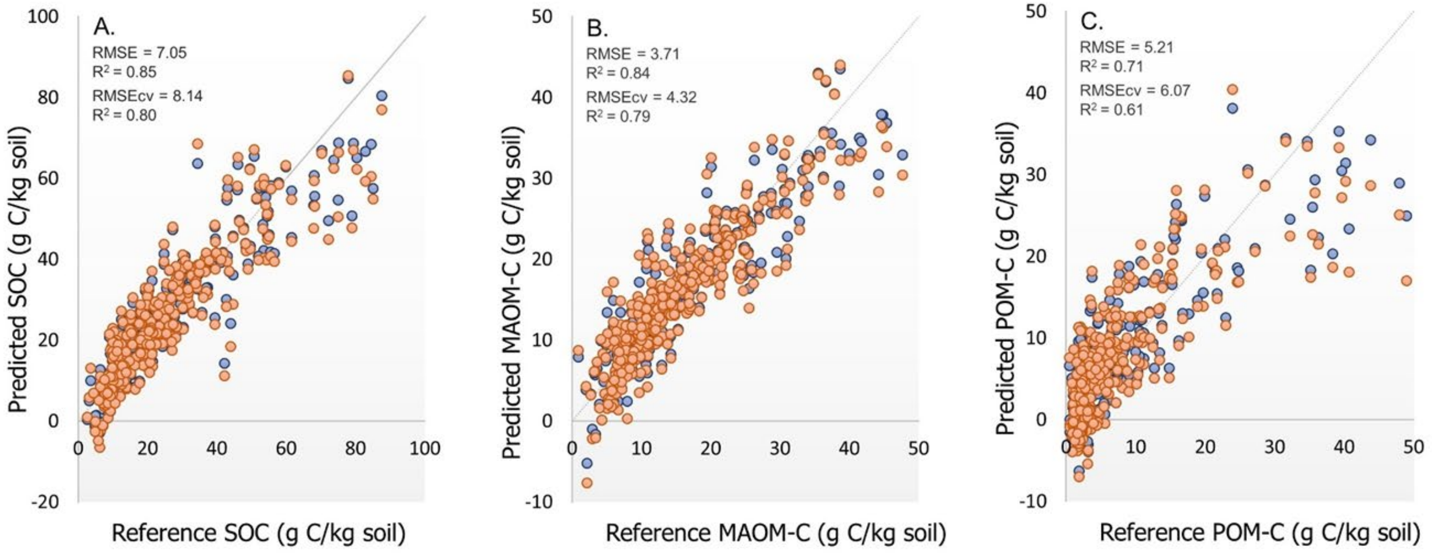
Merging conceptual with procedural definition of POM and MAOM

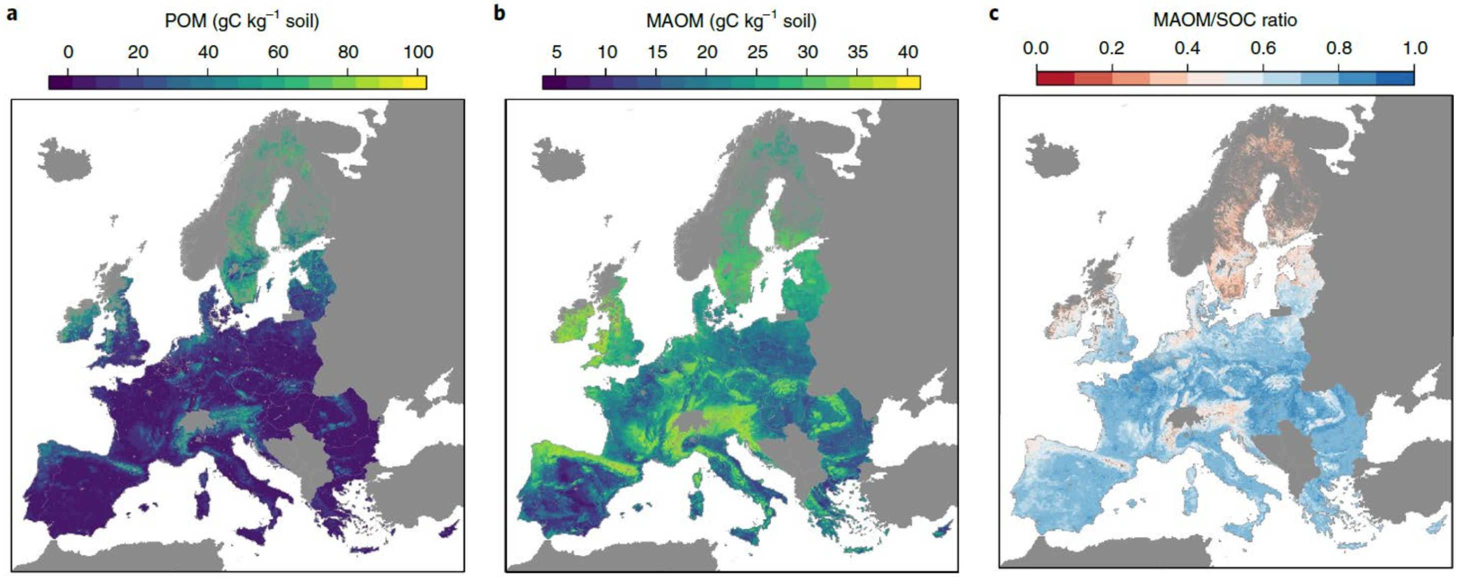


Lavallee et al., 2020

Increasing throughput of soil C measurements in POM and MAOM to bring understanding to scale



Use high-throughput soil C analytical approaches, such as FTIR (Ramirez et al.,2021)



Artificial Intelligence techniques to estimate C and fractions at large scale (Cotrufo et al., 2019, Lugato et al., 2021)

Production of isotopically labeled plant, exudate and pyOM for field and lab incubation

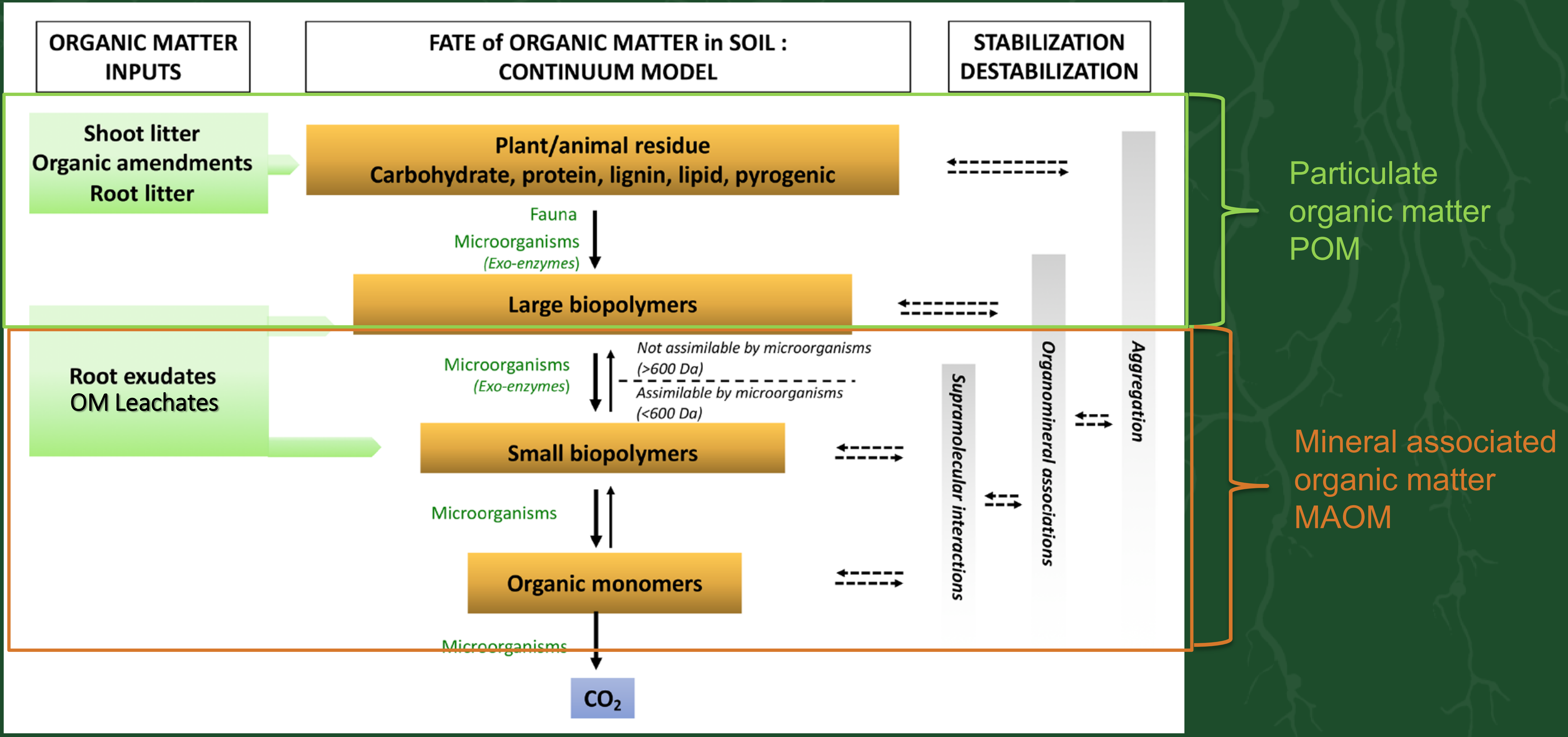
Soong et al., JoVE, 2013

What have we learned?

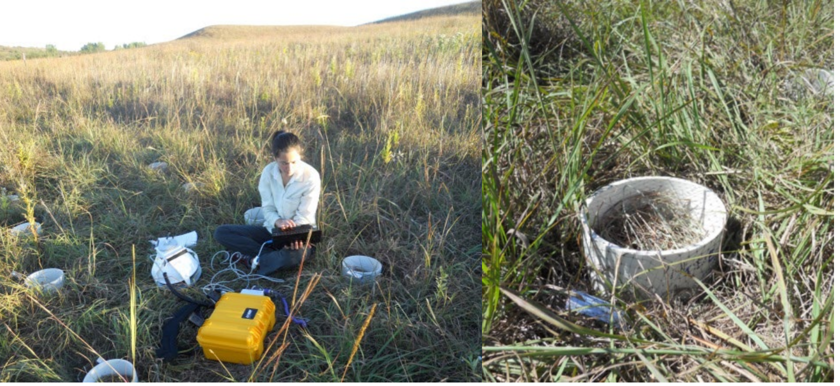
POM and MAOM formation and stabilization

Mechanisms and controls
of formation & stabilization

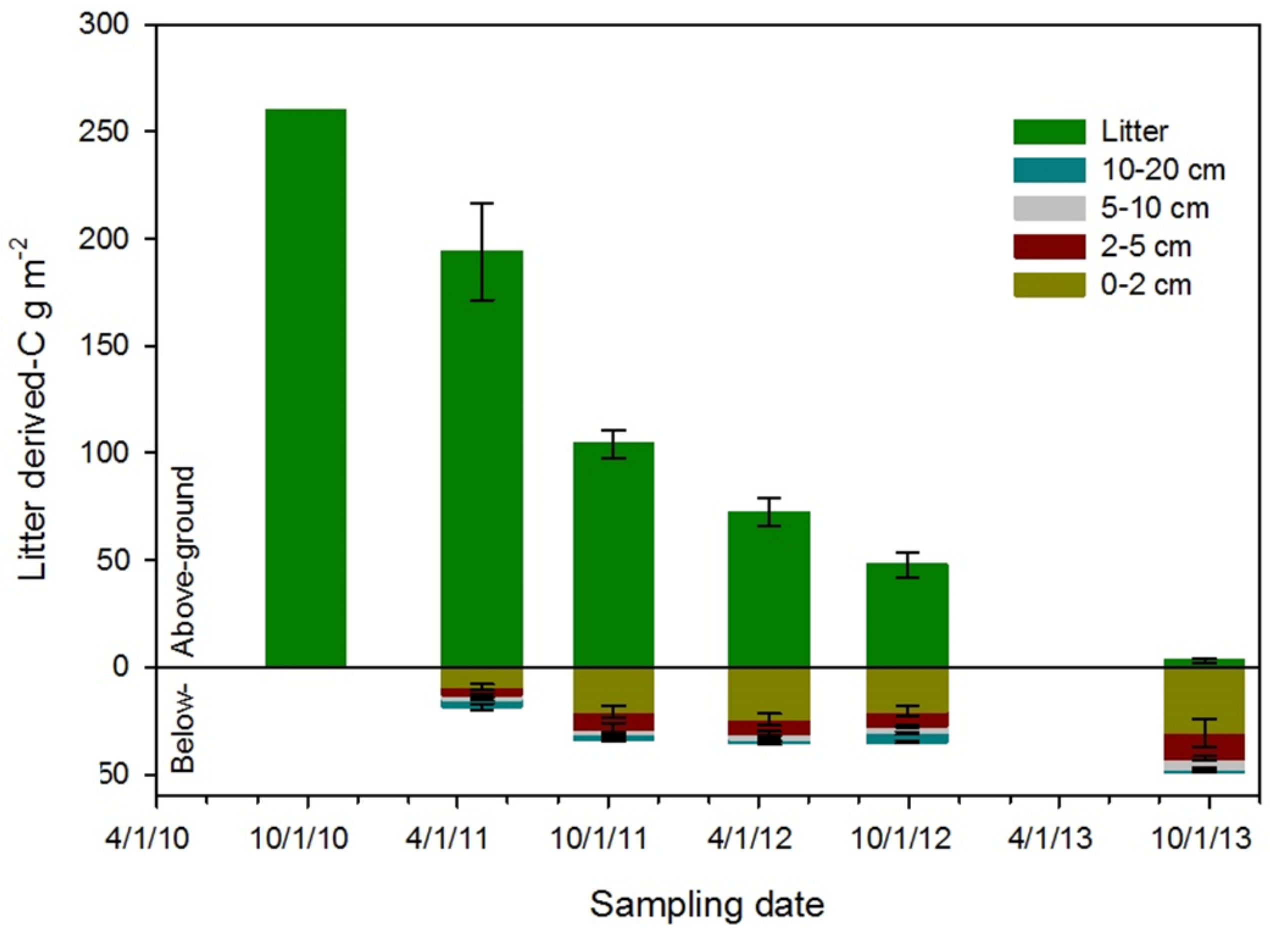
Soil Organic Matter forms from both structural and soluble inputs



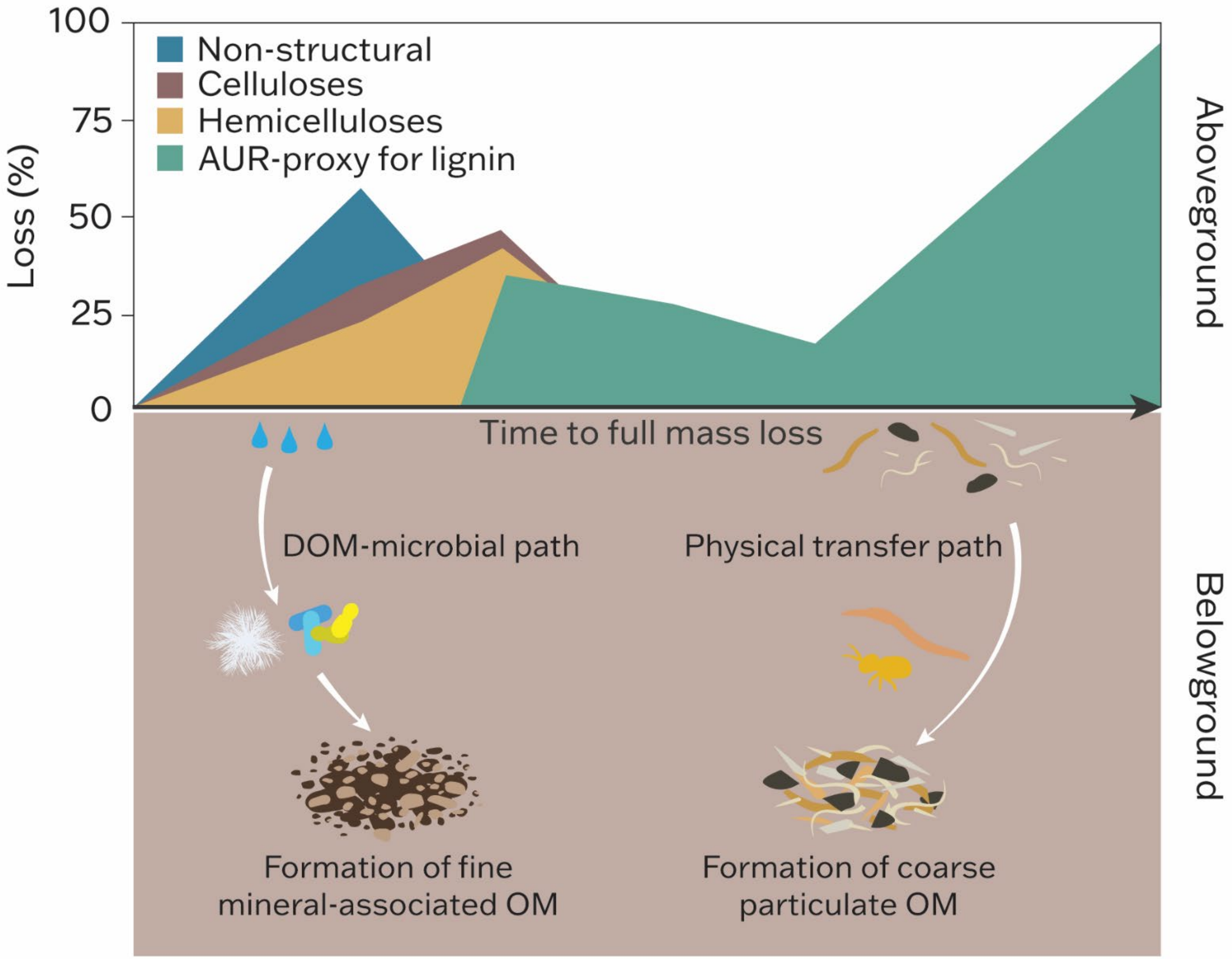
Basile-Doelsch et al., 2020, Cotrufo et al., 2015, Lehmann and Kleber, 2015,,



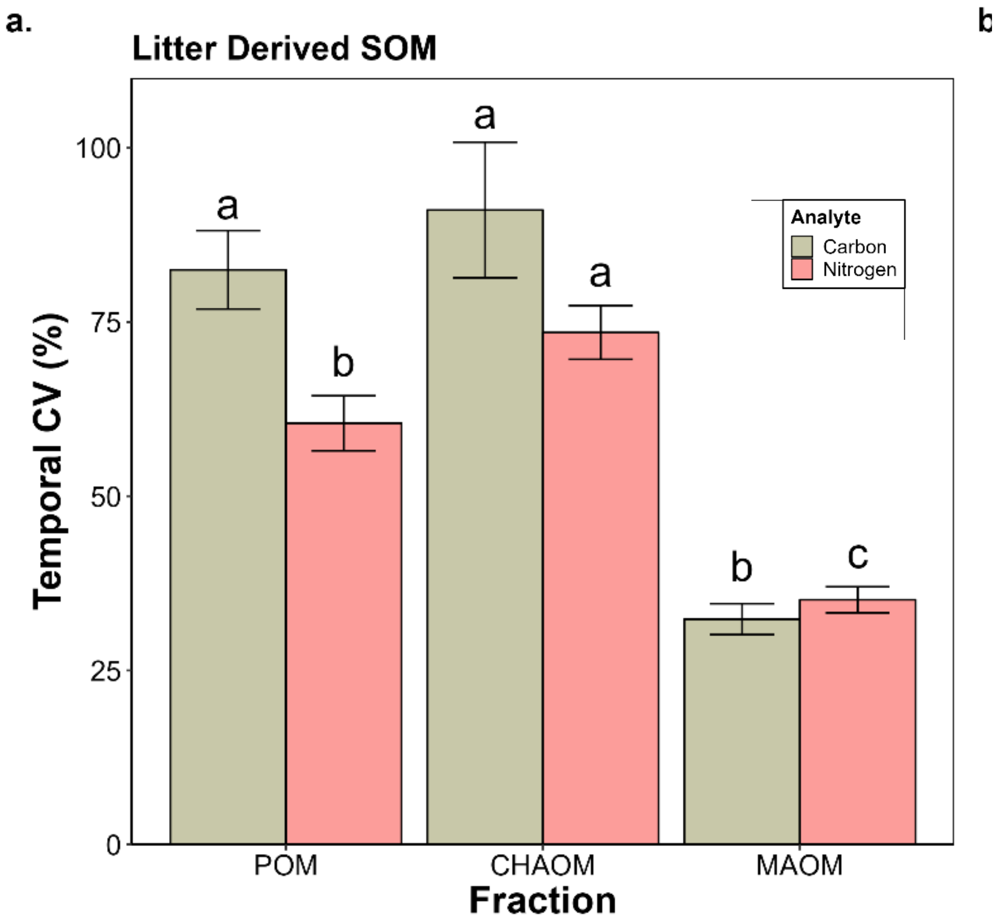
Two pathways of SOM formation



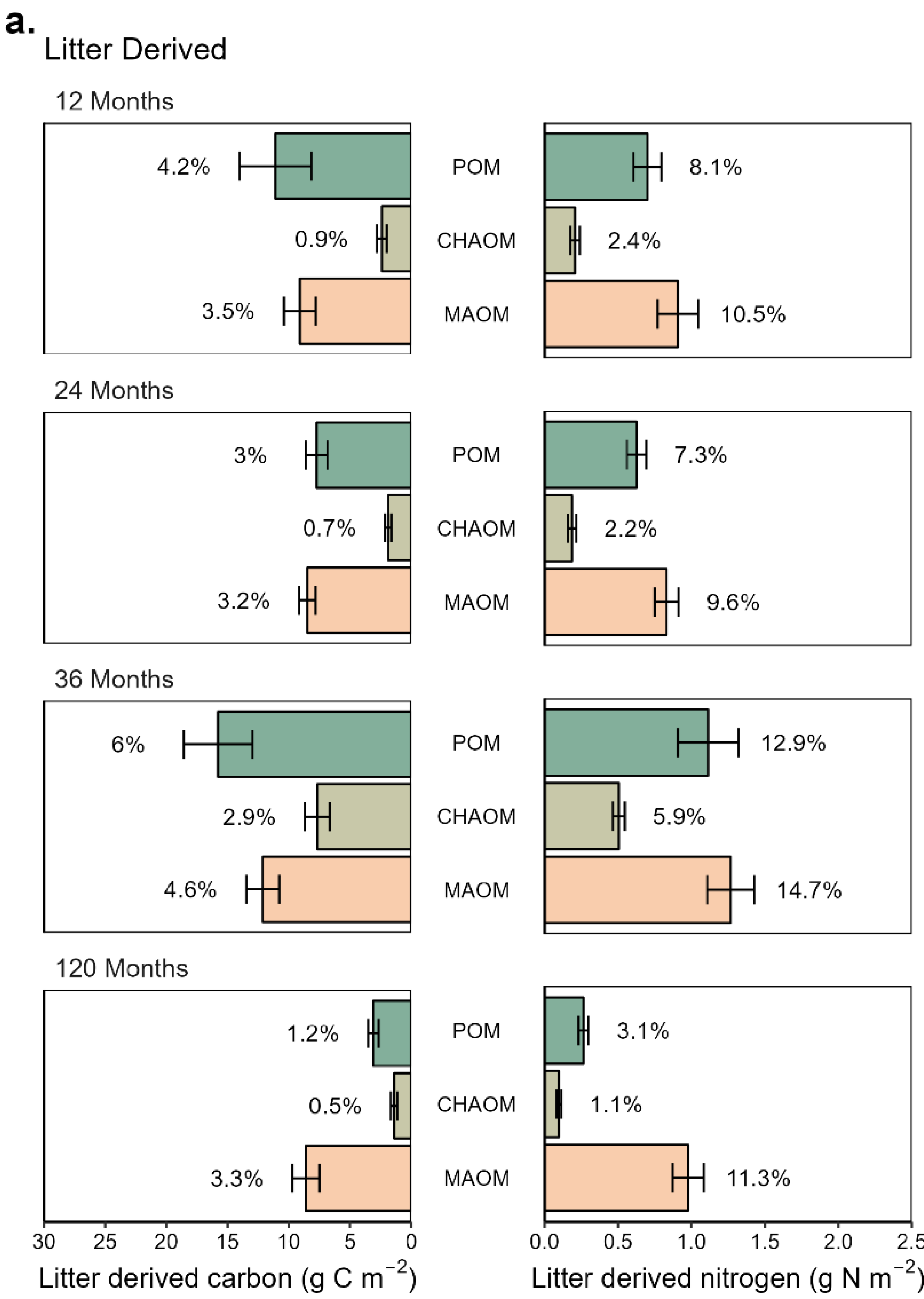
Cotrufo et al., *Nature Geoscience*, 2015



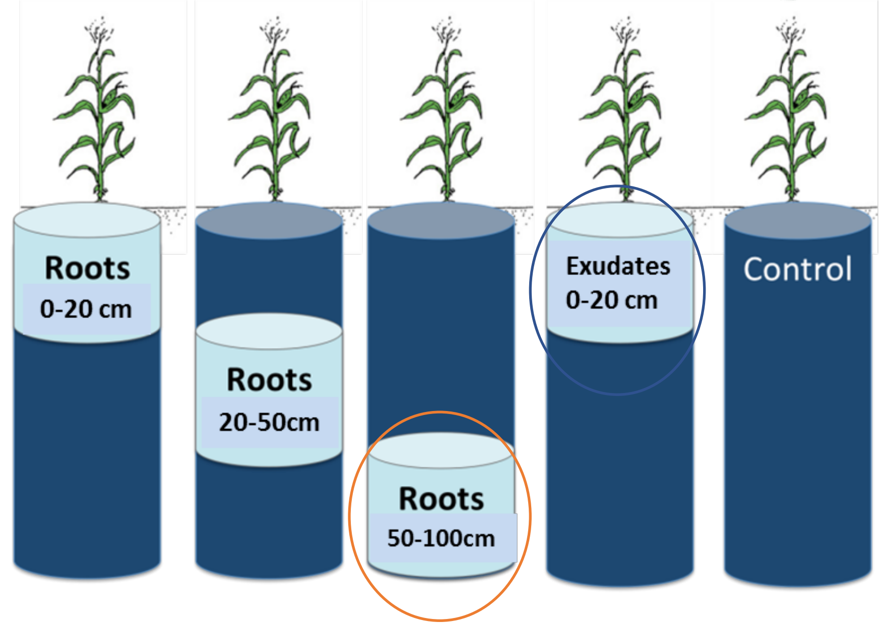
Two pathways confirmed after 10yr, with litter derived MAOM remained unchanged

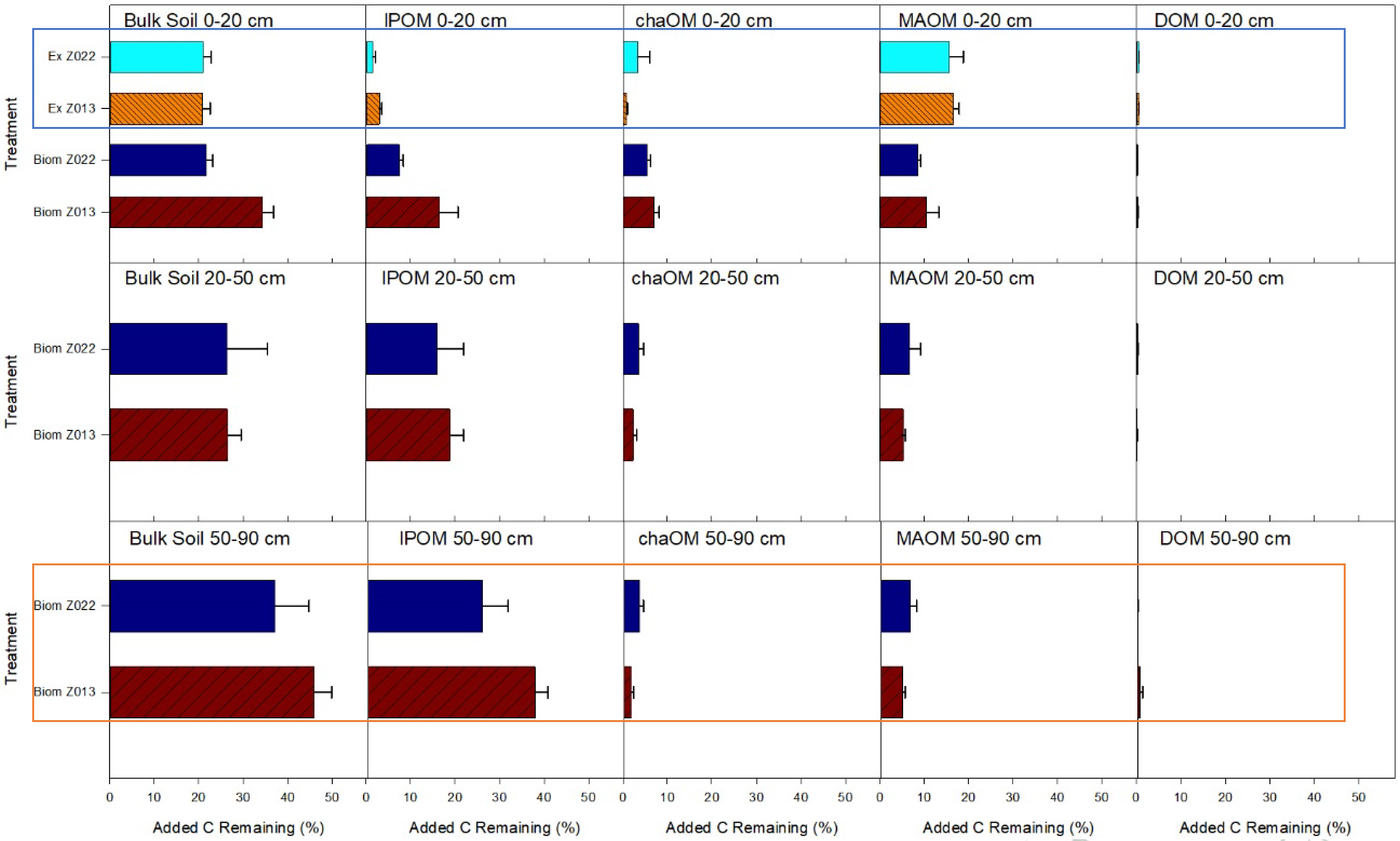


Leuthold et al., Nature geosciences, *in press*



The two pathways confirmed from mechanistic laboratory and field incubations in top and subsoil



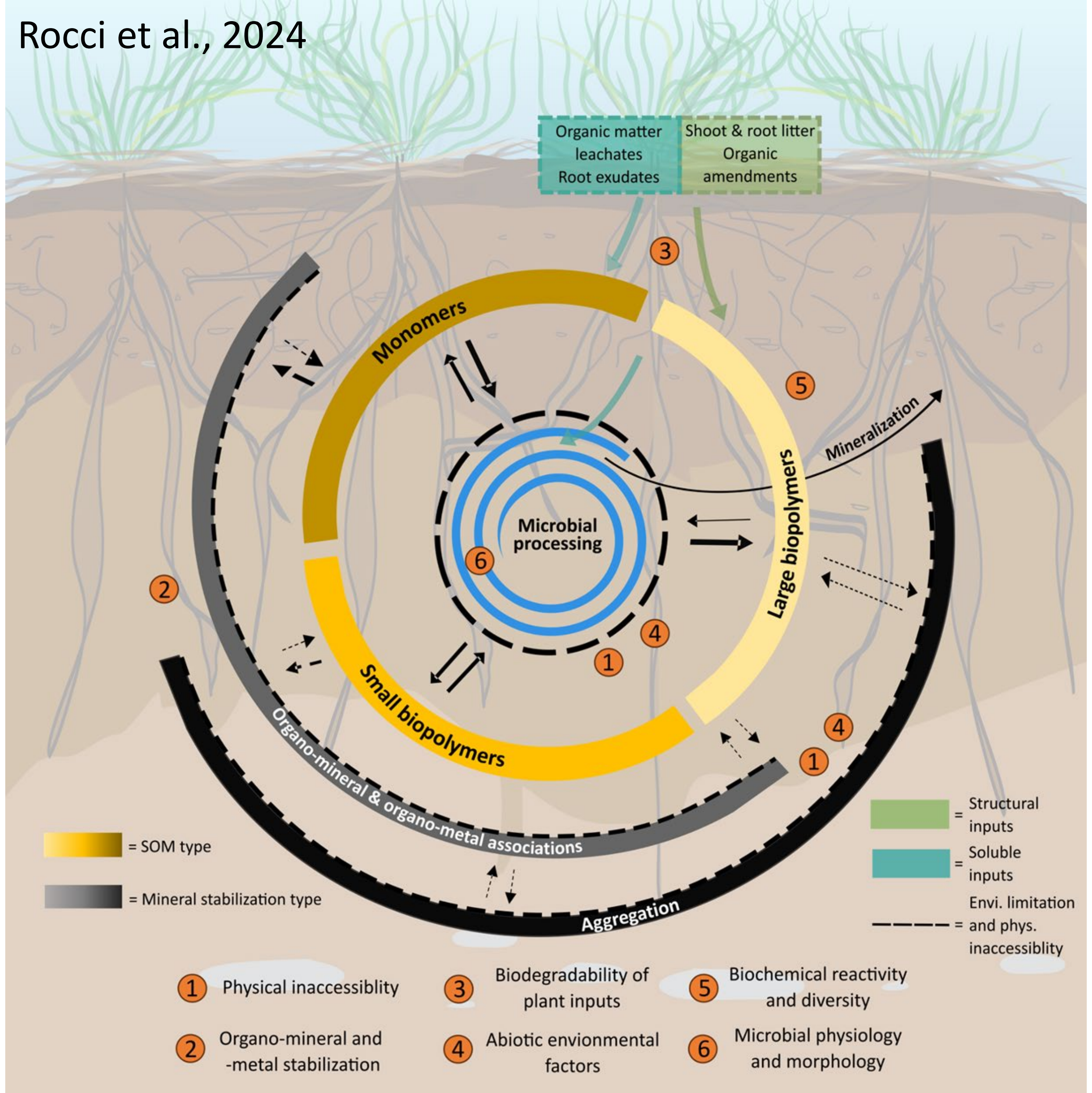


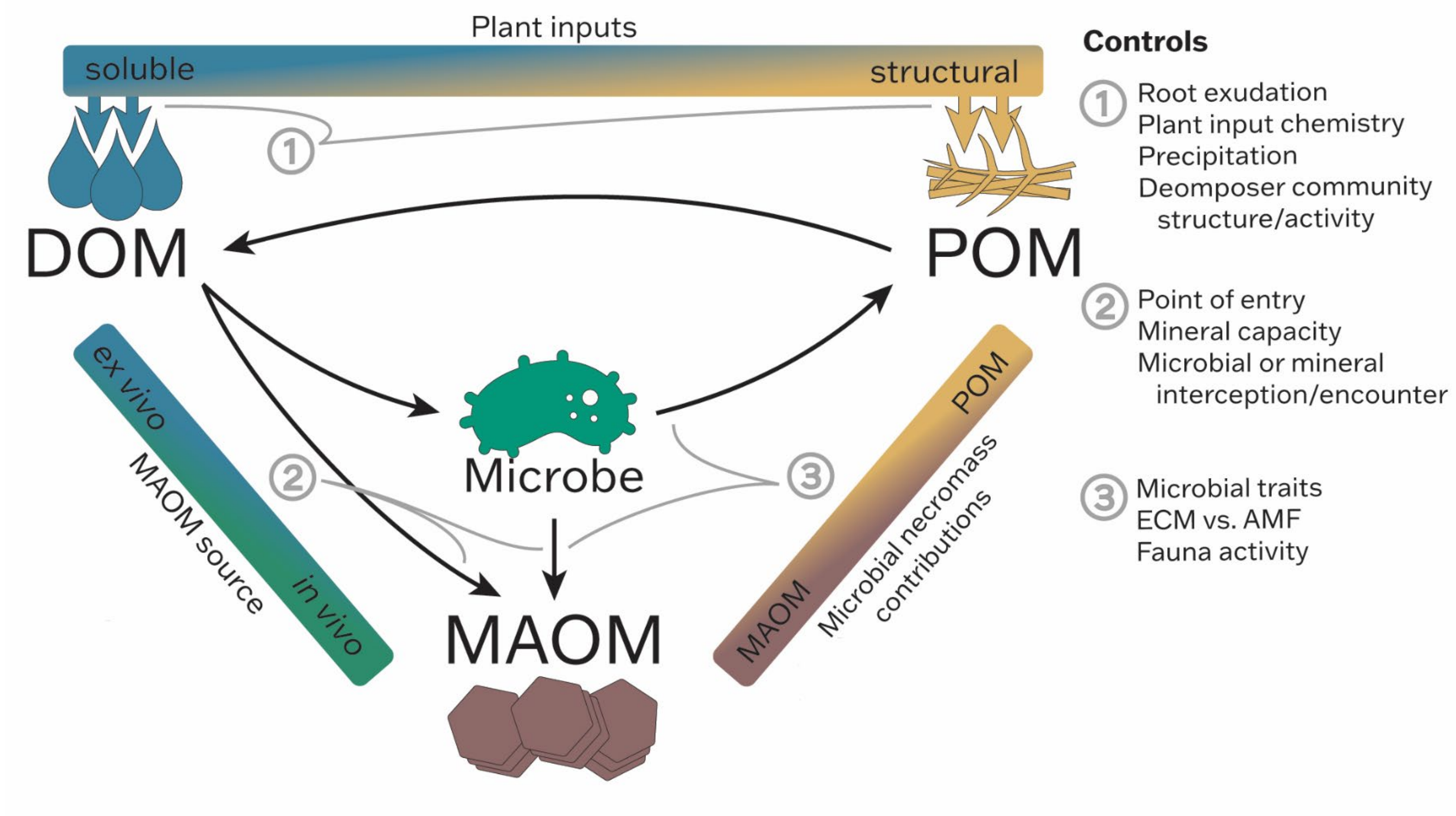
Plant and specifically roots structures contributes most to POM
Root exudates and other soluble inputs contributes most to MAOM
Formation efficiencies are typically around 20-30%, and increase significantly with depths

Cotrufo et al., GCB, 2024

Microbes are central drivers to the formation, turnover and stabilization of SOM

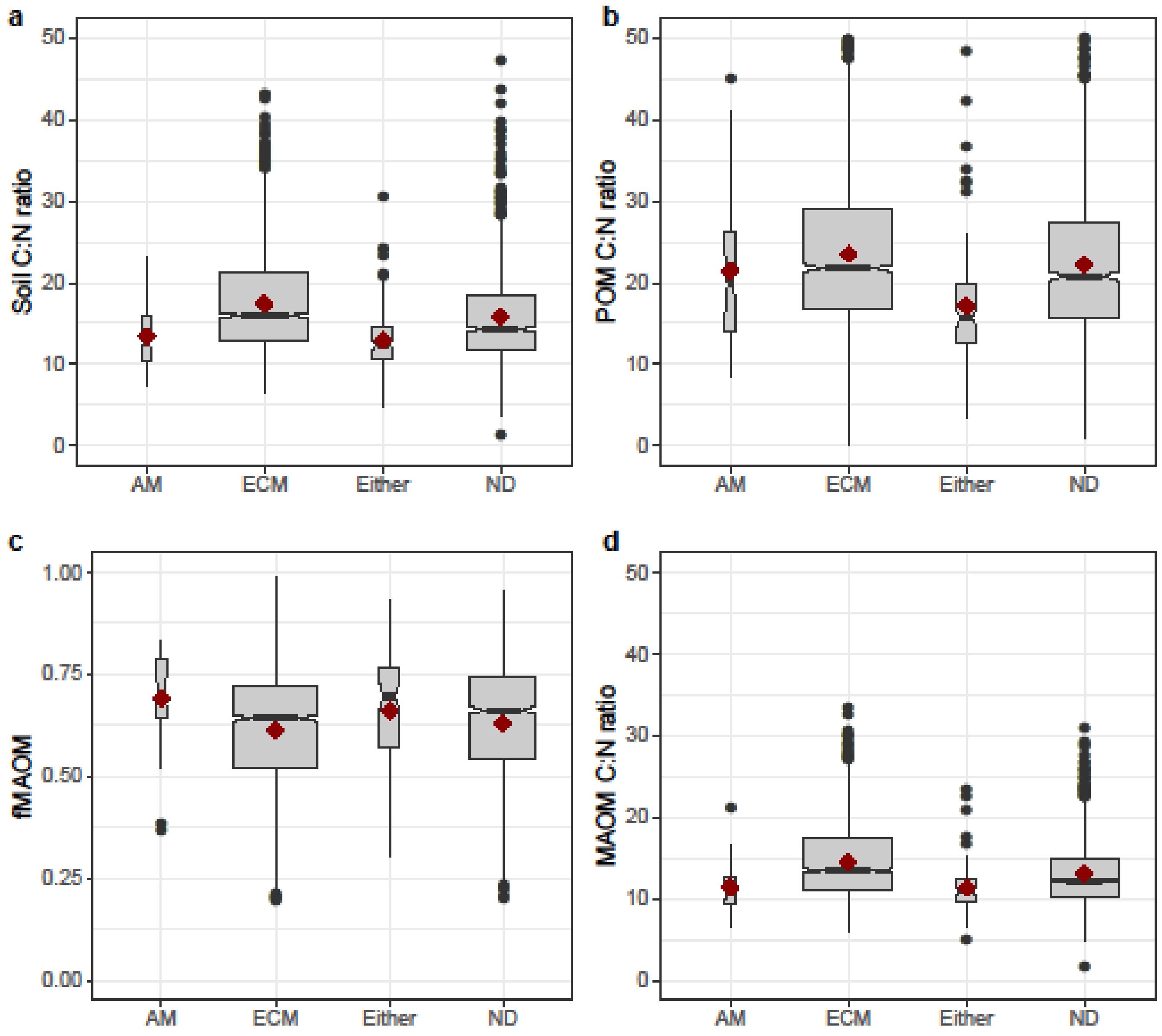
Rocci et al., 2024

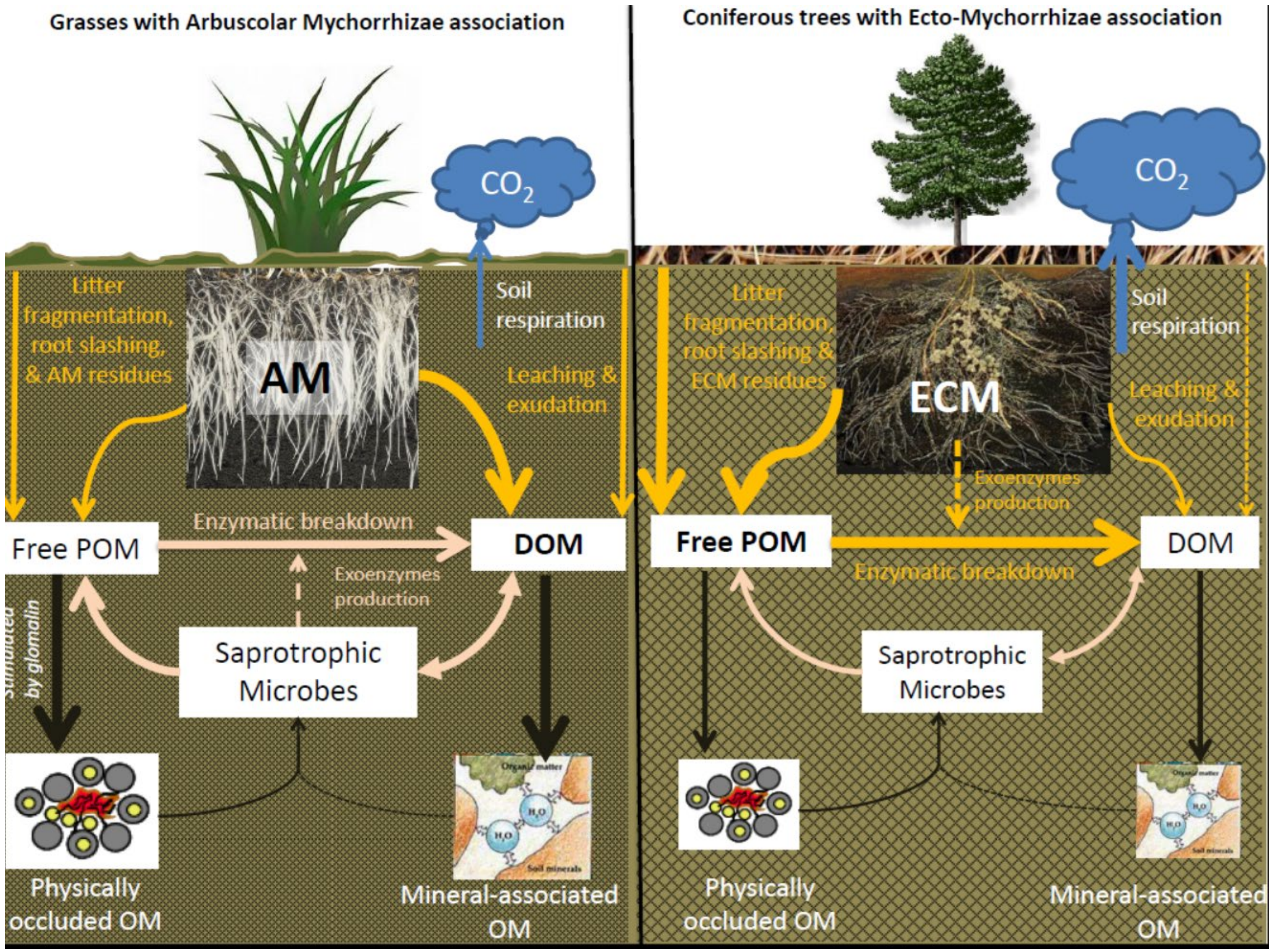




Cotrufo & Lavallee, 2022

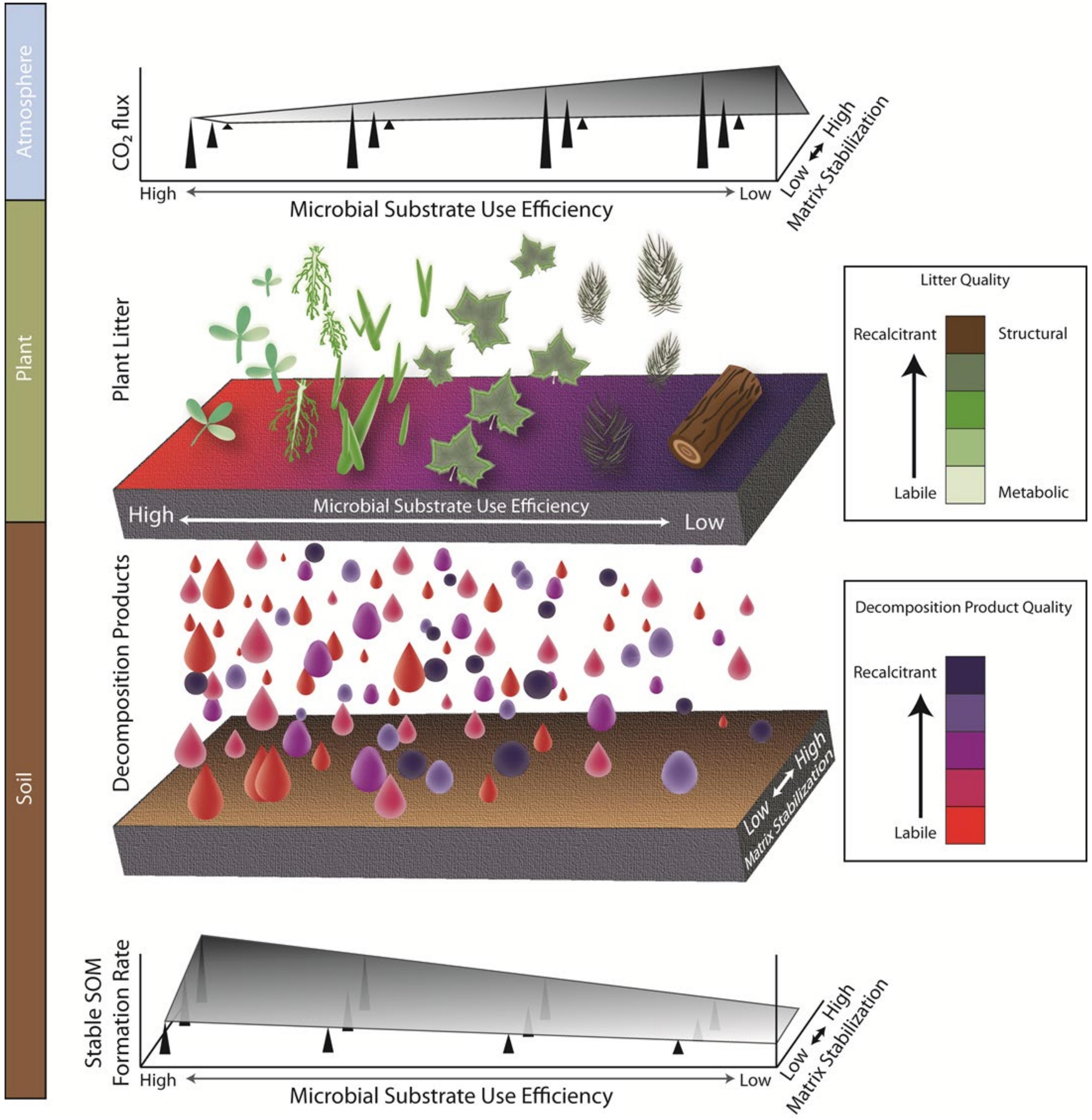
Mycorrhizas drive the relative abundance and C:N of MAOM and POM



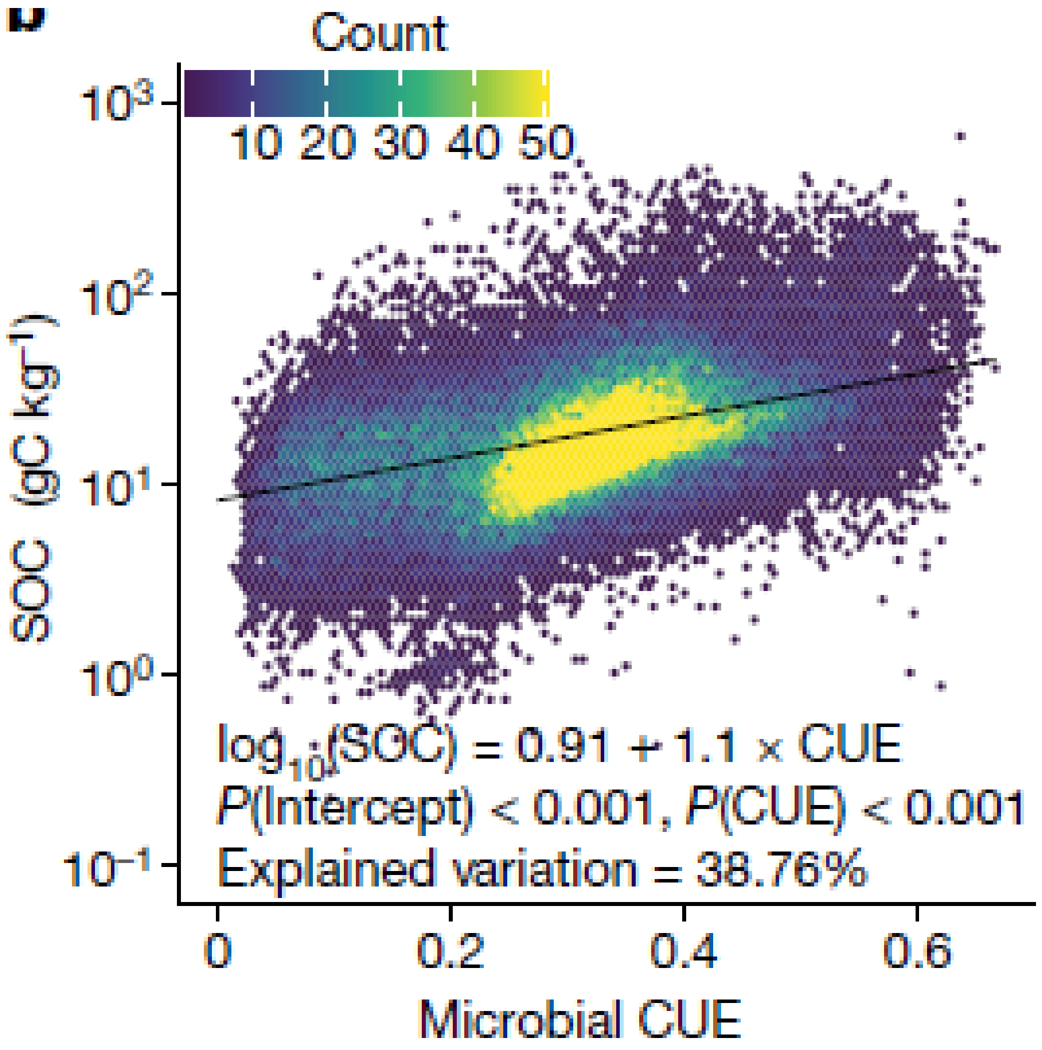


Cotrufo et al., 2019 Nature Geoscience

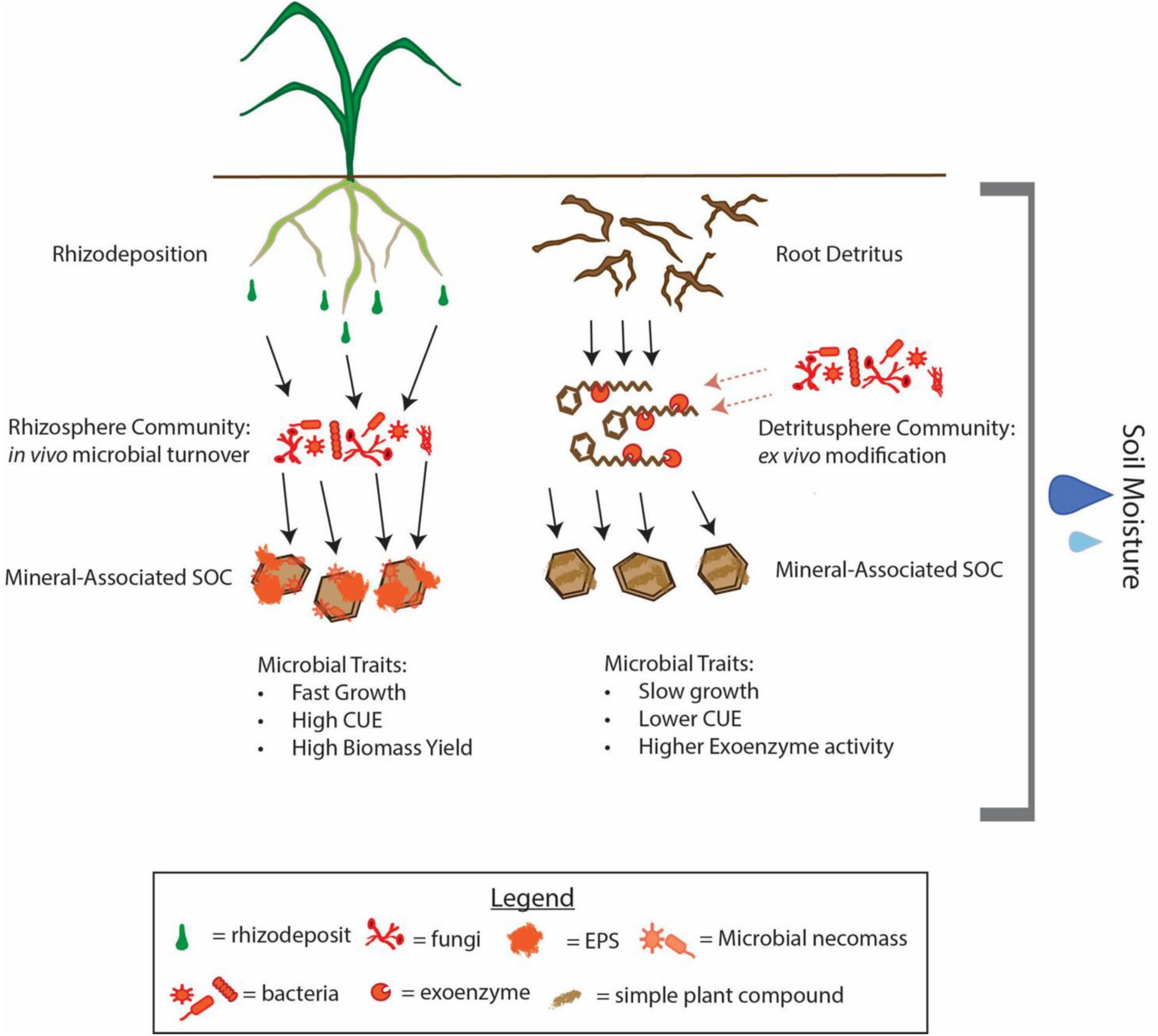
Microbial CUE



Cotrufo, et al., 2013



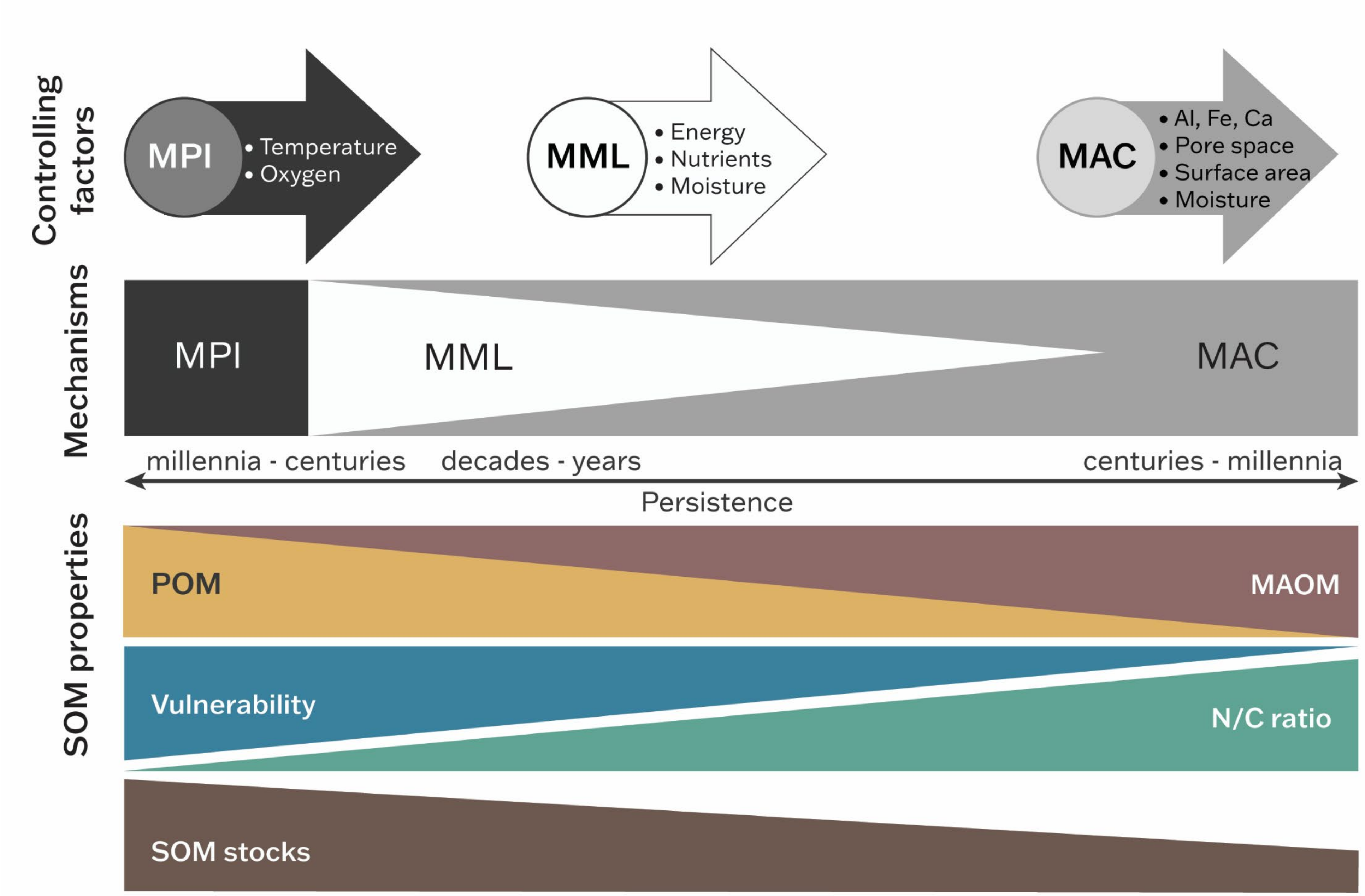
Feng et al., 2023



Habitat-specific microbial traits may shape MAOM formation

Sokol et al., 2024

Edaphic controls on microbial activity driving soil C dynamics

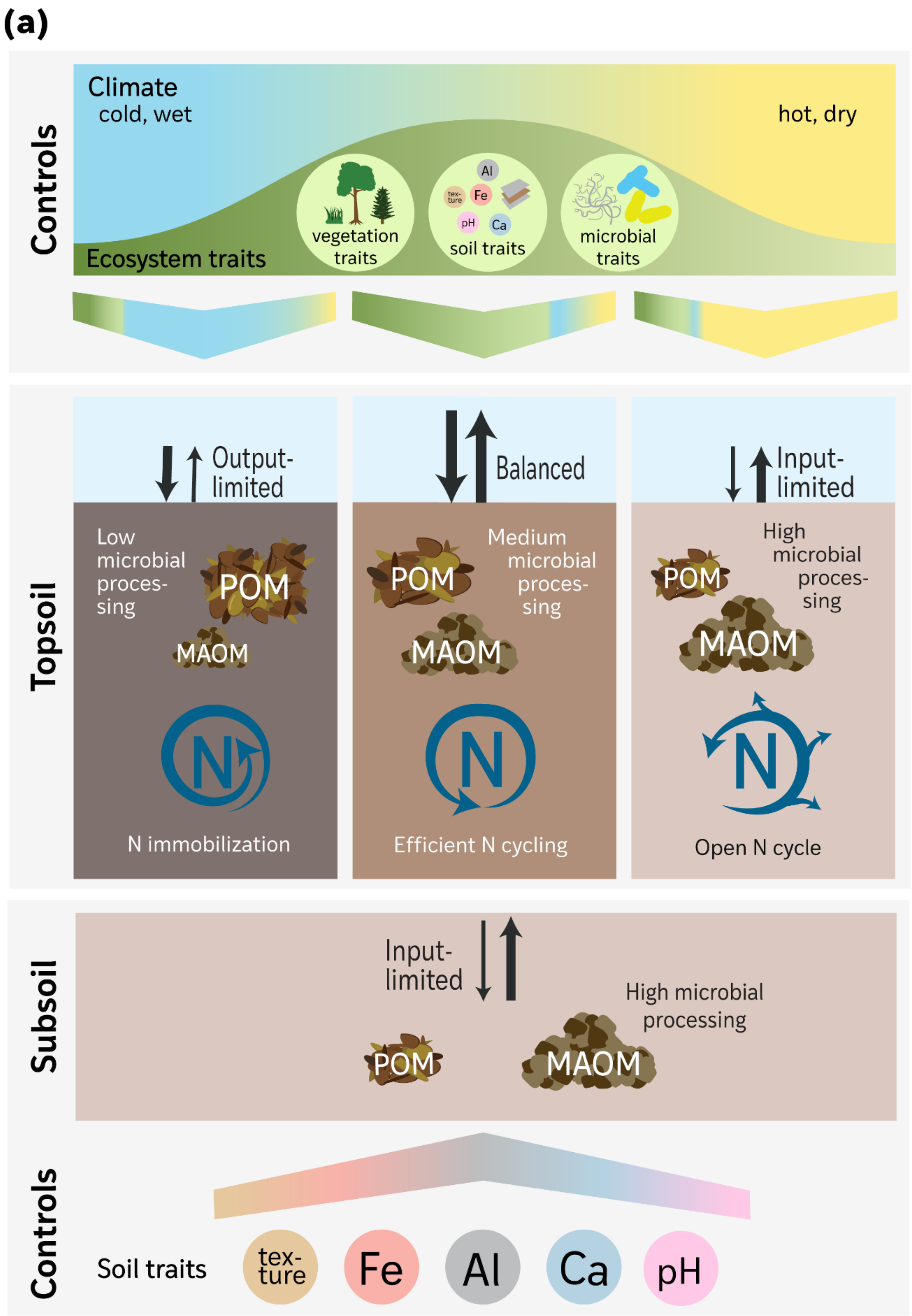


MPI = Microbial physiological Inhibition

MML = Microbial Metabolic Limitation

MAC= Microbial Access Constraint

Cotrufo & Lavallee, 2022
Advances in Agronomy Vol 172

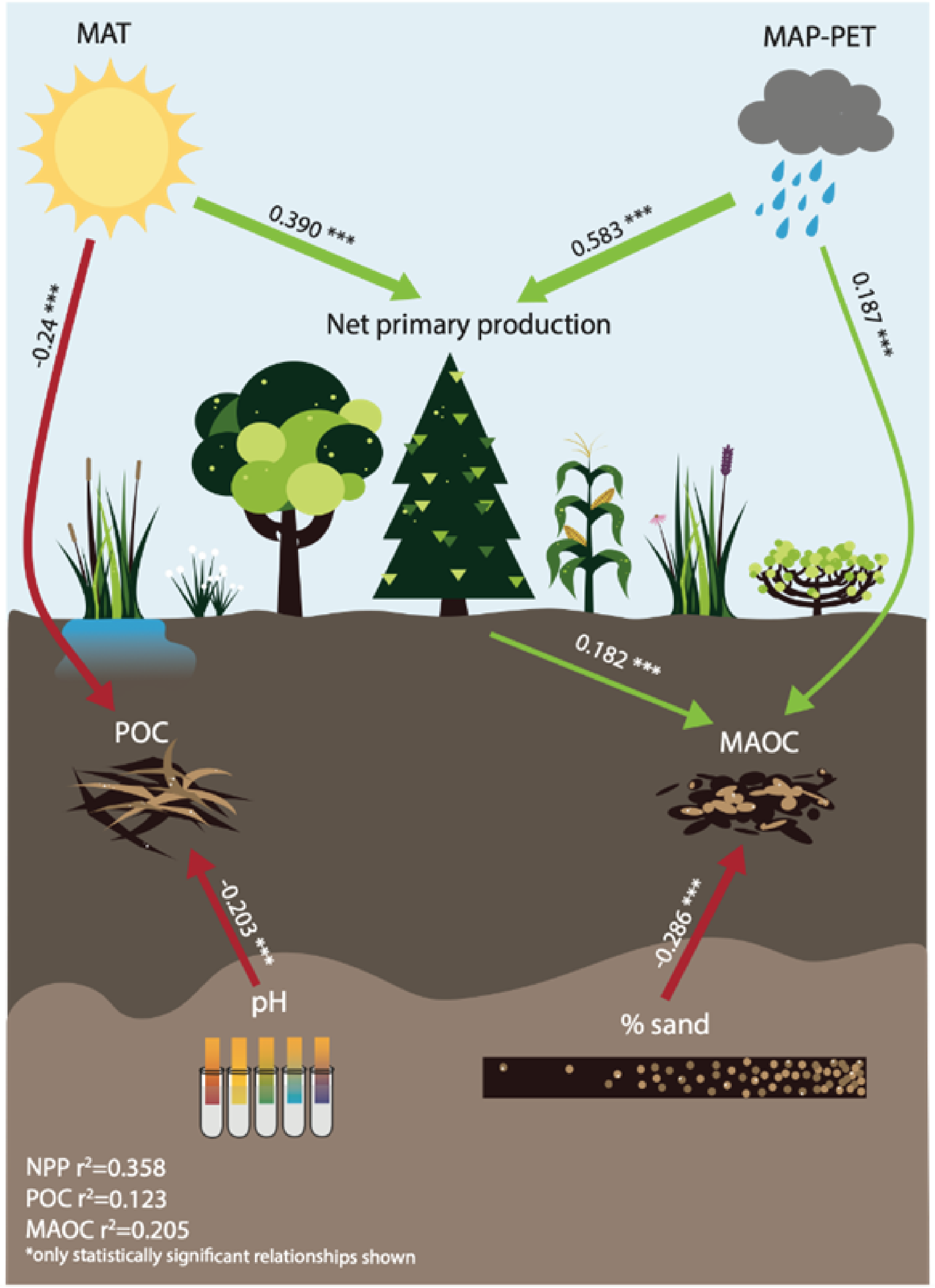


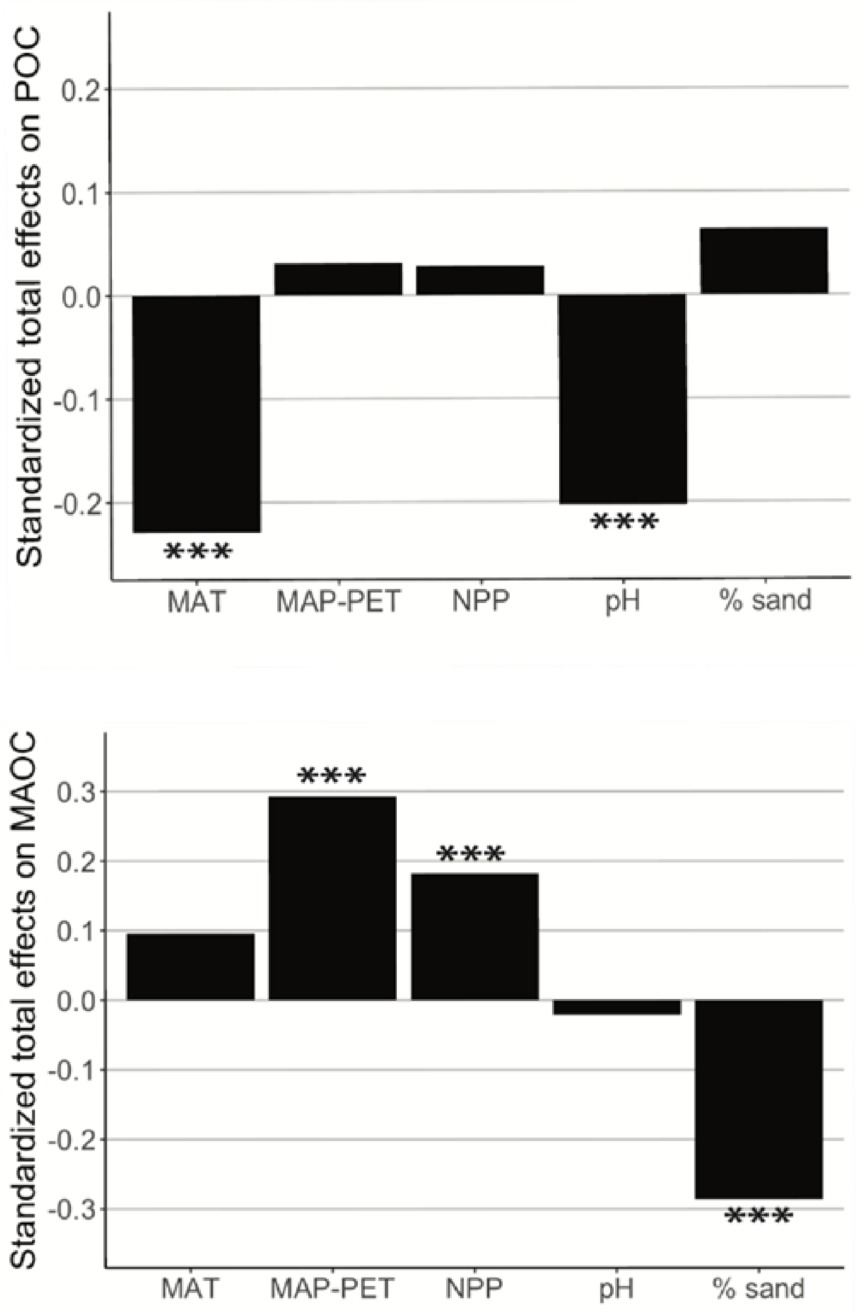
The In-N-out framework to determine a structure of controls of soil C and N

Integrating plants

with microbial responses

Cotrufo et al., 2021





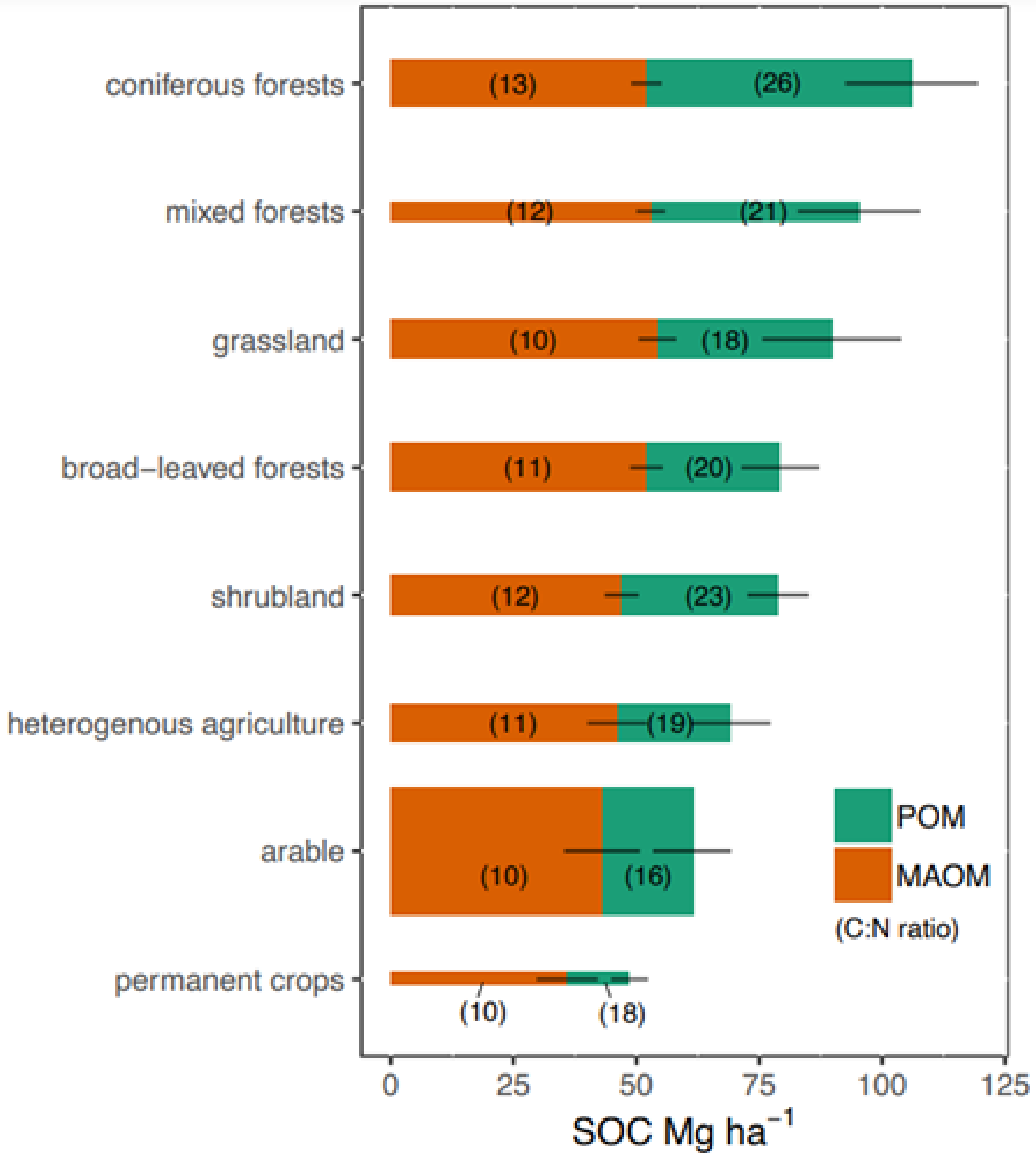
Hansen et al., GCB, 2023

POM and MAOM have different structures of controls

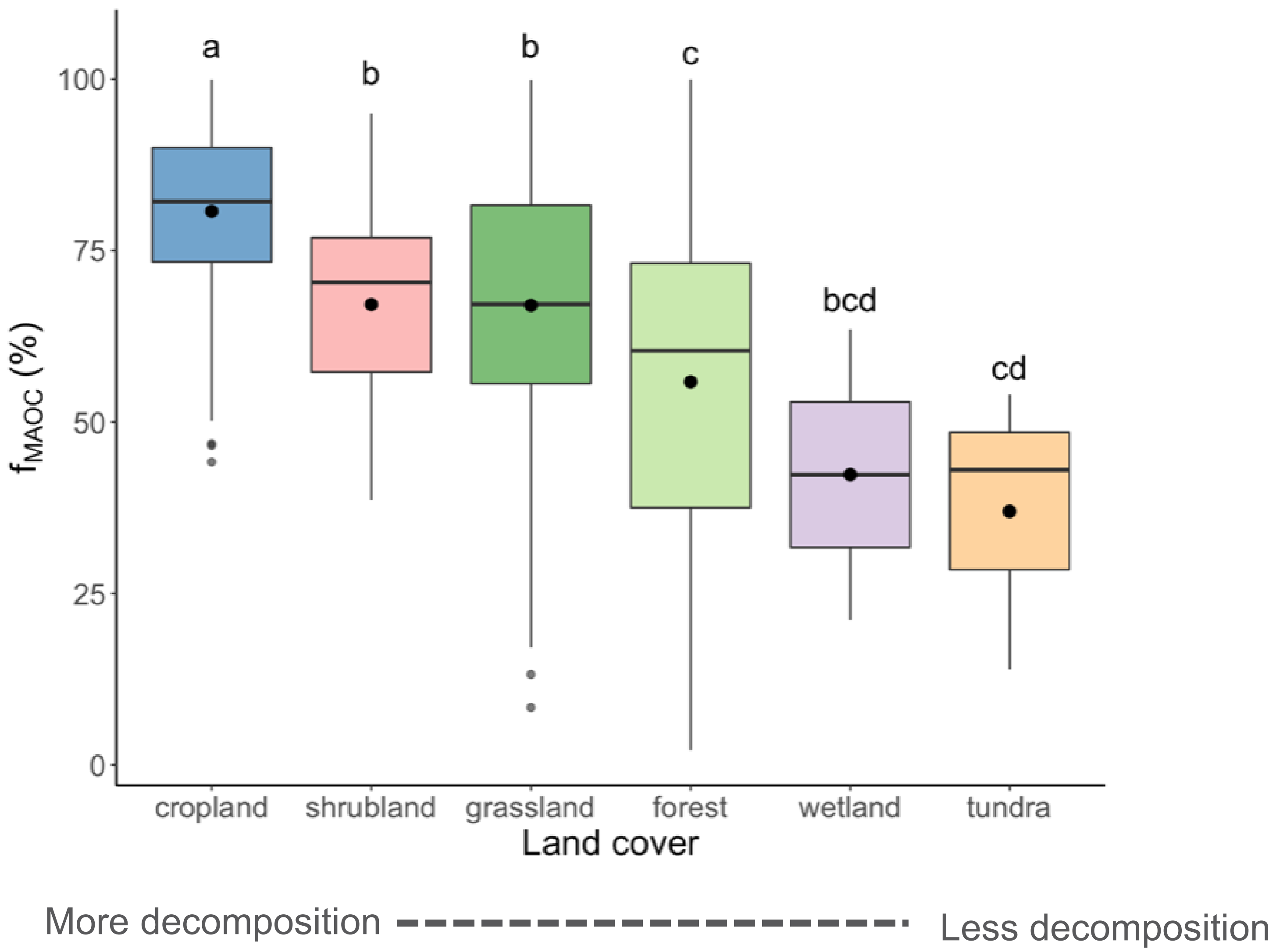
POM is controlled by constrains on decomposition and MAOM by constrains on inputs and soil ability to stabilize

However, only a small component of the variability is explained by this Path analyses

Carbon Stock distribution differs across ecosystems

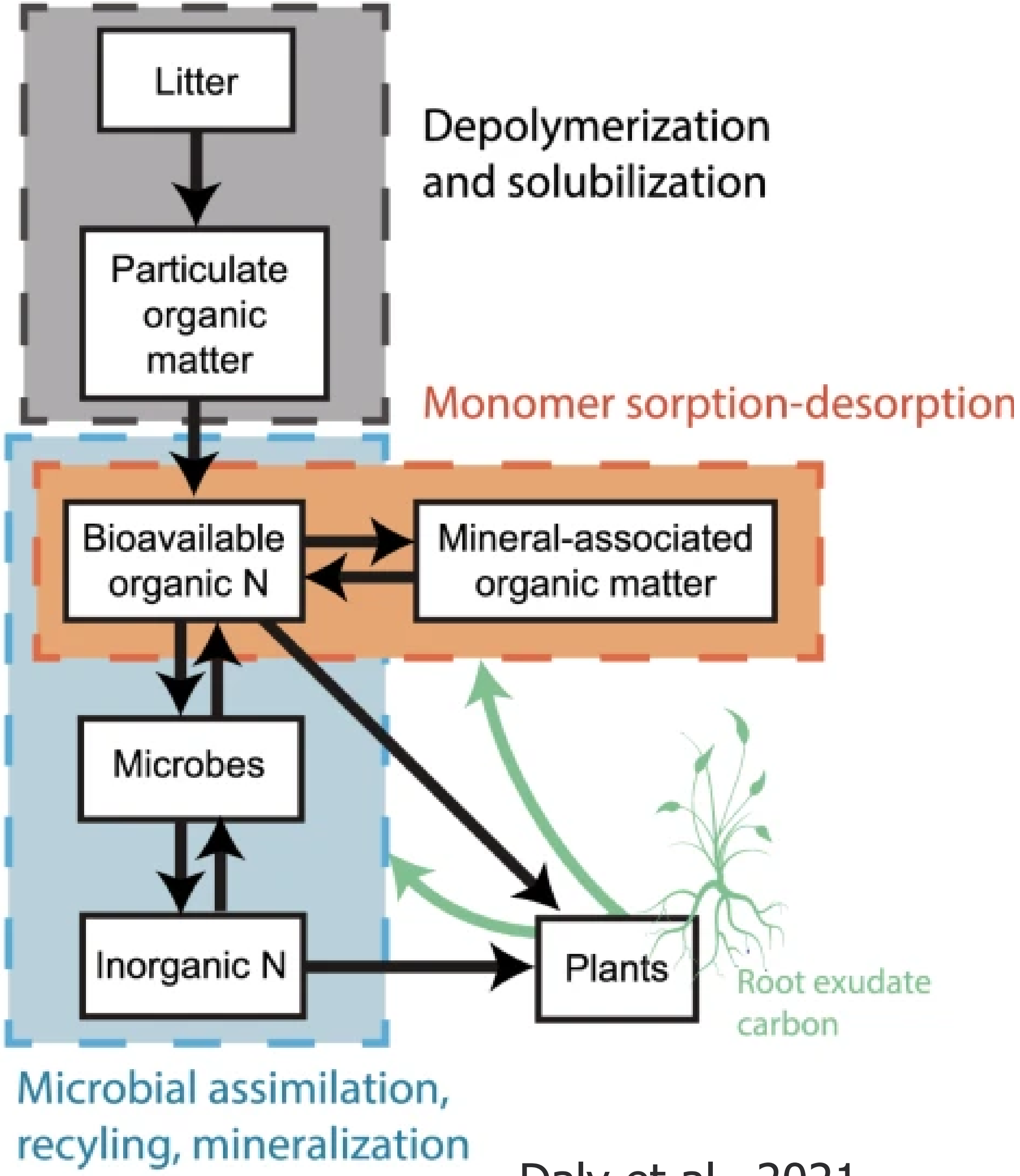


Lugato et al., Nature Geoscience. 2021

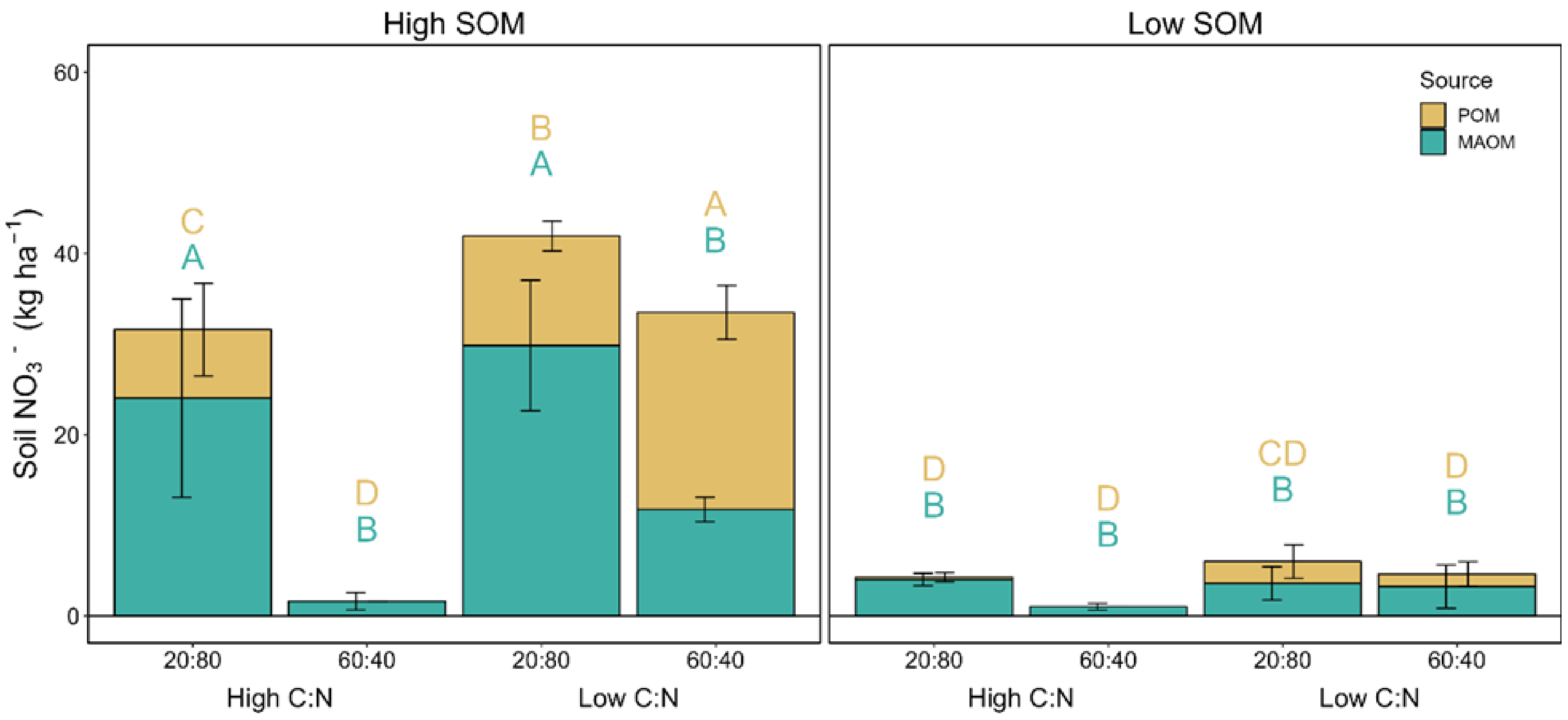


Hansen et al., GCB, 2023

The distribution of SOM between POM and MAOM may affect soil N dynamics



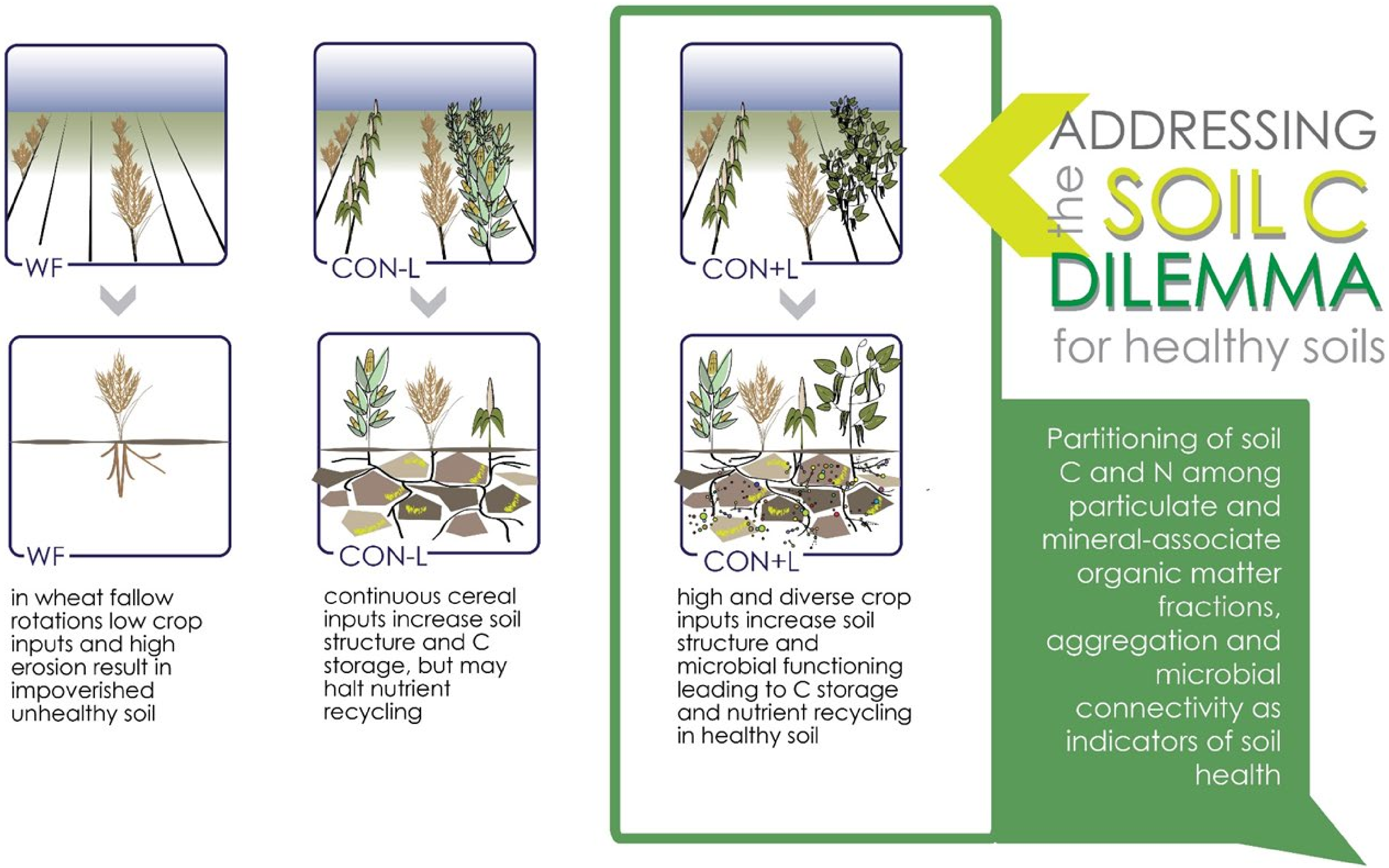
Daly et al., 2021



Leuthold, CSU PhD Dissertation, 2024

Using the POM vs MAOM framework

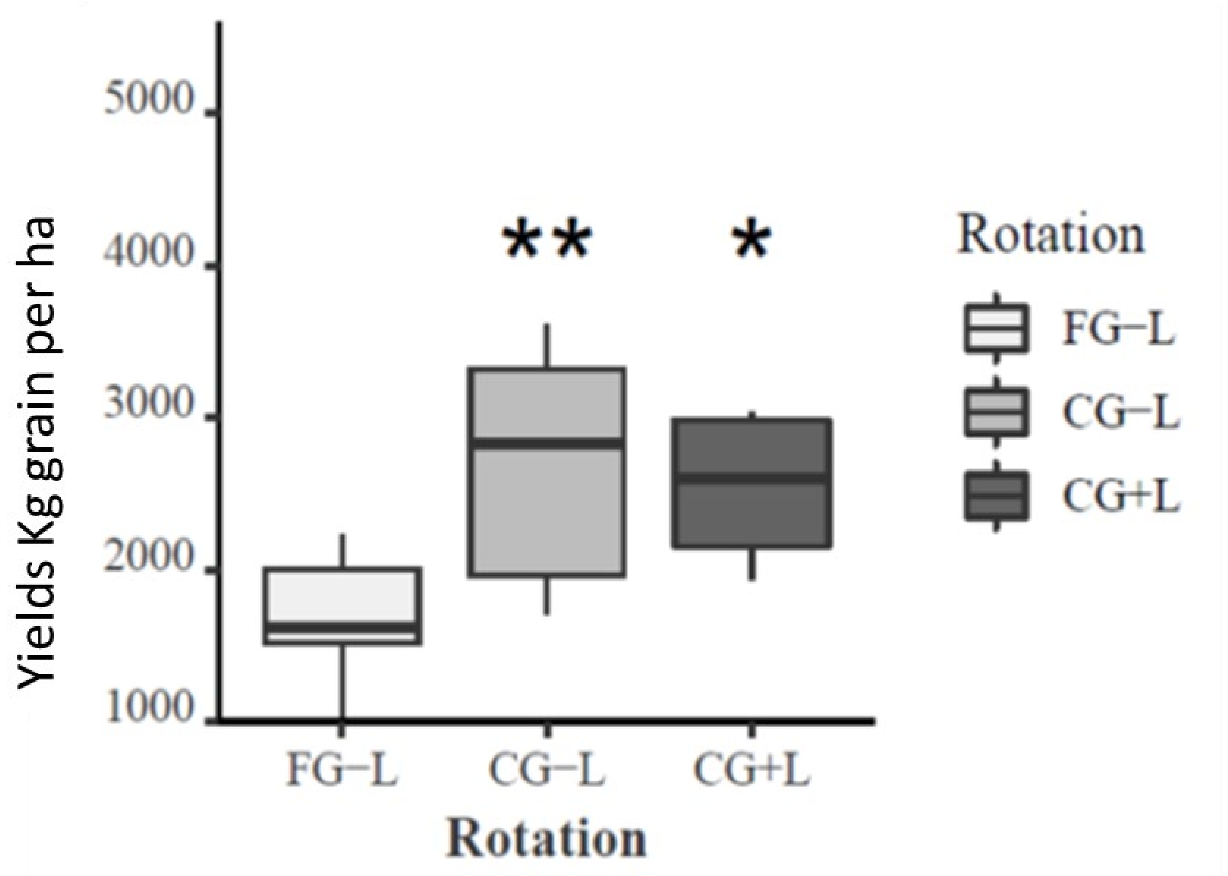
Management Solutions

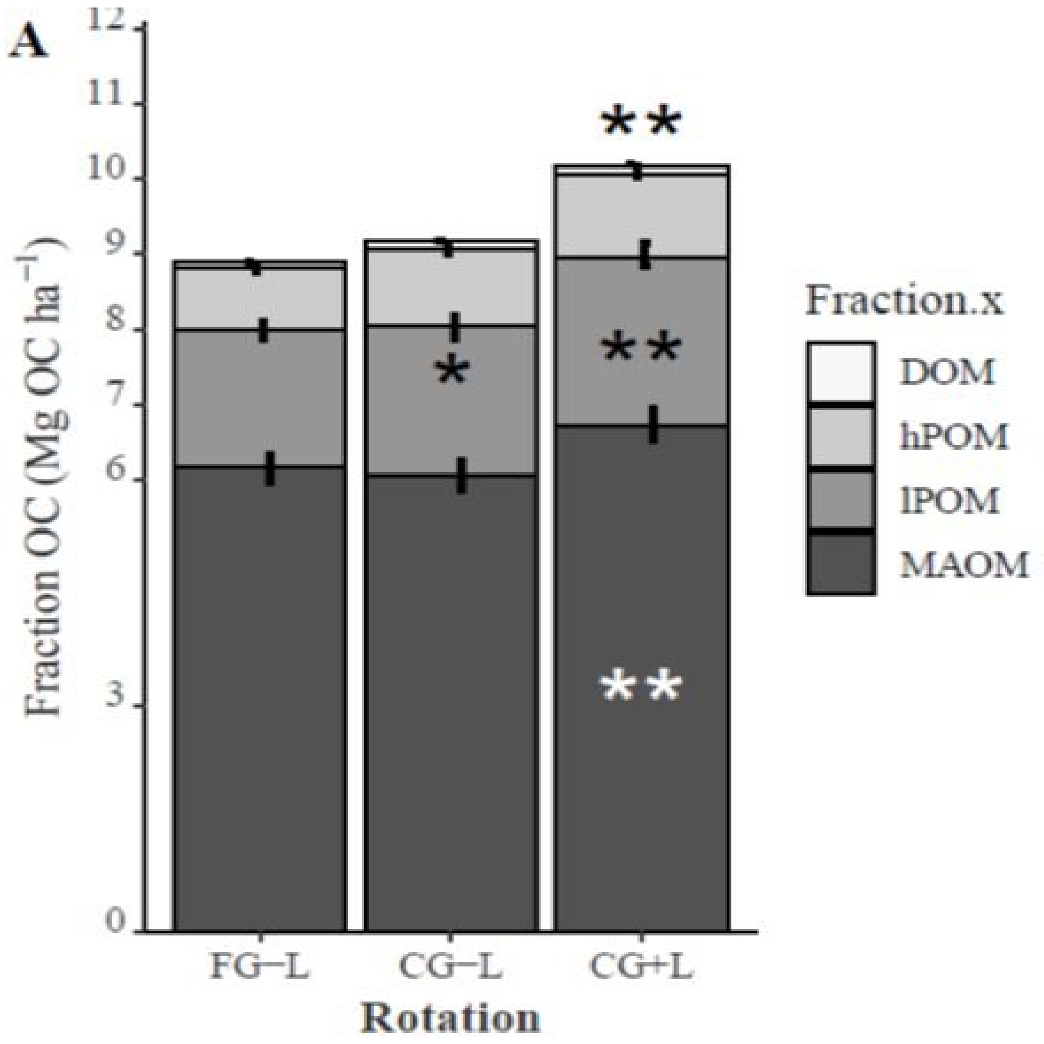


Intensification and Diversification of Dryland Cropping System by the addition of legumes can Sustain Productivity while Increasing Soil Carbon

Van der Pol et al., 2021

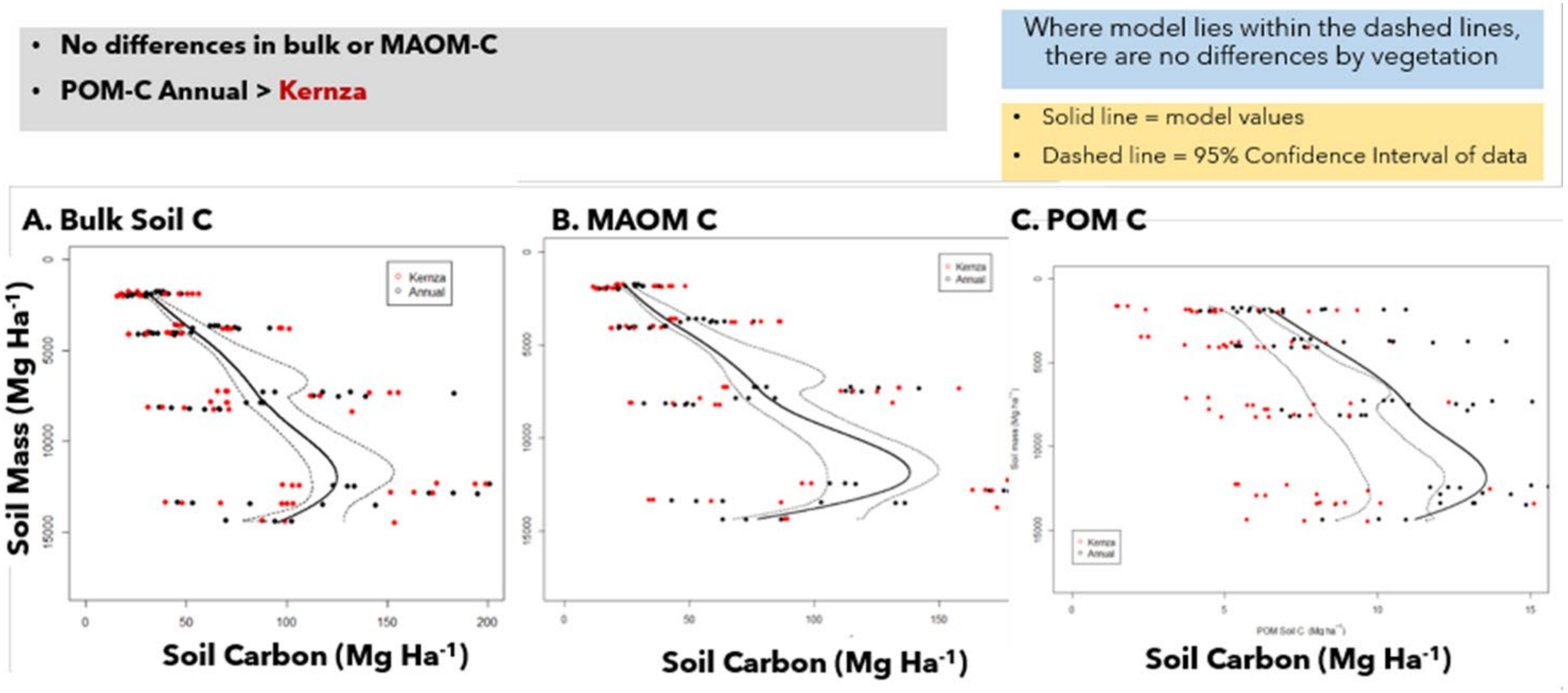
Cropping intensification and diversification with the addition of a legume cash crop increased SOC and cumulative crop production





Van der pol et al., AEE, 2022

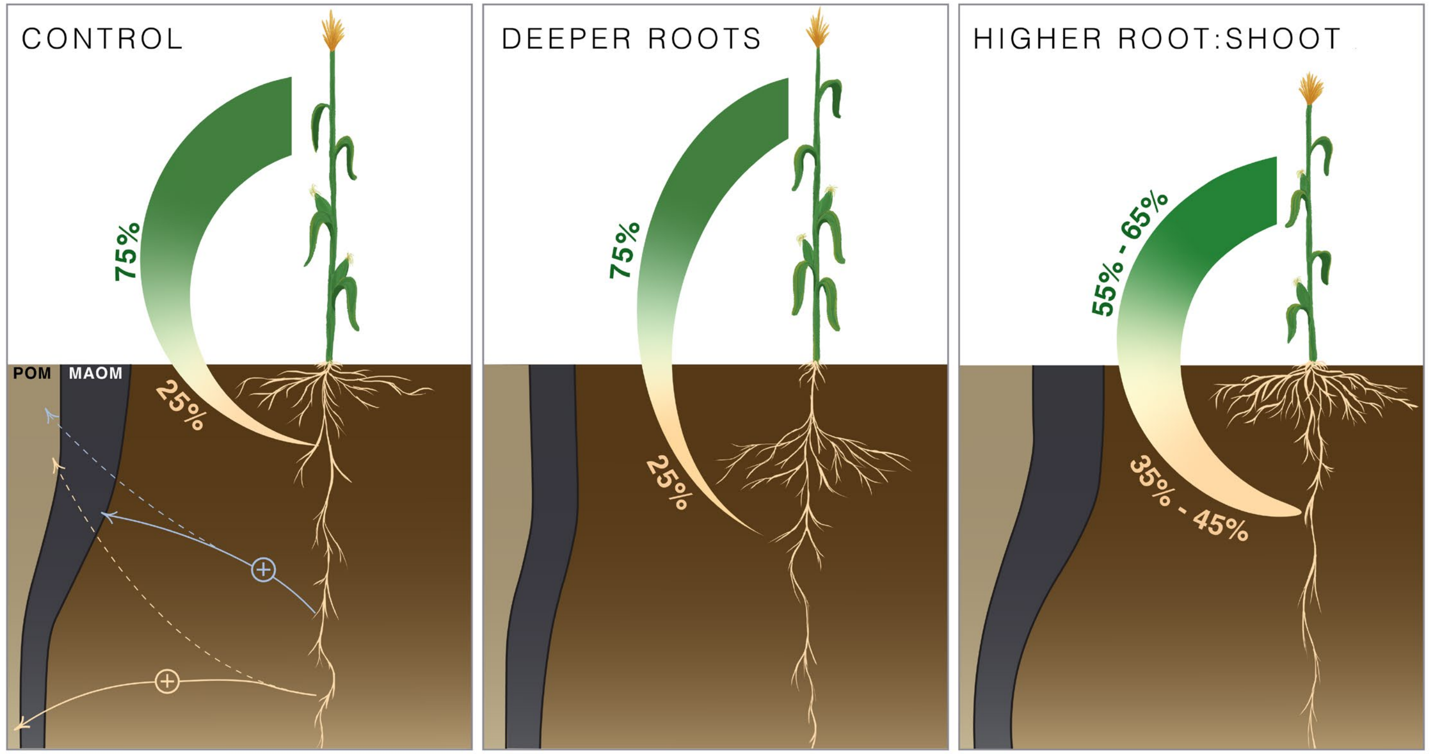
Can using perennial crops increase soil C?



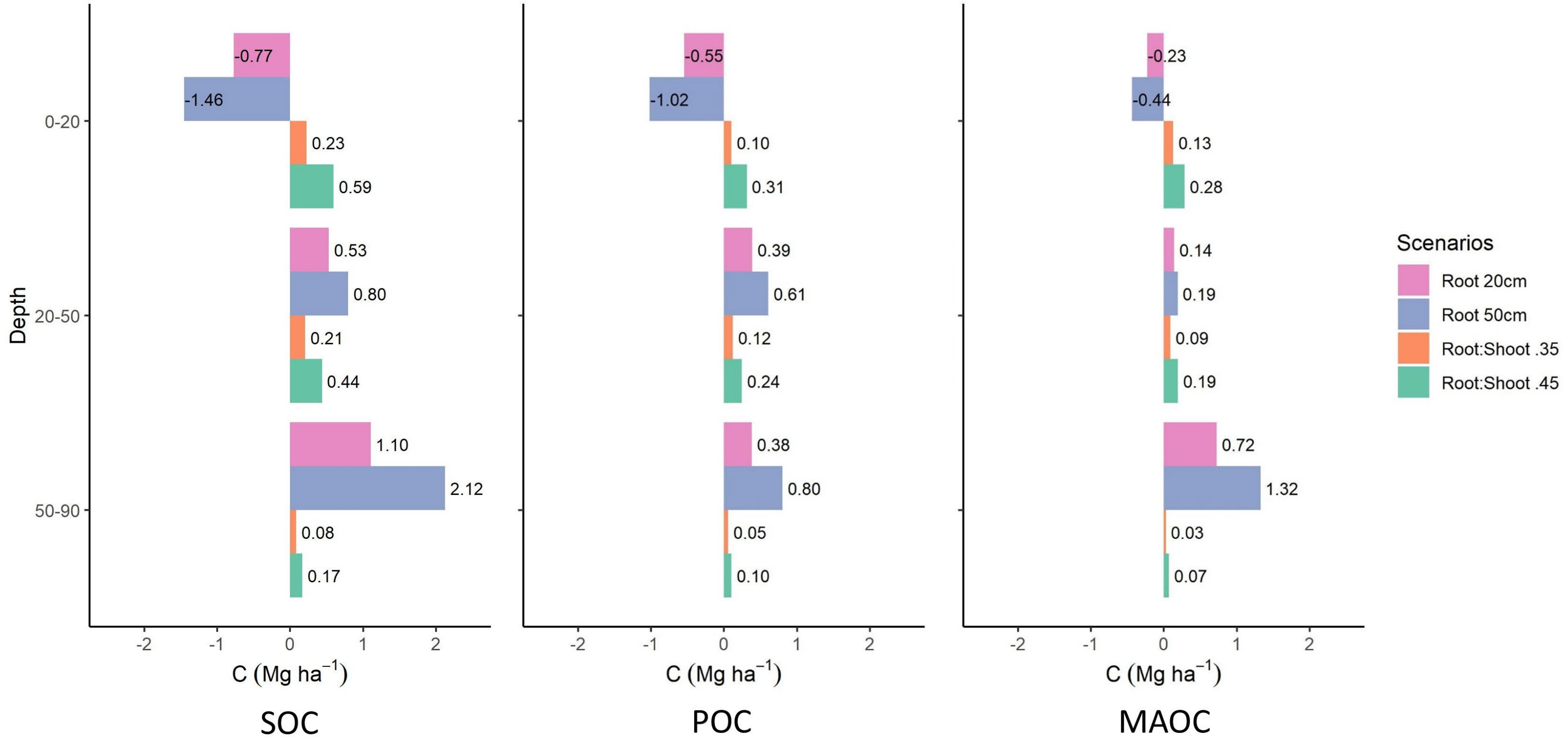
Van der Pol et al., 2022

Deepening root inputs:

POTENTIAL SOIL CARBON ACCRUAL FROM BREEDING FOR DEEPER ROOTED MAIZE



Shifting root inputs to deeper layer or increasing NPP allocation to roots resulted in only marginal increases in SOC,
ranging from 0.05 to 0.15 Mg C ha^{-1} per year across the full soil profile, with slight SOC decreases in the topsoil.



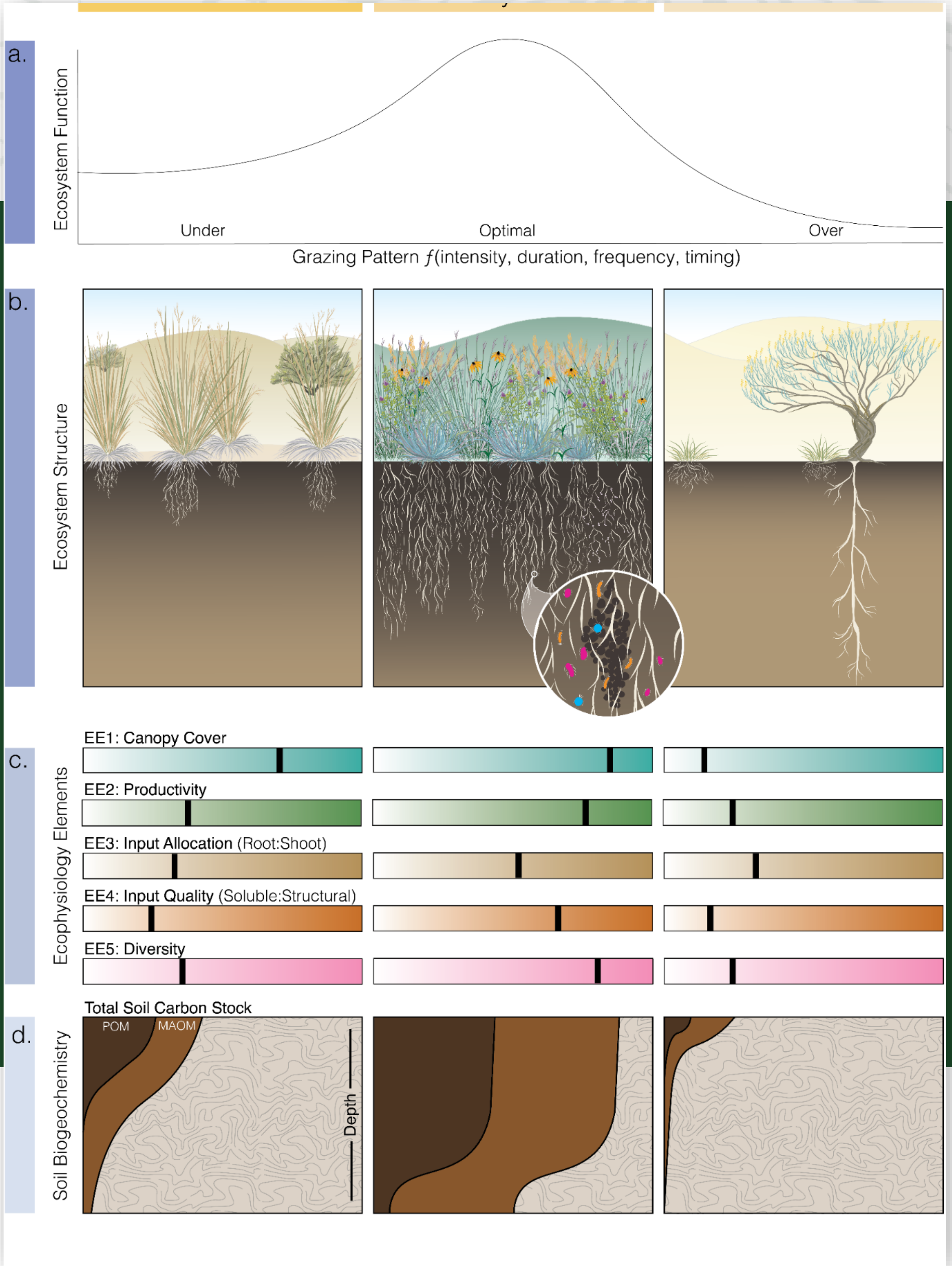
Cotrufo et al. GCB, 2024

An ecosystem response

Applying current understanding to inform grazing management

Each of the three grazing patterns: undergrazing, optimal grazing, and overgrazing

is expected to result in different ecosystem, ecophysiological responses in terns resulting in distinct soil biogeochemical outcomes.

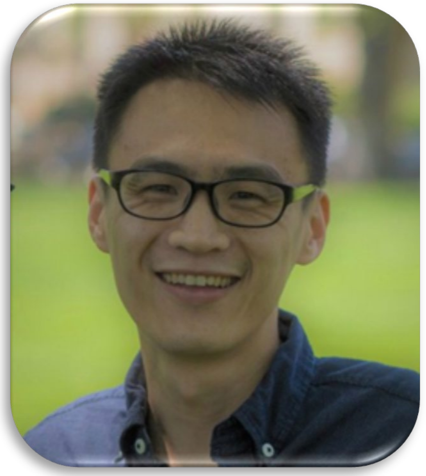


Stanley et al., 2024

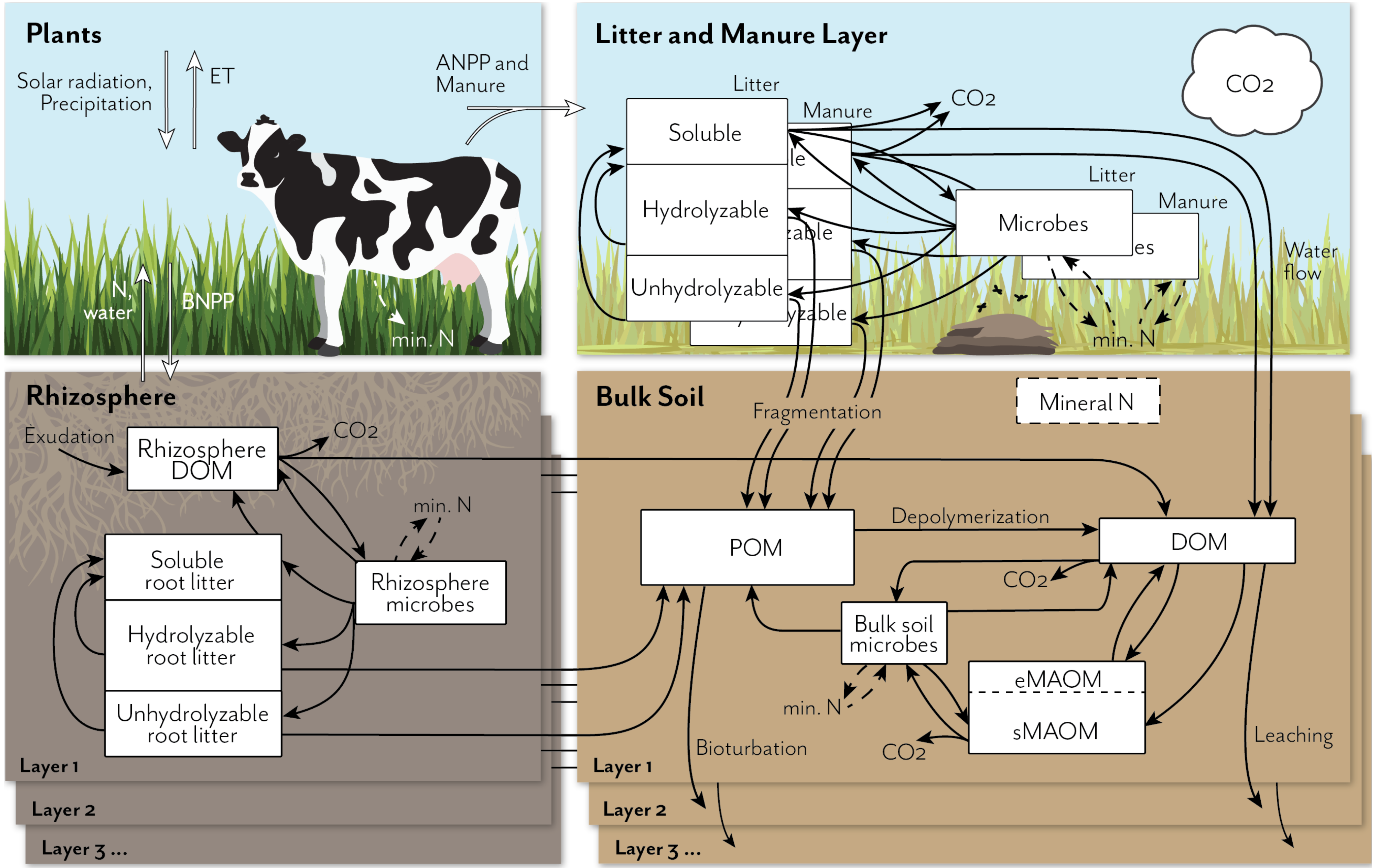
Transferring this knowledge to a useful tool for scientific inquiry and decision making:

The MEMS model

MEMS Ecosystem model: *modelling the measurable*



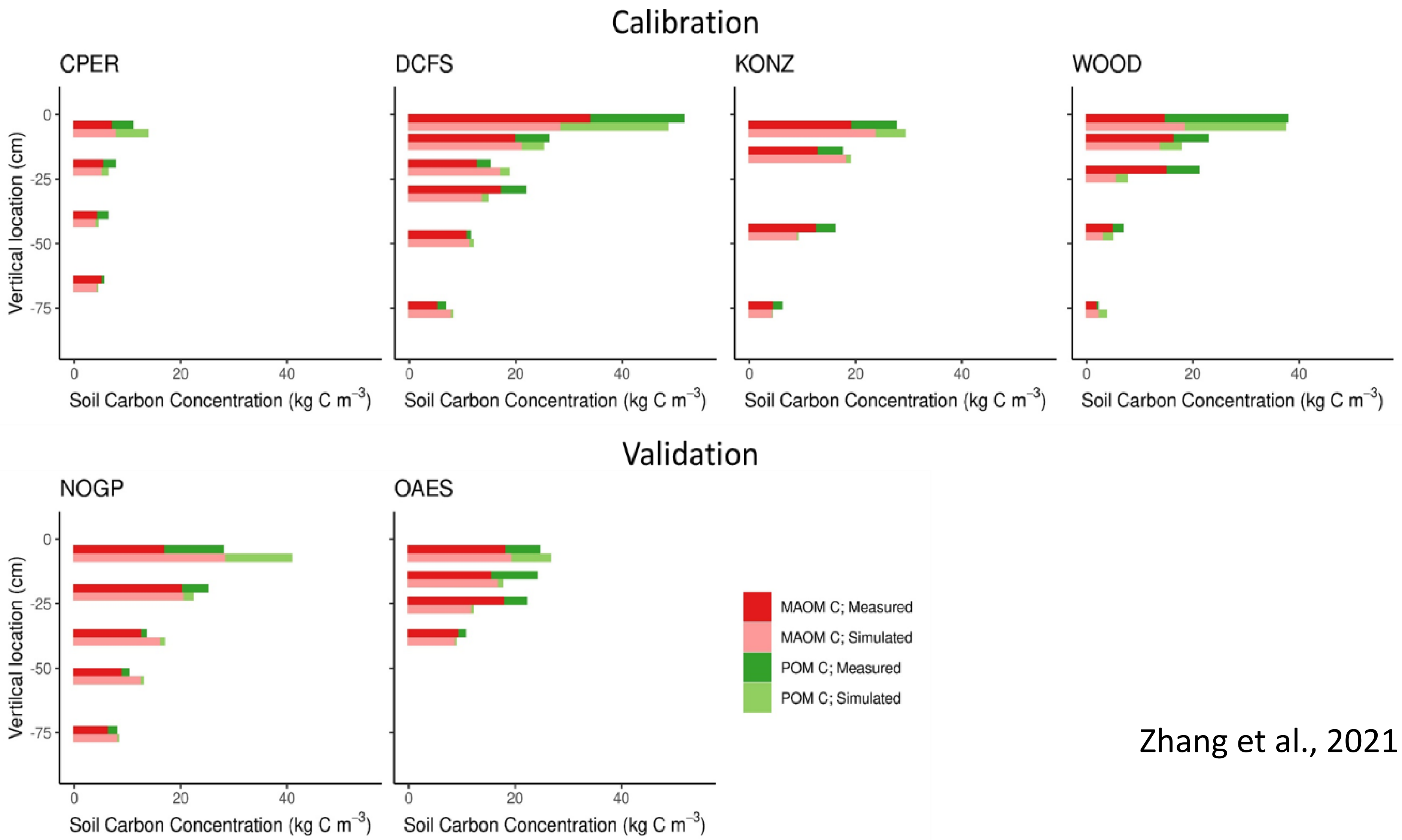
Dr. Yao Zhang



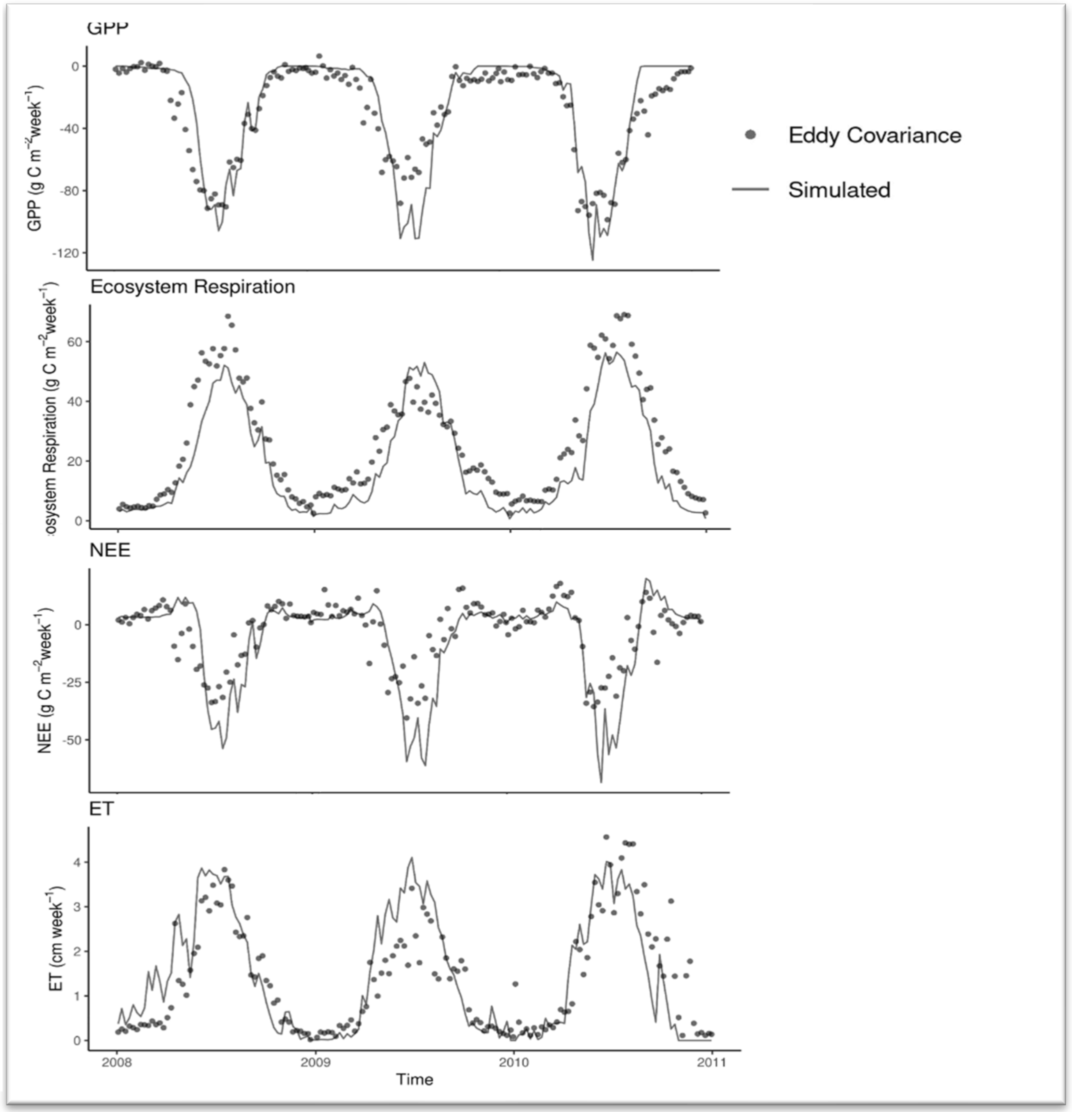
Zhang et al., 2021; Zhang et al., 2023; Santos et al., 2024

MEMS 2.0

calibrated and validated on US grasslands

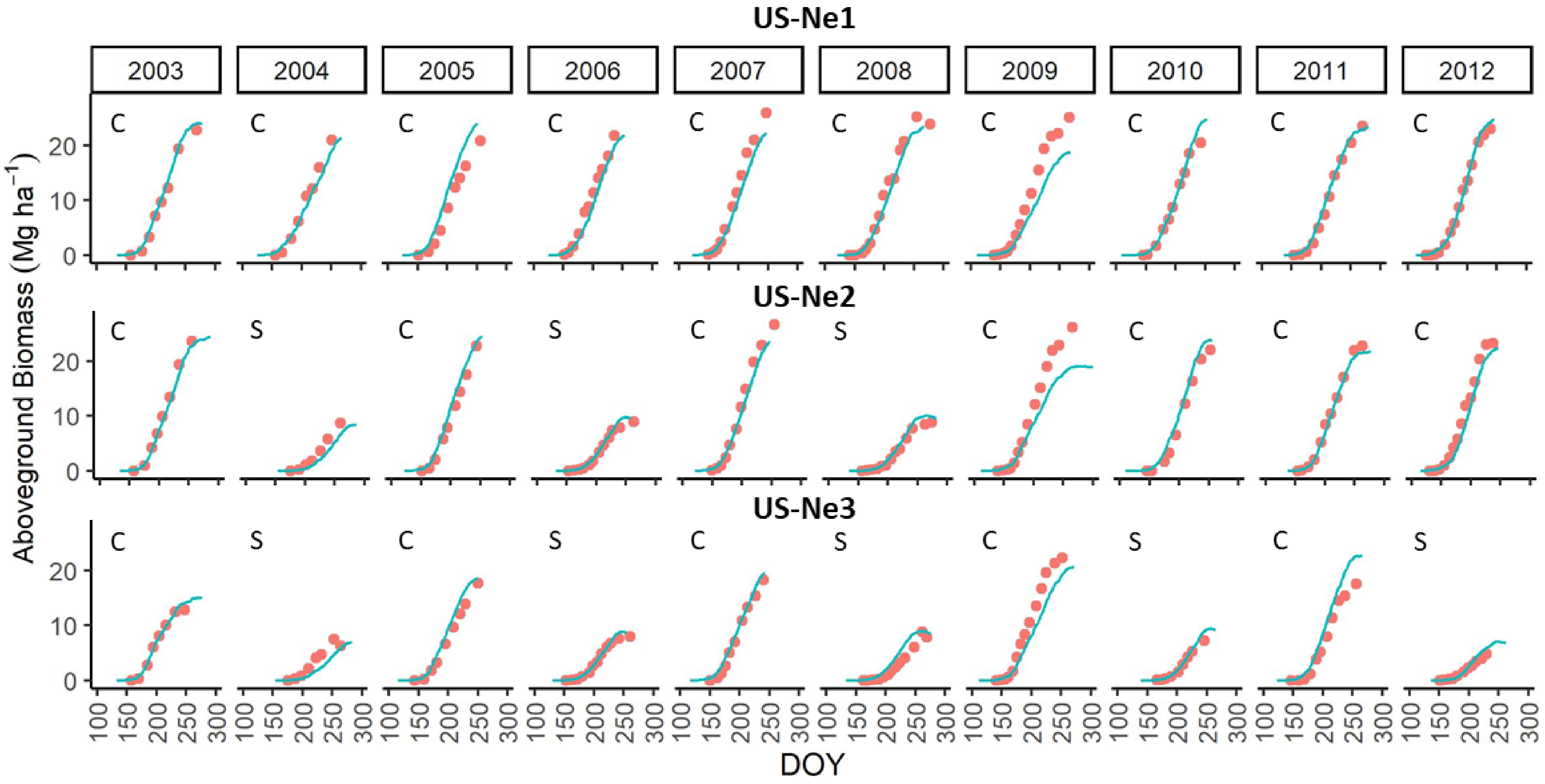


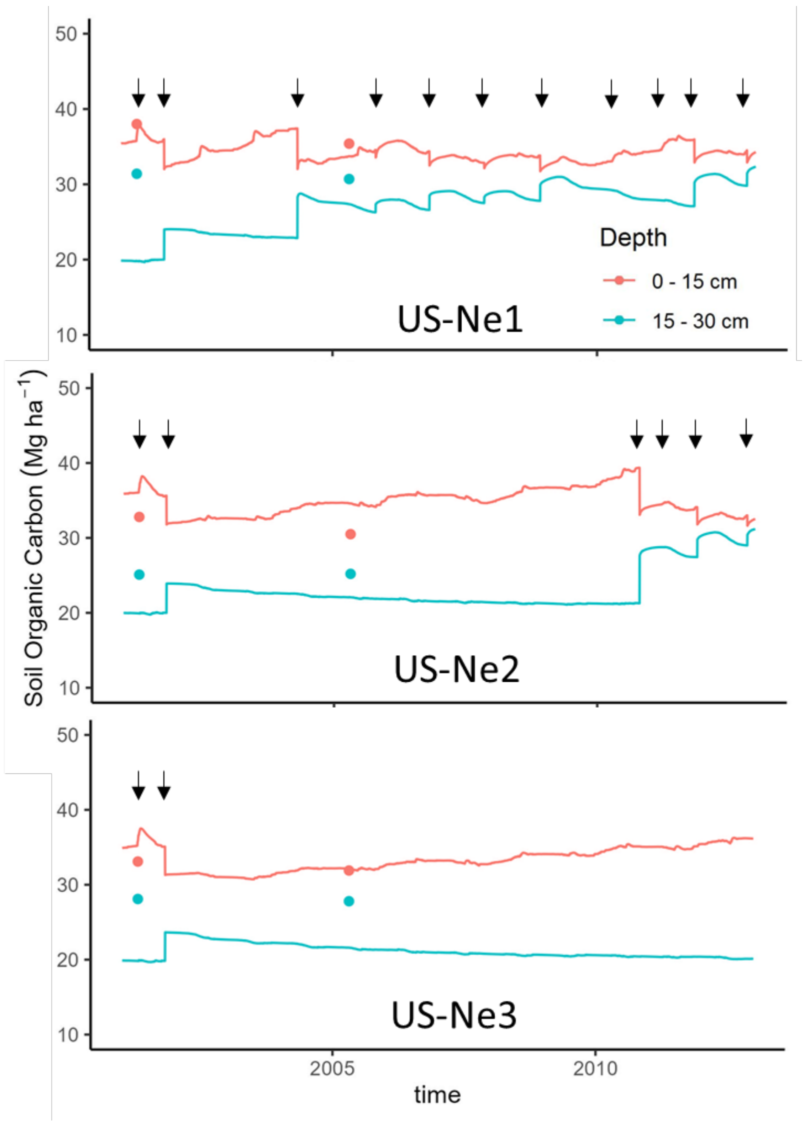
Zhang et al., 2021



MEMS 2.14

developing crops and management

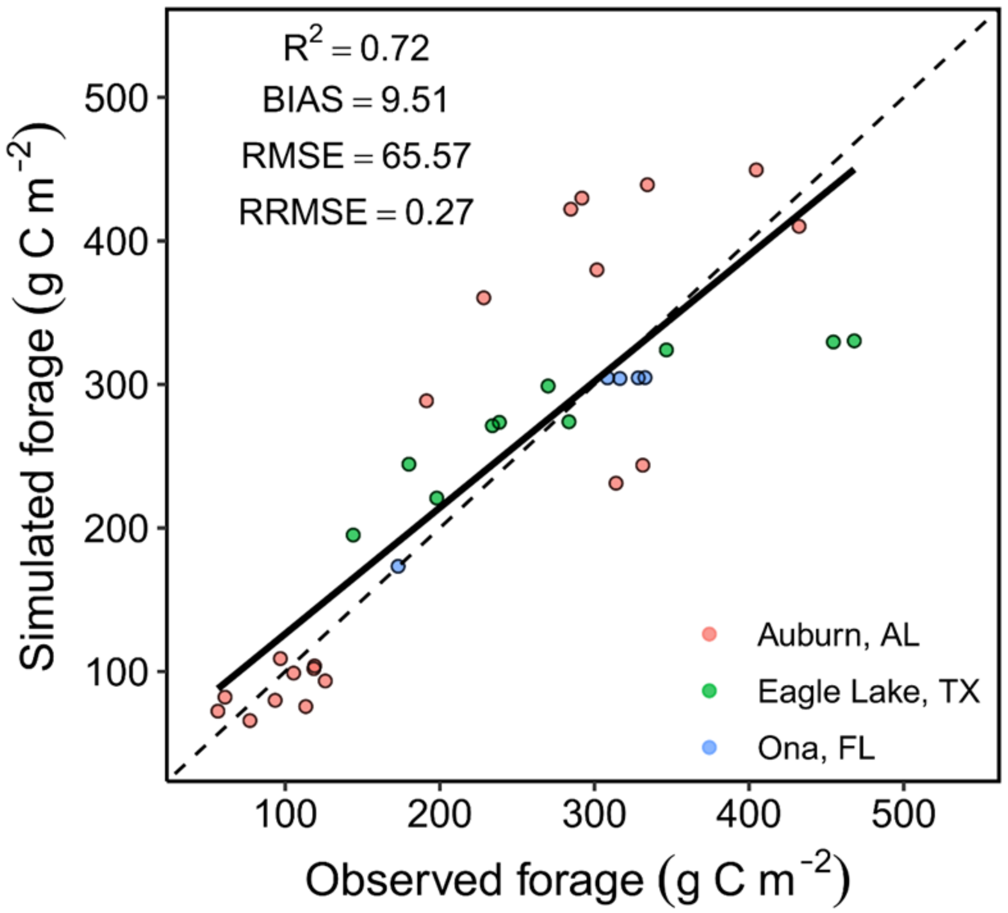


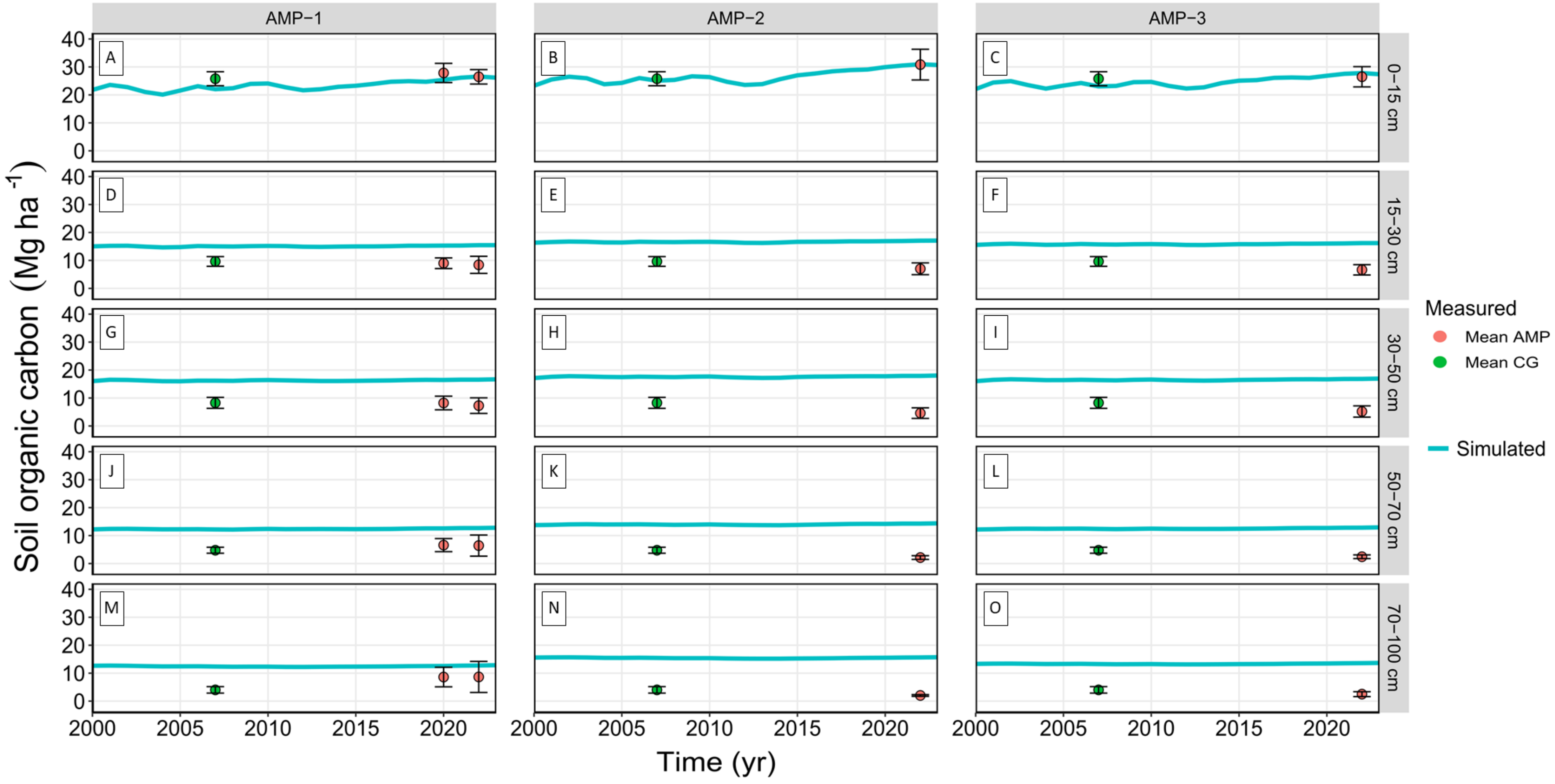


Zhang et al., 2024

MEMS 2.34

developing grazing management

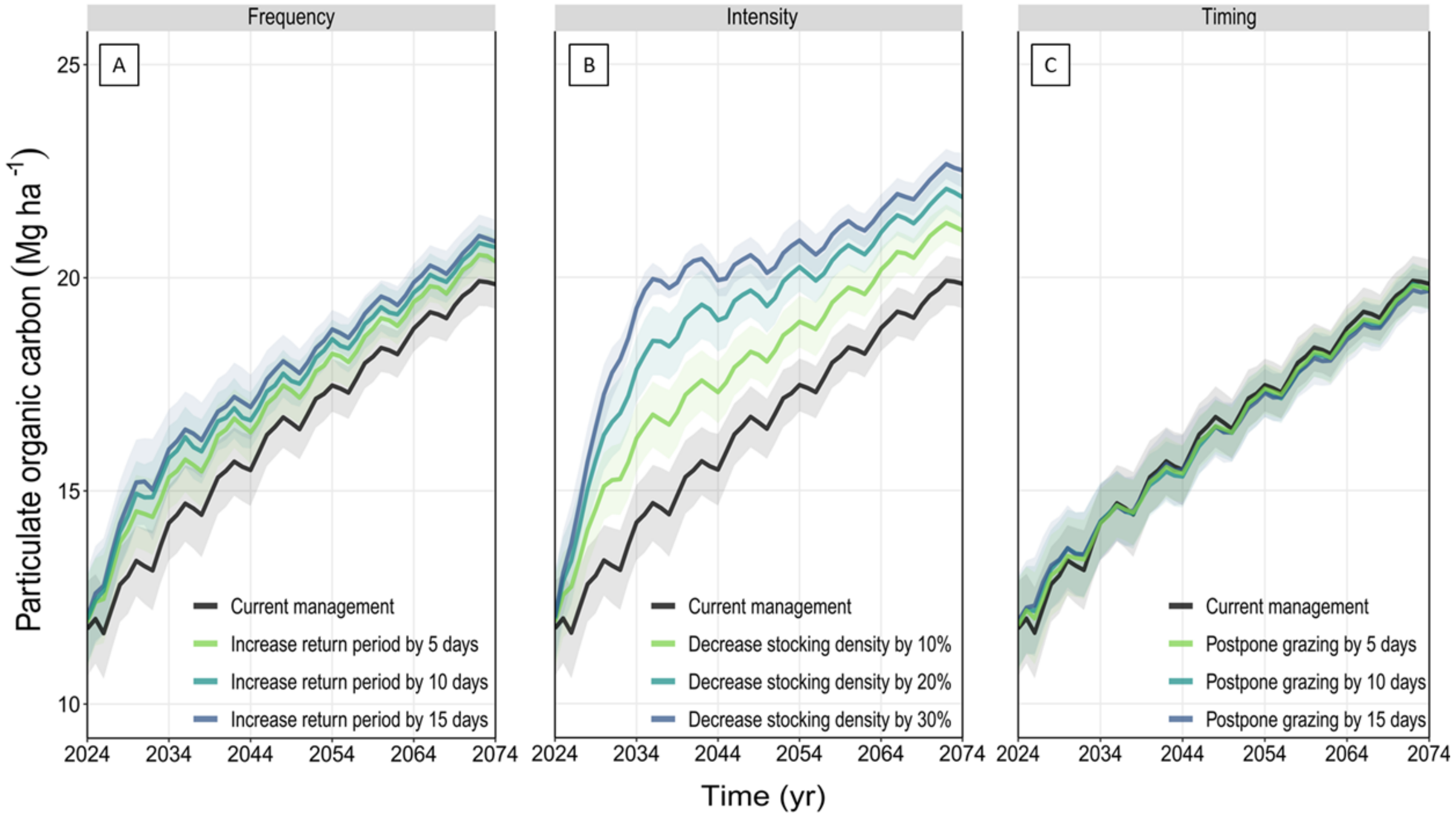


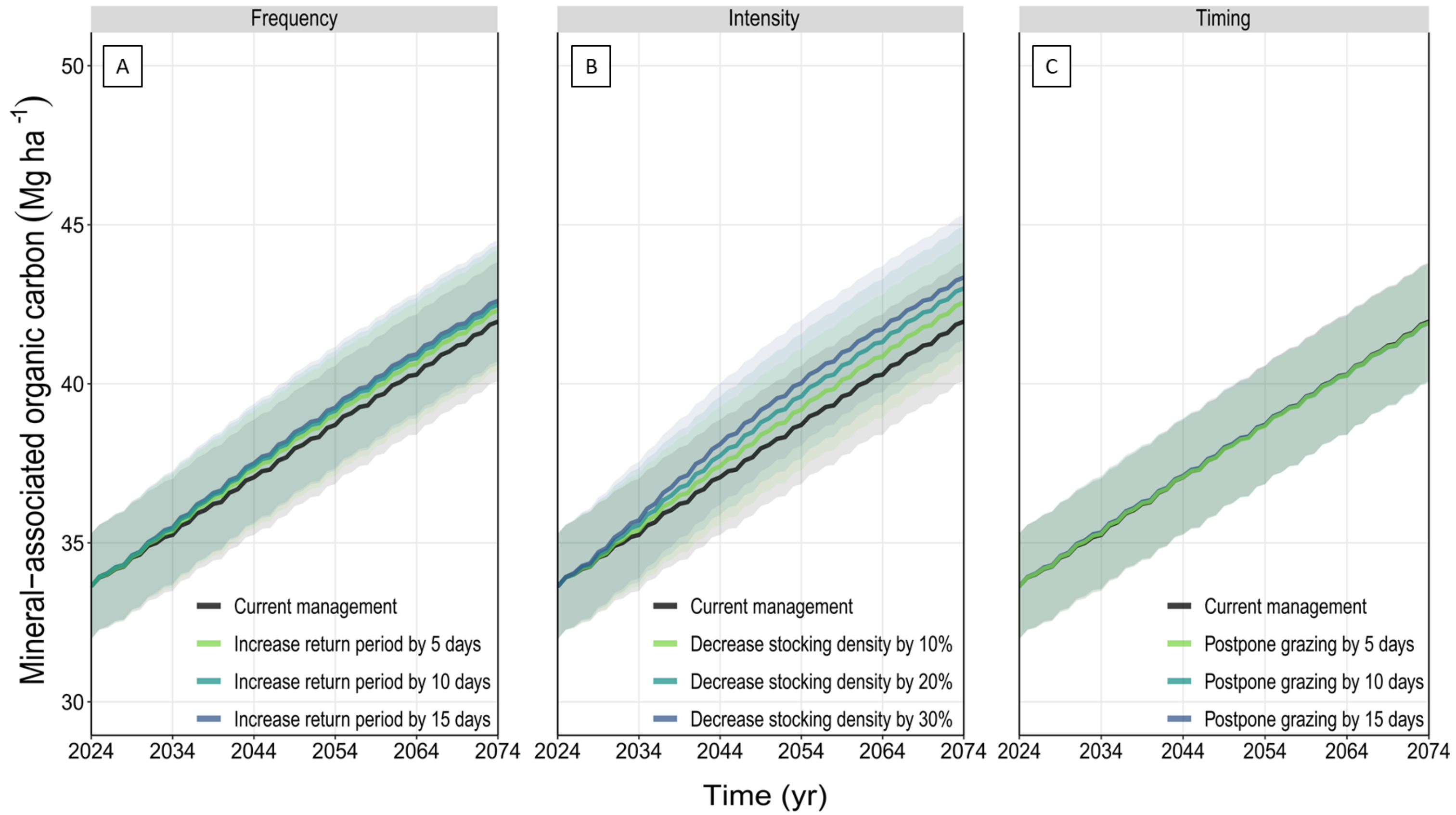


Santos et al., 2024

MEMS 2.34

developing grazing management





Adaptive management confirmed to have potentials to increase soil C in both POM and MAOM in the Southeast US: Optimizing frequency and intensity of grazing can modify SOC accrual

Santos et al., 2024

Ecosystem modeling and data consortium

Contact us if you are interested in joining – Launched in January 2024

https://www.soilcarbonsolutionscenter.com/consortium

Enabling rigorous science-based MRV for supply chain, GHG accounting, C markets

Global technical expertise immediately leveraged to improve and share tools

Beyond carbon, holistic perspective on soil dynamics in agricultural systems

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Thank You!