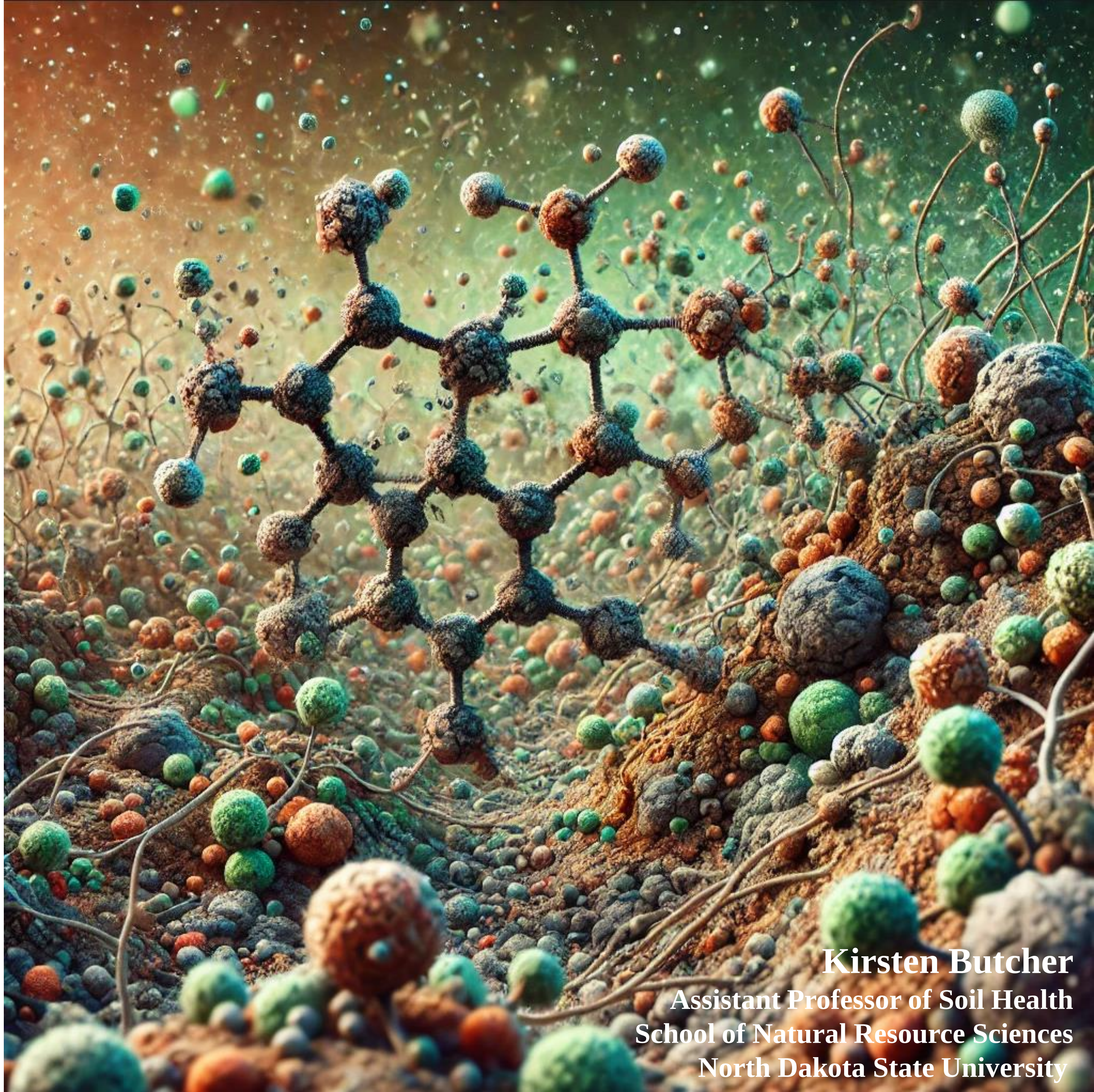
Not All Soil Carbon is Created Equally



Kirsten Butcher
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Not All Soil Carbon is Created Equally

1) *Soil Organic Carbon*
   i. Soil carbon cycling
   ii. Soil carbon and climate change
   iii. Carbon in agricultural systems
   iv. New paradigm of soil carbon

2) *The Knowns and Unknowns of Soil C*
   i. Soil microbes and soil carbon
   ii. Soil carbon saturation and deficit
   iii. Maximum MAOC vs Attainable MAOC

3) *Carbon Credits?*
   i. Can we monetize C sequestration?

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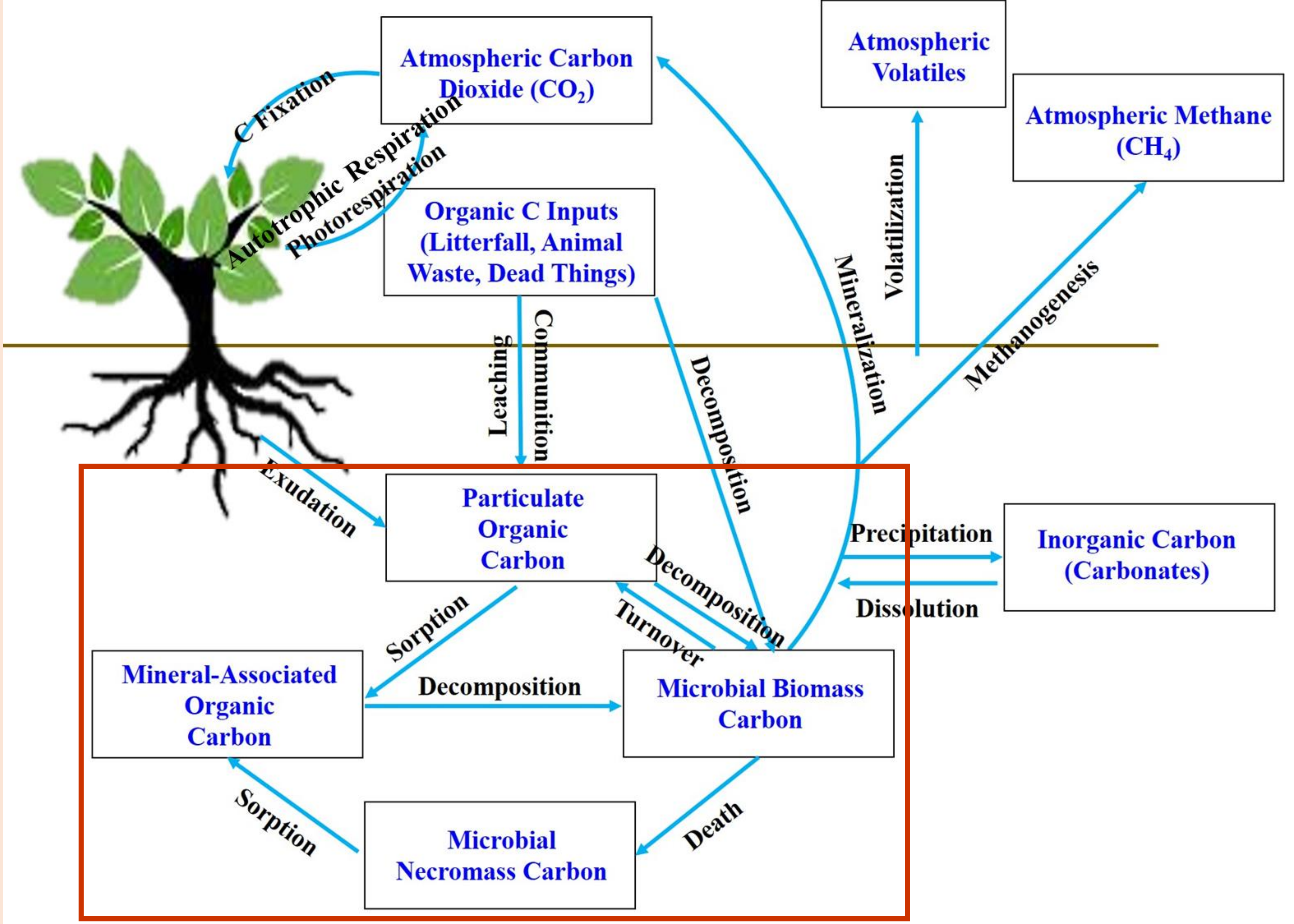
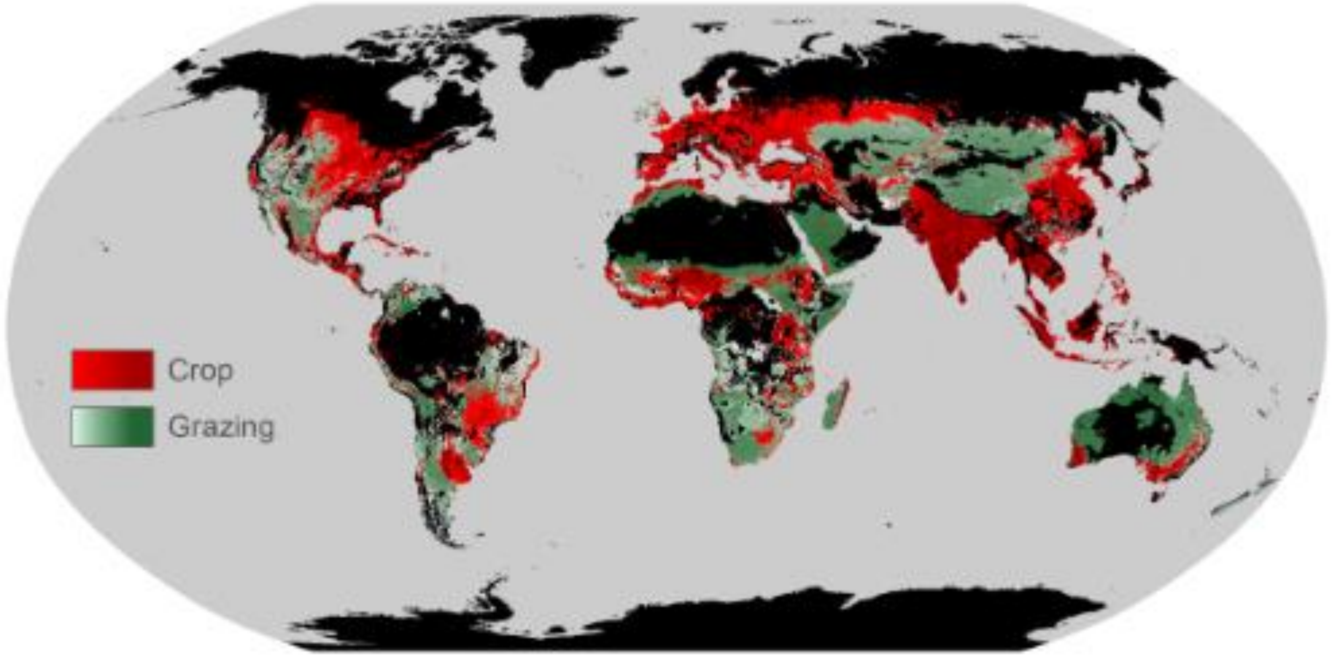
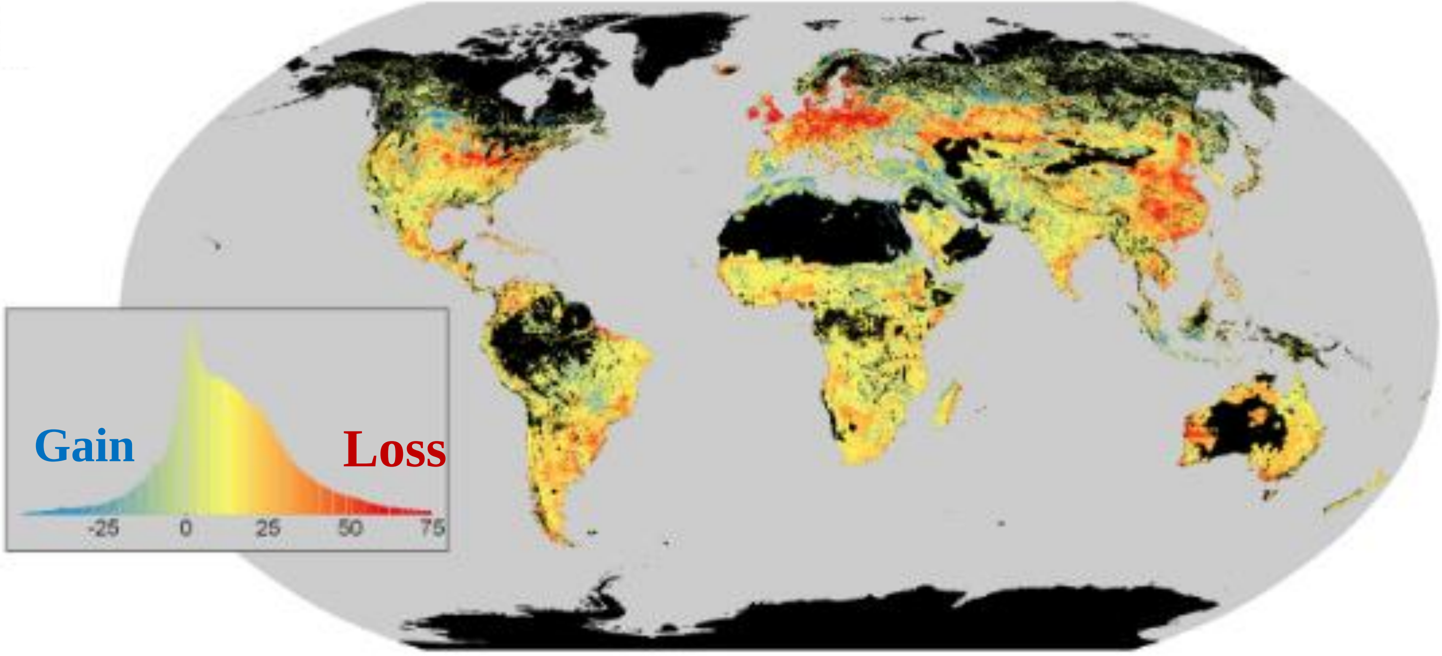
Soil Carbon Cycle



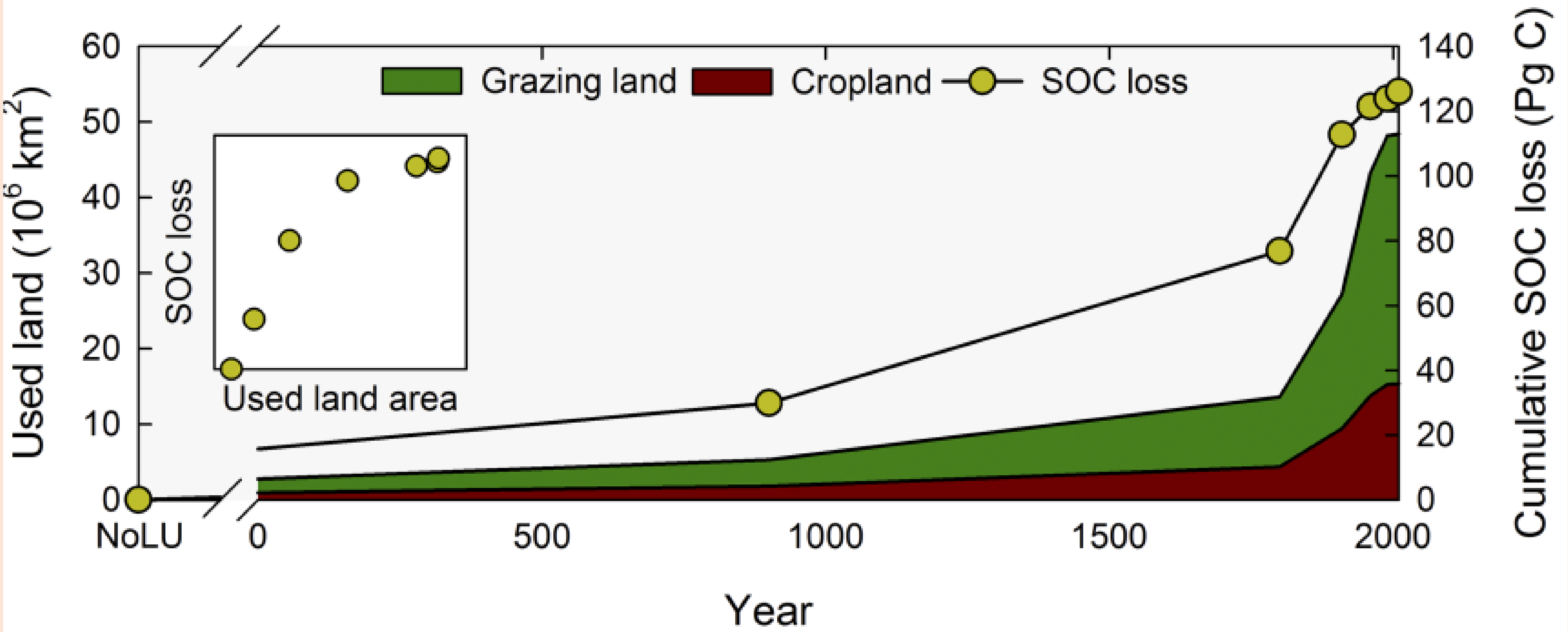
Soil Carbon and Climate Change

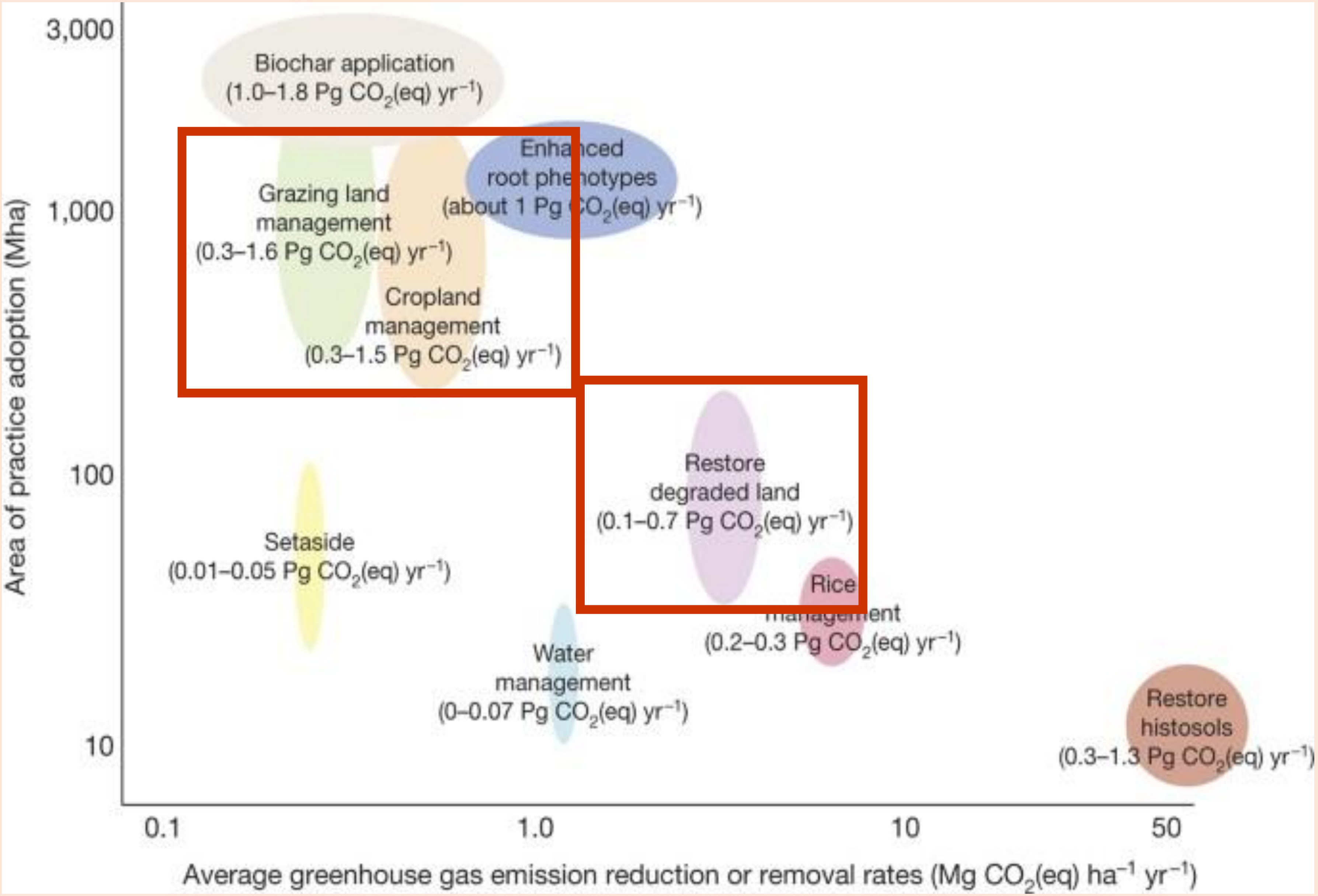
- Agriculture contributes upwards of 30% of total CO_2 emissions globally
  - **About half of that contribution is a result of soil management**
    - ***Current estimated soil C losses around 120 billion metric tons***





Cumulative Loss of Soil Carbon in Cropping and Range Systems

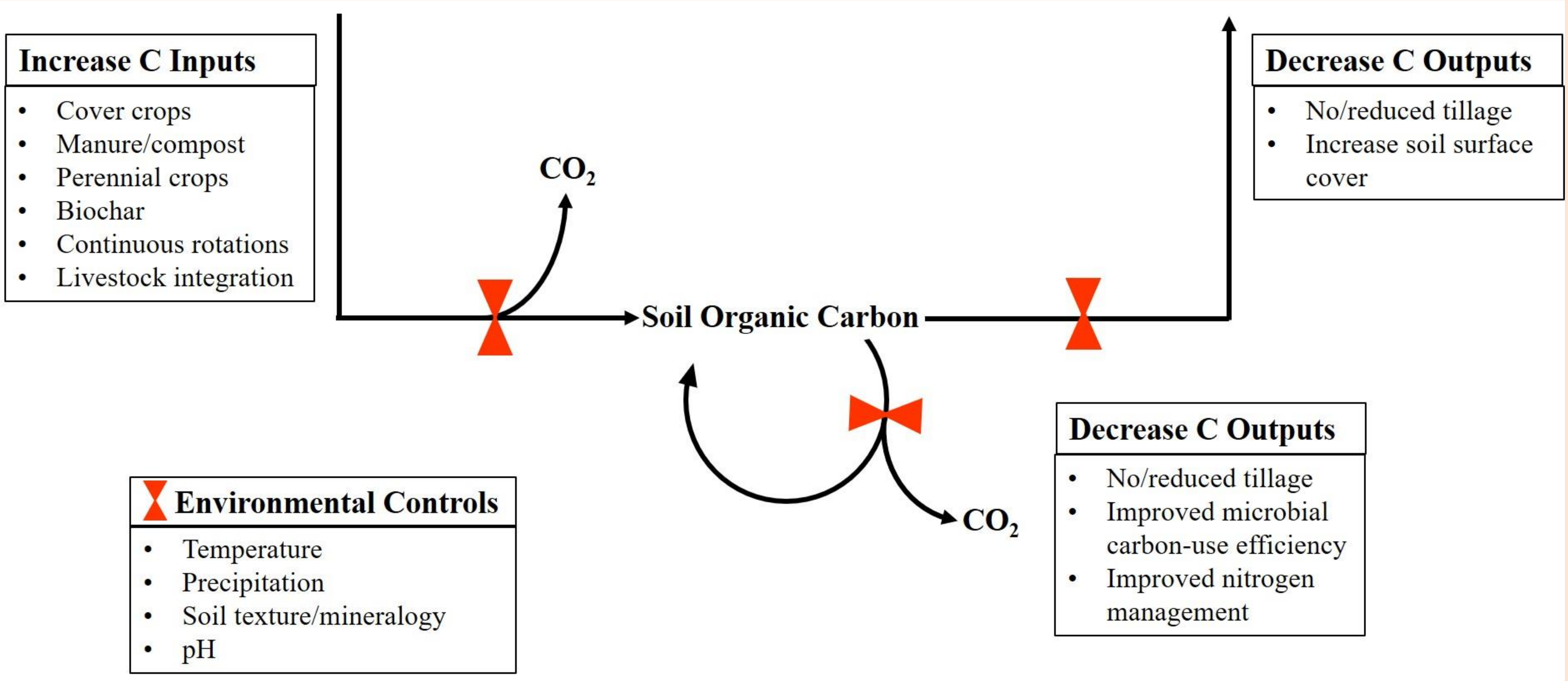




Cropping and range ecosystems present valuable opportunities for building soil carbon

- **Agricultural systems tend to be carbon limited/depleted**
- **Historically, agricultural systems stored large amounts of carbon**
- **These systems are already managed**

Soil Carbon Storage: Balance Between C Inputs and C Outputs



Increasing Carbon Inputs DOES NOT Always Translate to Increases in SOC Stocks

Have we reached the turning point? Looking for evidence SOC increase under conservation agriculture and cover cr practices

Carlo Camarotto, Ilaria Piccoli, Nicola Dal Ferro, Riccardo Polese, Francesca Chiarini, Lorenzo Fu
Francesco Morari

First published: 29 February 2020 | https://doi.org/10.1111/ejss.12953 | Citations: 25

Funding information: Seventh Framework Programme (FP7), Grant/Award Number: 603498

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Abstract

Increasing soil organic carbon (SOC) stocks in agricultural soils is currently of speci interest because it can help mitigate global warming through atmospheric carbon sequestration. Recommended management practices, such as conservation agricu (CA) and conventional tillage with cover crops (CC), could have significant implicati C sequestration potential. A field experiment was carried out in northeast Italy to compare the implementation of CA and CC with conventional agriculture (CV). The experiment began in 2010 on three farms to evaluate SOC stock variation over a 6 period. Two extensive soil sampling operations were conducted in 2011 and 2017 locations, for a total of 1,440 analysed soil samples, considering the SOC stratificat within a 0–50-cm profile. The results suggested that CA changed the SOC distribut rather than the total amount of SOC. Compared to CV, after the introduction of CA general increase in SOC (0.25 Mg C ha^{-1} y^{-1}) was observed in the 0–30-cm layer, wl no stock variation was observed in the 0–50-cm layer. In contrast, compared to CV use of CC decreased the SOC stocks by 0.74 Mg C ha^{-1} y^{-1} in the 0–50-cm layer. Ov year period, no benefit in SOC sequestration was observed with CA and CC. Howe hypothesize that these findings could still be affected by transitory dynamics, high the low soil reactivity to soil-improving agricultural systems. A longer study period be required to better understand the potential benefits of CA and CC on SOC sequestration.

Highlights

- We hypothesized that conservation practices increase SOC after a 6-year adop
- No-tillage enhanced SOC stratification in conservation agriculture
- C addition with cover crops induced SOC stock reductions due to a priming eff
- An SOC increase was not observed after 6 years of conservation practices

Cover crops do not increase soil organic carbon stocks as much as has been claimed: What is the way forward?

Vincent Chaplot[1,2] | Pete Smith[3]

[1]Laboratoire d'Océanographie et du Climat: Expérimentations et Approches Numériques, Institut de Recherche pour le Développement (IRD), UMR 7159, IRD-CNRS-UPMC-MNHN, Paris, France

[2]SAEES, University of KwaZulu-Natal, Scottsville, South Africa

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Correspondence
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When compared to virgin land (forest and grassland), croplands store significantly lower amounts of organic carbon (OC), mainly as a result of soil tillage, and decreased plant inputs to the soil over the whole year. Doubts have been expressed over how much reduced and zero tillage agriculture can increase OC in soils when the whole soil profile is considered. Consequently, cover-crops that are grown in-between crops instead of leaving soils bare appear as the "last man standing" in our quest to enhance cropland OC stocks. Despite the claim by numerous meta-analyses of a mean carbon sequestration rate by cover crops to be as high as 0.32 ± 0.08 ton C ha^{-1} year^{-1}, the present analysis showed that all of the 37 existing field studies worldwide only sampled to a depth of 30 cm or less and did not compare treatments on the basis of equivalent soil mass. Thirteen studies presented information on OC content only and not on OC stocks, had inappropriate controls ($n = 14$), had durations of 3 years or lower ($n = 5$), considered only one to two data points per treatment ($n = 4$), or used cover crops as cash crops (i.e., grown longer that in-between two crops) instead of catch crops ($n = 2$), which in all cases constitutes shortcomings. Of the remaining six trials, four showed non-significant trends, one study displayed a negative impact of cover crops, and one study displayed a positive impact, resulting in a mean OC storage of 0.03 ton ha^{-1} year^{-1}. Models and policies should urgently adapt to such new figure. Finally, more is to be done not only to improve the design of cover-crop studies for reaching sound conclusions but also to understand the underlying reasons of the low efficiency of cover crops for improved carbon sequestration into soils, with possible strategies being suggested.

KEYWORDS
land, management, organic matter, quality, soil

Deep soil inventories reveal that impacts of cover crops and ost on soil carbon sequestration differ in surface and ırface soils

Tautges, Jessica L. Chiartas, Amélie C. M. Gaudin, Anthony T. O'Geen, Israel Herrera, cow

ished: 13 July 2019 | https://doi.org/10.1111/gcb.14762 | Citations: 162

nd Chiartas share joint first authorship.

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stract

asing soil organic carbon (SOC) via organic inputs is a key strategy for increasing term soil C storage and improving the climate change mitigation and adaptation ntial of agricultural systems. A long-term trial in California's Mediterranean climate lled impacts of management on SOC in maize-tomato and wheat–fallow cropping ms. SOC was measured at the initiation of the experiment and at year 19, at five increments down to 2 m, taking into account changes in bulk density. Across the 2 m profile, SOC in the wheat–fallow systems did not change with the addition of N zer, winter cover crops (WCC), or irrigation alone and decreased by 5.6% with no s. There was some evidence of soil C gains at depth with both N fertilizer and tion, though high variation precluded detection of significant changes. In maize– to rotations, SOC increased by 12.6% (21.8 Mg C/ha) with both WCC and composted ry manure inputs, across the 2 m profile. The addition of WCC to a conventionally aged system increased SOC stocks by 3.5% (1.44 Mg C/ha) in the 0–30 cm layer, but ased by 10.8% (14.86 Mg C/ha) in the 30–200 cm layer, resulting in overall losses of Mg C/ha. If we only measured soil C in the top 30 cm, we would have assumed an ase in total soil C increased with WCC alone, whereas in reality significant losses in occurred when considering the 2 m soil profile. Ignoring the subsoil carbon mics in deeper layers of soil fails to recognize potential opportunities for soil C estration, and may lead to false conclusions about the impact of management ices on C sequestration.

Decreasing Carbon Outputs DOES NOT Always Translate to Increases in SOC Stocks

Long-term effect of contrasted tillage crop management on soil carbon dyn during 41 years

Bassem Dimassi [a], Bruno Mary [a], Richard Wylleman [c], Jérôme Labreuche [b], Daniel Couture [b], François Piraux [b], Jean-Pierre Cohan [b]

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https://doi.org/10.1016/j.agee.2014.02.014 Get ri

Highlights

- 40 years of full inversion, shallow or no-tillage lead to similar SOC stocks over the ploughed layer or down to 60cm.
- In the reduced tillage treatments, SOC accumulated in the upper layer (0–10cm) but declined continuously below 10cm.
- The amount of C sequestered due to reduced tillage followed a non monotonic pattern over time.
- Changes in SOC over time in the upper layer of no-till were negatively correlated with the water balance.
- C sequestration rate was positive in dry periods and negative in we conditions.

Limited potential of no-till agriculture for climate change mitigation

David S. Powlson, Clare M. Stirling, M. L. Jat, Bruno G. Gerard, Cheryl A. Palm, Pedro A. Sanchez & Kenneth G. Cassman

Nature Climate Change **4**, 678–683 (2014) | Cite this article

Abstract

The Emissions Gap Report 2013 from the United Nations Environment Programme resta the claim that changing to no-till practices in agriculture, as an alternative to conventio tillage, causes an accumulation of organic carbon in soil, thus mitigating climate change through carbon sequestration. But these claims ignore a large body of experimental evi showing that the quantity of additional organic carbon in soil under no-till is relatively s in large part apparent increases result from an altered depth distribution. The larger concentration near the surface in no-till is generally beneficial for soil properties that of though not always, translate into improved crop growth. In many regions where no-till i practised it is common for soil to be cultivated conventionally every few years for a rang agronomic reasons, so any soil carbon benefit is then lost. We argue that no-till is benefi for soil quality and adaptation of agriculture to climate change, but its role in mitigatior widely overstated.

Can no-tillage stimulate carbon sequestration in agricultural soils? A meta-analysis of paired experiments

Zhongkui Luo [a b], Enli Wang [b], Osbert J. Sun [c]

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Abstract

Adopting no-tillage in agro-ecosystems has been widely recommended as a means of enhancing carbon (C) sequestration in soils. However, study results are inconsistent and varying from significant increase to significant decrease. It is unclear whether this variability is caused by environmental, or management factors or by sampling errors and analysis methodology. Using meta-analysis, we assessed the response of soil organic carbon (SOC) to conversion of management practice from conventional tillage (CT) to no-tillage (NT) based on global data from 69 paired-experiments, where soil sampling extended deeper than 40cm. We found that cultivation of natural soils for more than 5 years, on average, resulted in soil C loss of more than 20 $t\,ha^{-1}$, with no significant difference between CT and NT. Conversion from CT to NT changed distribution of C in the soil profile significantly, but did not increase the total SOC except in double cropping systems. After adopting NT, soil C increased by 3.15±2.42 $t\,ha^{-1}$ (mean±95% confidence interval) in the surface 10cm of soil, but declined by 3.30±1.61 $t\,ha^{-1}$ in the 20–40cm soil layer. Overall, adopting NT did not enhance soil total C stock down to 40cm. Increased number of crop species in rotation resulted in less C accumulation in the surface soil and greater C loss in deeper layer. Increased crop frequency seemed to have the opposite effect and significantly increased soil C by 11% in the 0–60cm soil. Neither mean annual temperature and mean annual rainfall nor nitrogen fertilization and duration of adopting NT affected the response of soil C stock to the adoption of NT. Our results highlight that the role of adopting NT in sequestrating C is greatly regulated by cropping systems. Increasing cropping frequency might be a more efficient strategy to sequester C in agro-ecosystems. More information on the effects of increasing crop species and frequency on soil C input and decomposition processes is needed to further our understanding on the potential ability of C sequestration in agricultural soils.

Not all soil carbon is created equally

Soil Carbon

Soil Inorganic Carbon (SIC)

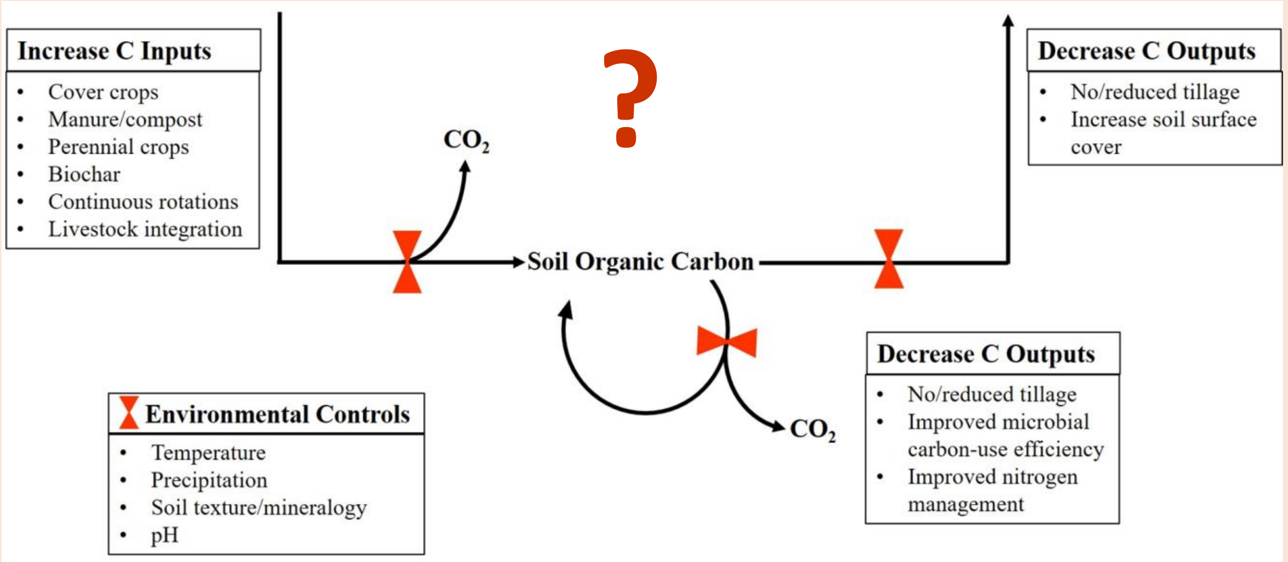
Soil Organic Carbon (SOC)

Particulate Organic Carbon

Organic carbon originating from plants and microbes (e.g., crop residue, root exudates, microbial products)

Mineral-Associated Organic Carbon

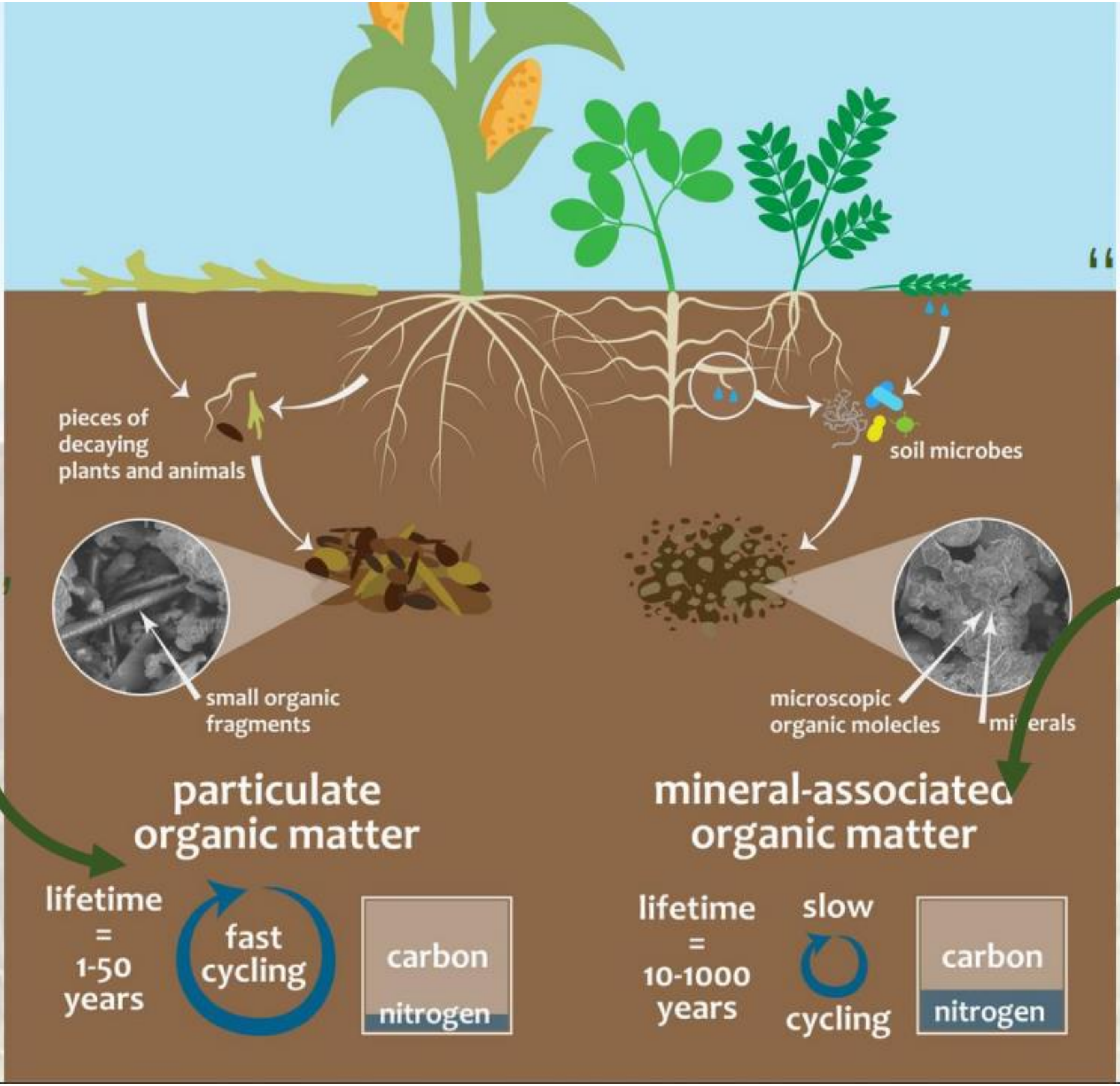
Organic carbon bonded to the surface of a soil minerals (e.g., silts, clays)



Soil Carbon

POM = "Vulnerable"

MAOM = "Protected"



Particulate Organic Carbon (POC)

Mineral-Associated Organic Carbon (MAOC)

Source
Dr. Jocelyn Lavallee
https://source.colostate.edu/soil-carbon-is-a-valuable-resource-but-all-soil-carbon-is-not-created-equal/

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Particulate Organic Carbon

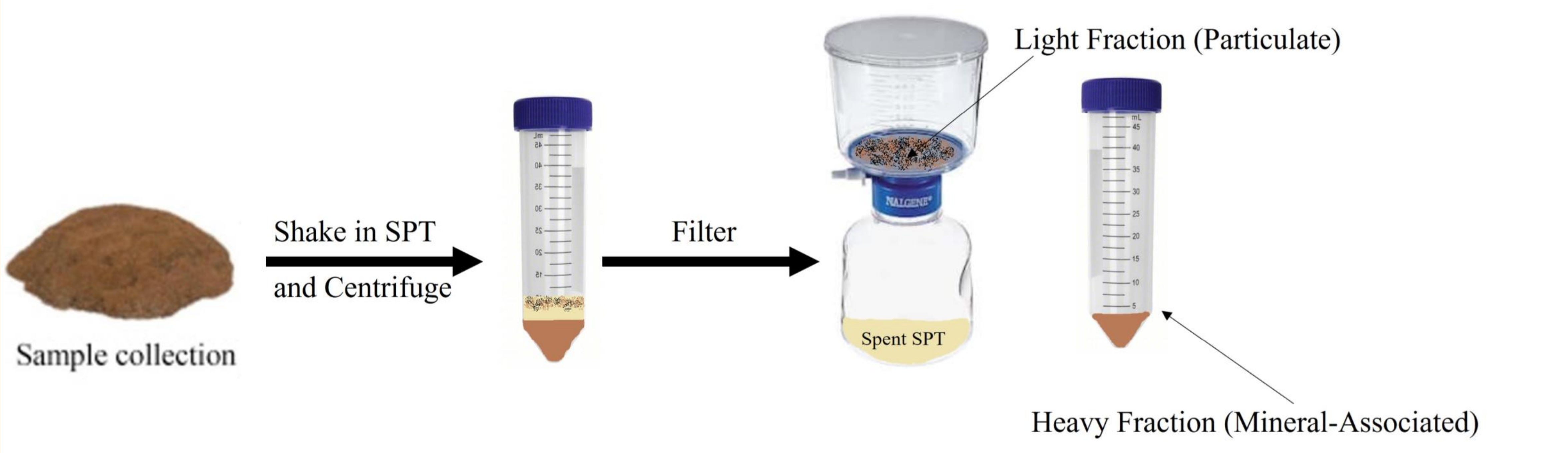
- Plant-derived carbon
  - Consists of plant biomass and decaying materials
  - Fast cycling C pool
    - ***Easily decomposed by soil microorganisms*** but easily replenished by plant inputs
  - **Can accumulate indefinitely in soil**

Mineral-Associated Organic Carbon

- Primarily **microbially-derived** carbon
  - Consists of microbial necromass but can include simple plant compounds (exudates)
  - Slow cycling C pool
    - **Decomposition takes centuries** *unless disturbance event occurs*
  - **Carbon accumulation limited by availability of mineral surfaces**

Measuring POC and MAOC

- Density Fractionation
  - Separation of light fraction (POC) and heavy fraction (MAOC) using a high-density liquid (e.g., sodium polytungstate; SPT)
    - Fractions are measured on a C analyser



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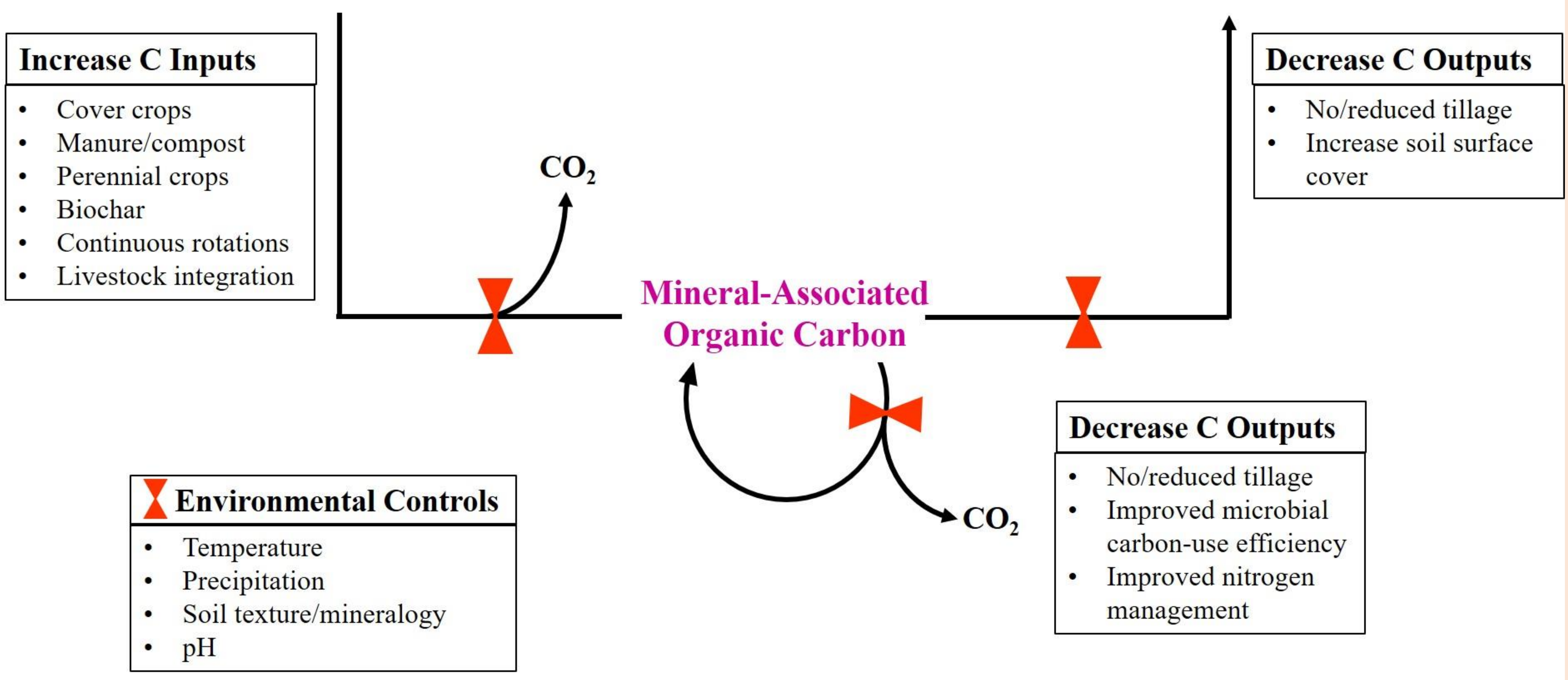

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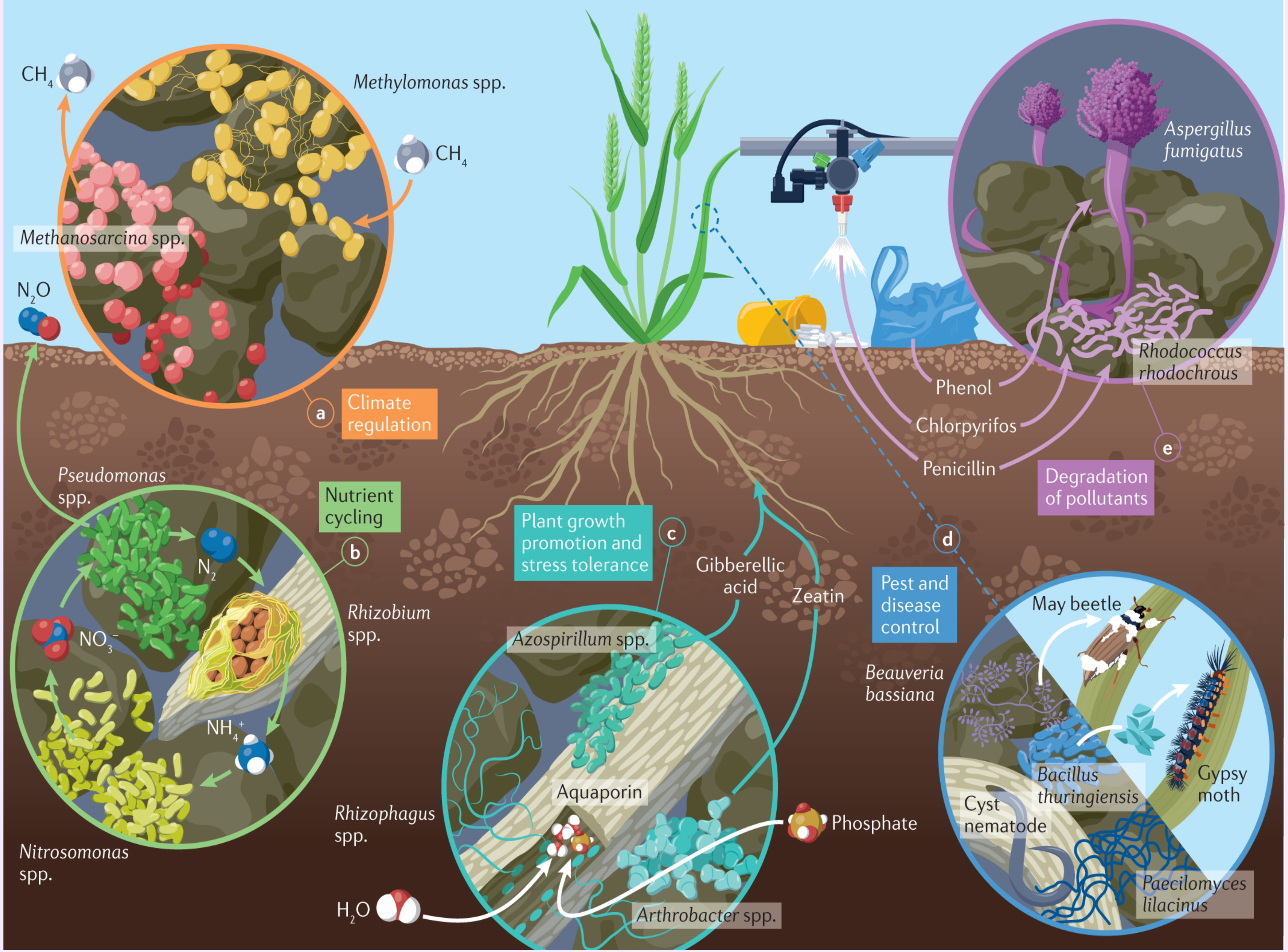


Ecosystem Services and Functions:

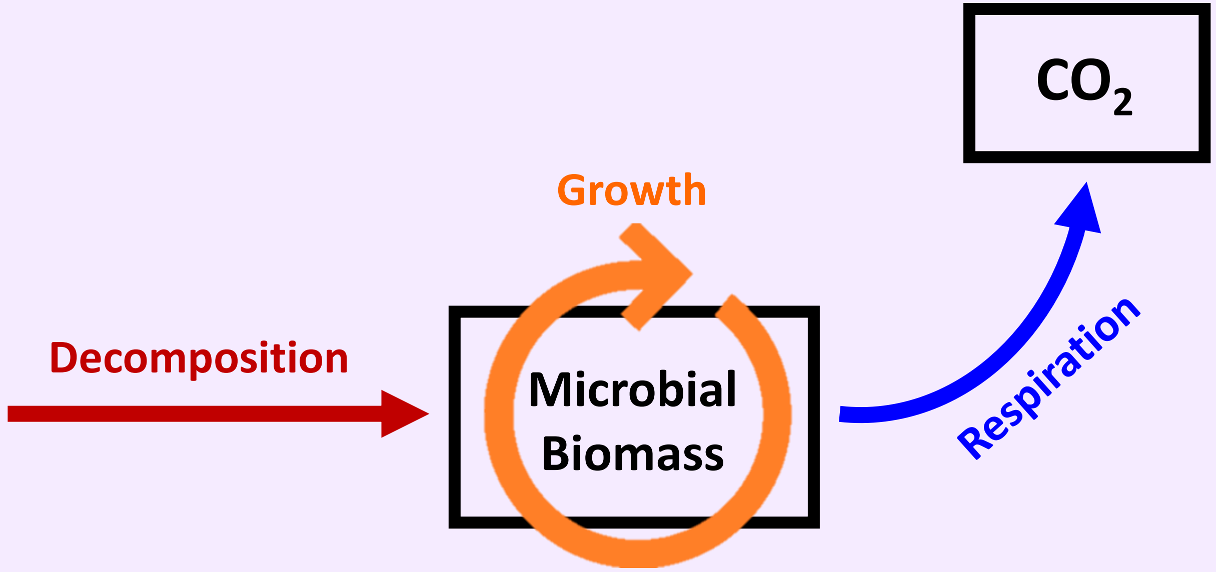
- **Climate Regulation**
- **Nutrient Cycling**
- **Plant Growth Promotion and Stress Tolerance**
- **Pest and Disease Control**
- **Degradation of Pollutants**
- **SOC Formation and Sequestration**

Microbial Carbon Cycling *–processes involving microbial decomposition of soil carbon that results in either 1) carbon incorporation into their biomass or 2) carbon loss as CO_2 (mineralization/respiration)*

1) **Microbes consume organic carbon in the soil (decomposition)**

2) **A portion of consumed carbon is incorporated into microbial biomass (growth)**
   - *Potential to create sequestered carbon*

3) **The remainder of the consumed carbon is mineralized to carbon dioxide (respiration)**
   - *Carbon is lost from the soil*



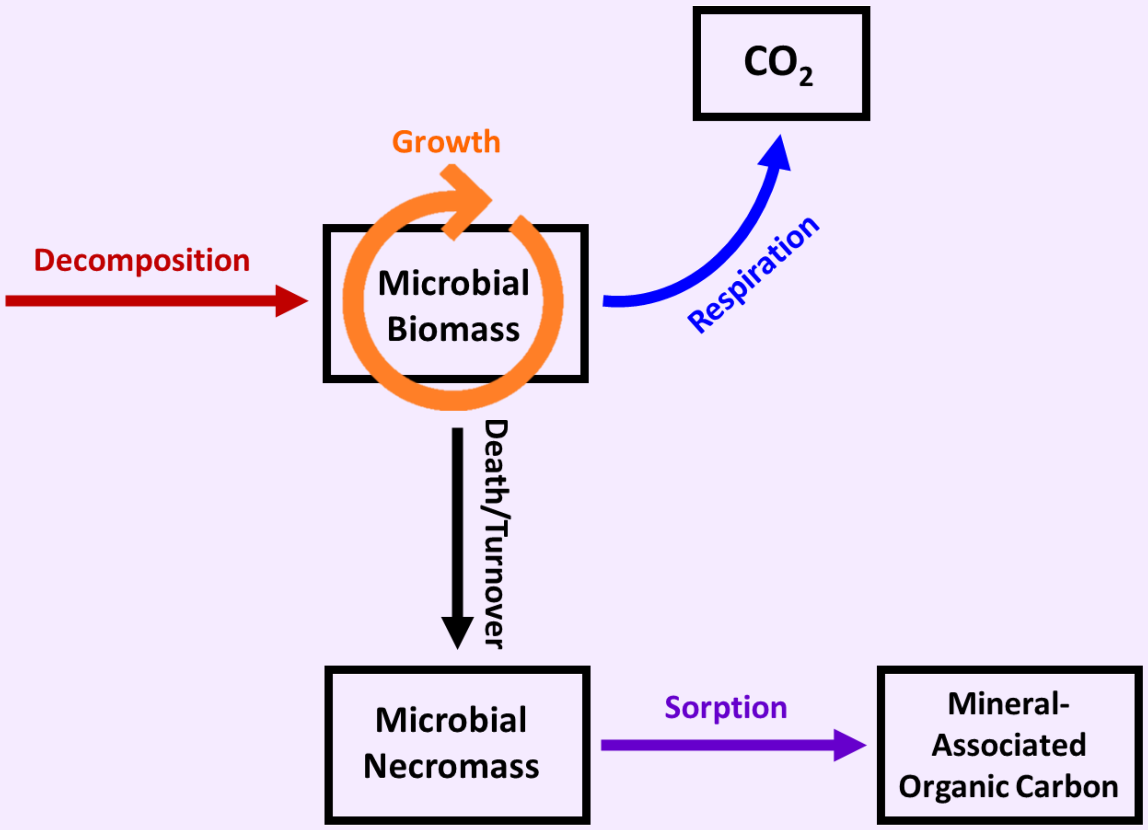
Microbial Carbon Cycling and MAOC –

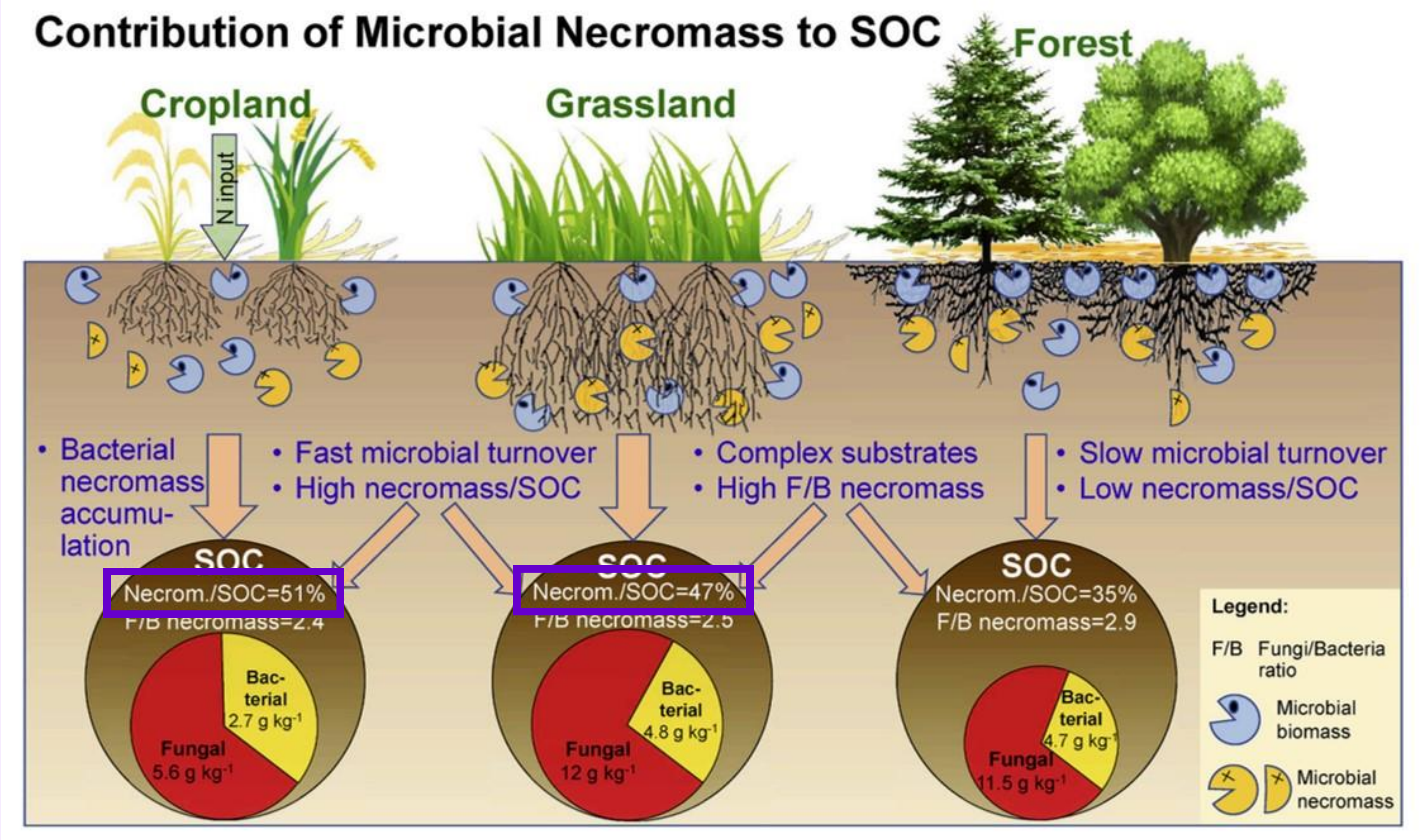
microbial residues (necromass) preferentially sorb onto soil mineral surfaces to form mineral-associated organic carbon

1) Microbes consume organic carbon in the soil (decomposition)

2) A portion of consumed carbon is incorporated into microbial biomass (growth)
   - More carbon stored in microbial cells results in more carbon that can sorb to mineral surfaces to form MAOC

3) The remainder of the consumed carbon is mineralized to carbon dioxide (respiration)




Contribution of Microbial Necromass to SOC
Cropland
Grassland
Forest
N input
• Bacterial necromass accumulation
• Fast microbial turnover
• High necromass/SOC
• Complex substrates
• High F/B necromass
• Slow microbial turnover
• Low necromass/SOC
SOC
Necrom./SOC=51%
F/B necromass=2.4
Bac-terial 2.7 g kg-1
Fungal 5.6 g kg-1
SOC
Necrom./SOC=47%
F/B necromass=2.5
Bac-terial 4.8 g kg-1
Fungal 12 g kg-1
SOC
Necrom./SOC=35%
F/B necromass=2.9
Bac-terial 4.7 g kg-1
Fungal 11.5 g kg-1
Legend:
F/B Fungi/Bacteria ratio
Microbial biomass
Microbial necromass

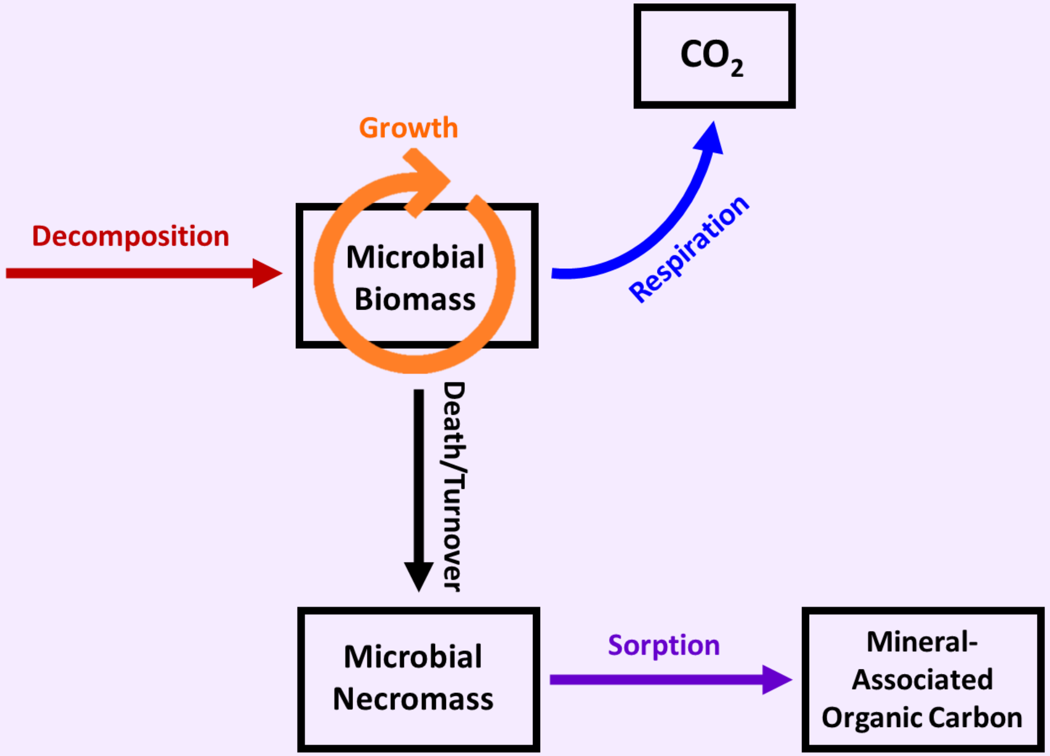
Microbial Carbon-Use Efficiency (CUE)

–proportion of C used for growth relative to the total C consumed (growth and respiration)

$$CUE = \frac{Growth}{Growth + Respiration}$$

- <u>Higher CUE</u>
  - Greater proportion of consumed C stored in microbial biomass
    - Increased necromass formed following cell death
      - *Greater potential for carbon sorption onto soil minerals*

- <u>Low CUE</u>
  - Greater proportion of consumed C lost as CO_2
    - Lower levels of necromass C
      - *Less substrate available to sorb to soil mineral surfaces*



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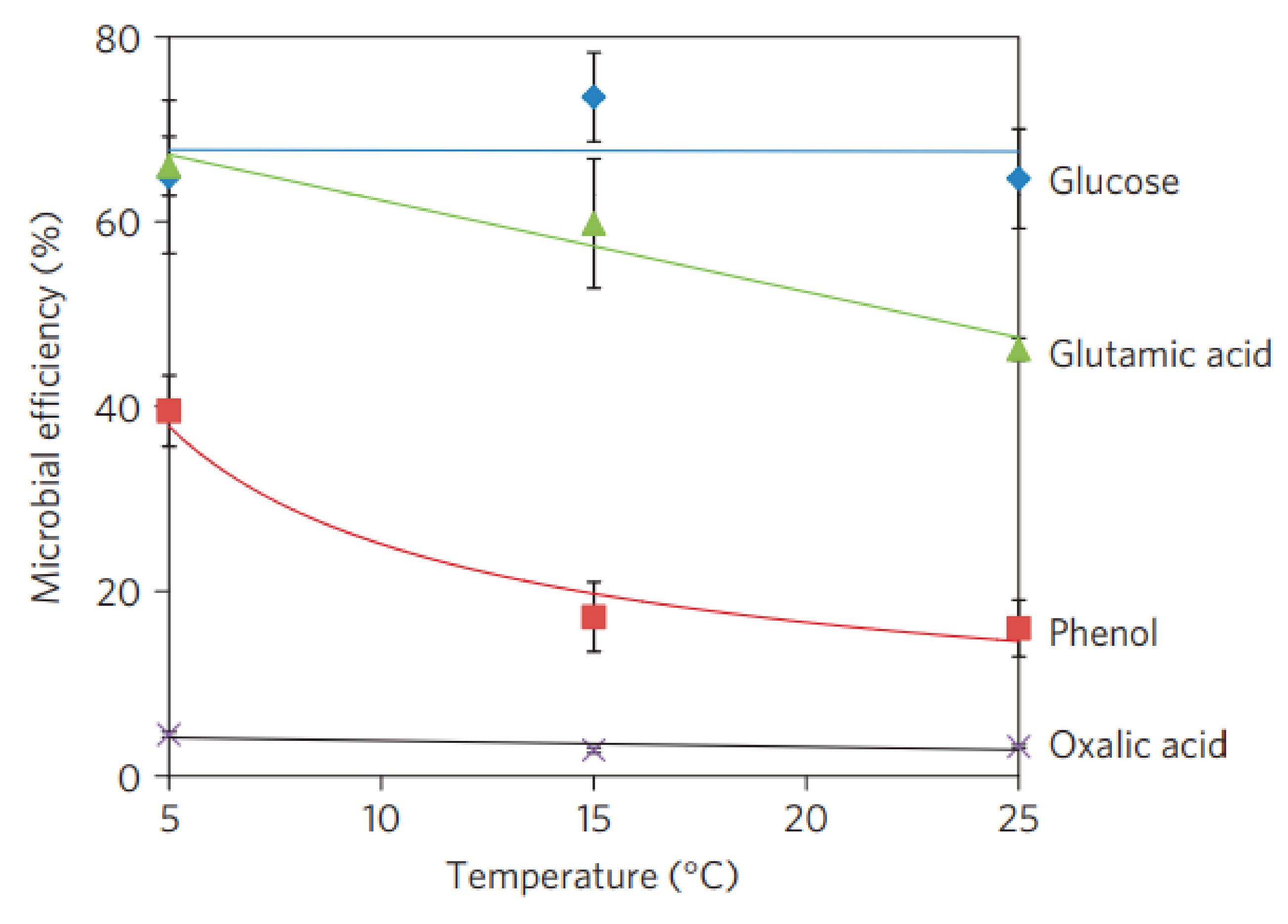
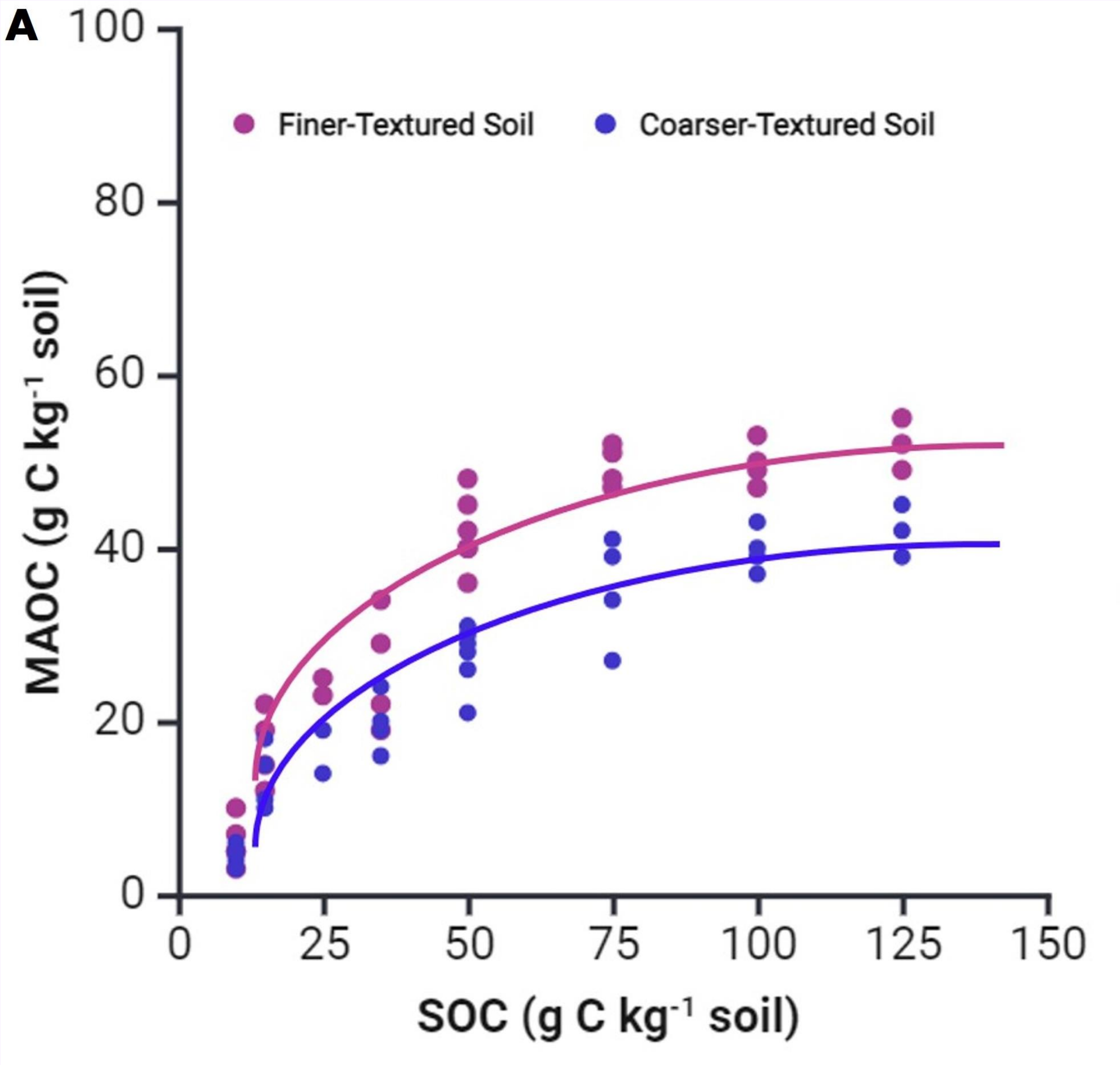


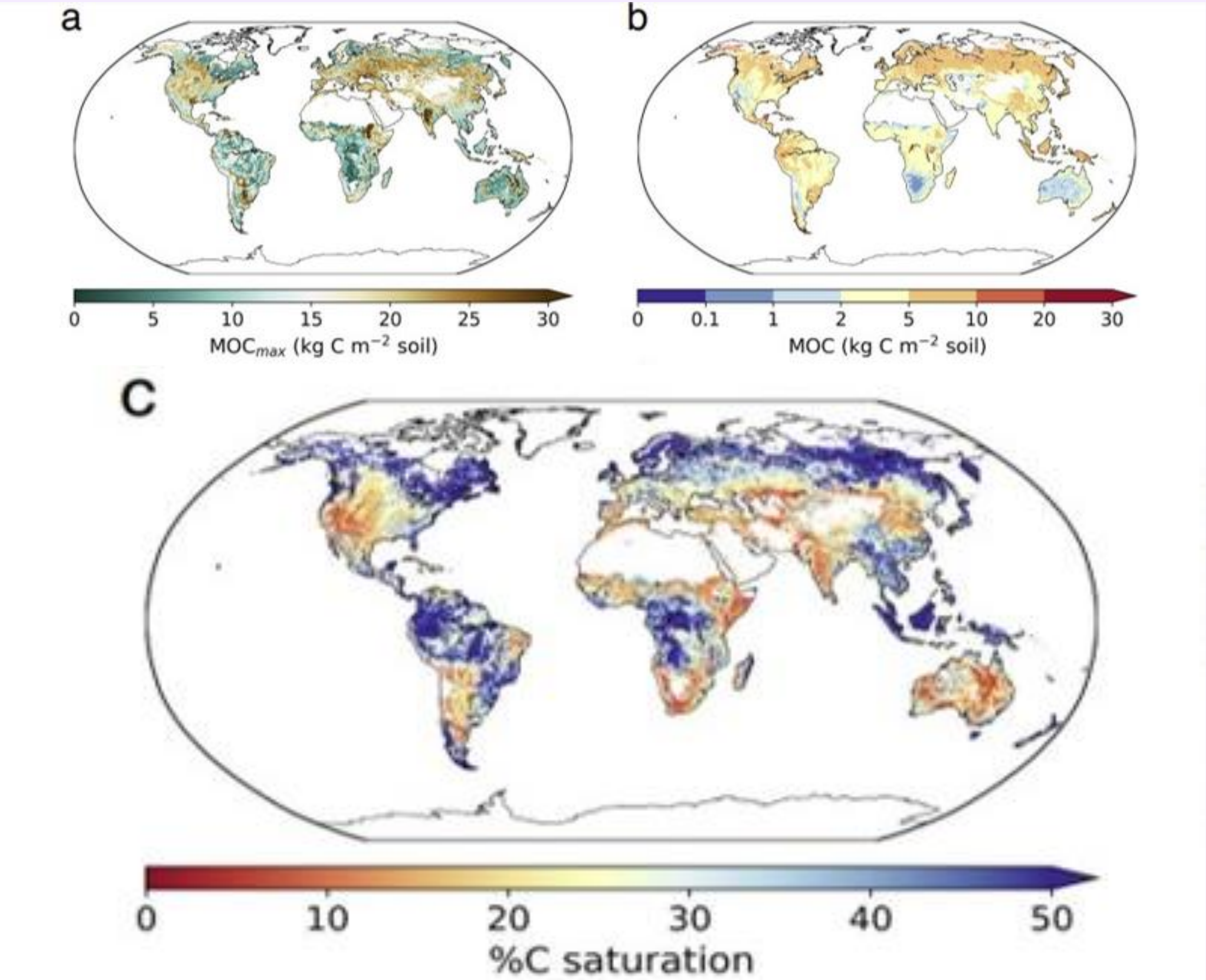
Not all soils are equal in their capacity to store carbon in MAOC

- Textural and mineralogical constraints of soil particles regulate the amount and type of C that can sorb to mineral surfaces
  - Higher surface area and increased mineral reactivity (finer-textured soils) can sorb more carbon
  - Lower surface area and decreased mineral reactivity (coarser-textured soils) sorb less carbon



SOIL CARBON SATURATION AND DEFICIT

- **Carbon Saturation** – the maximum amount of C that a soil can store through mineral-associated interactions ($MOAC_{Max}$; a)
- **Carbon Deficit** – The difference between the maximum (saturated) pool size of MAOC and the current pool size of MAOC (measured as percent saturation; c)



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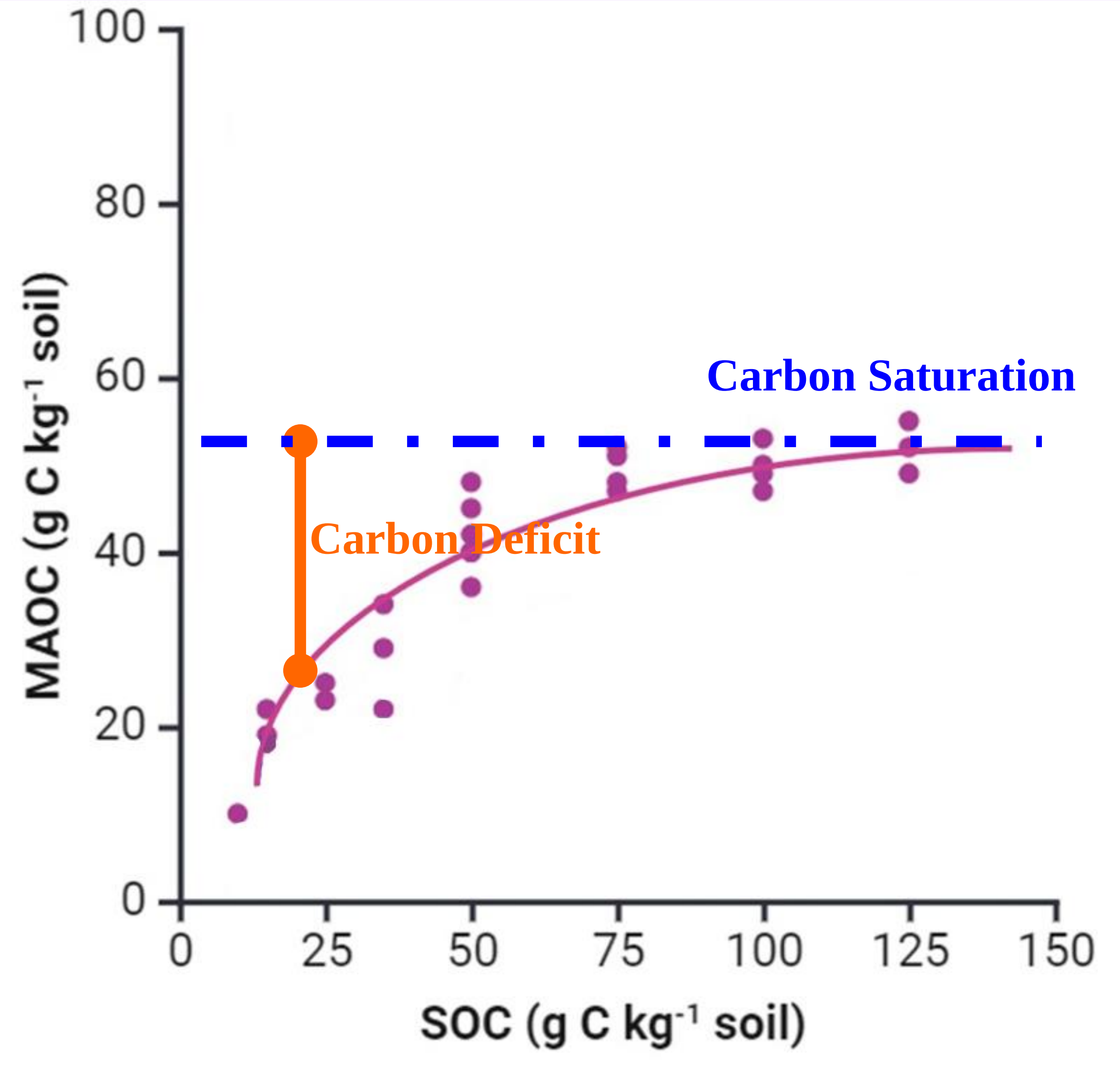
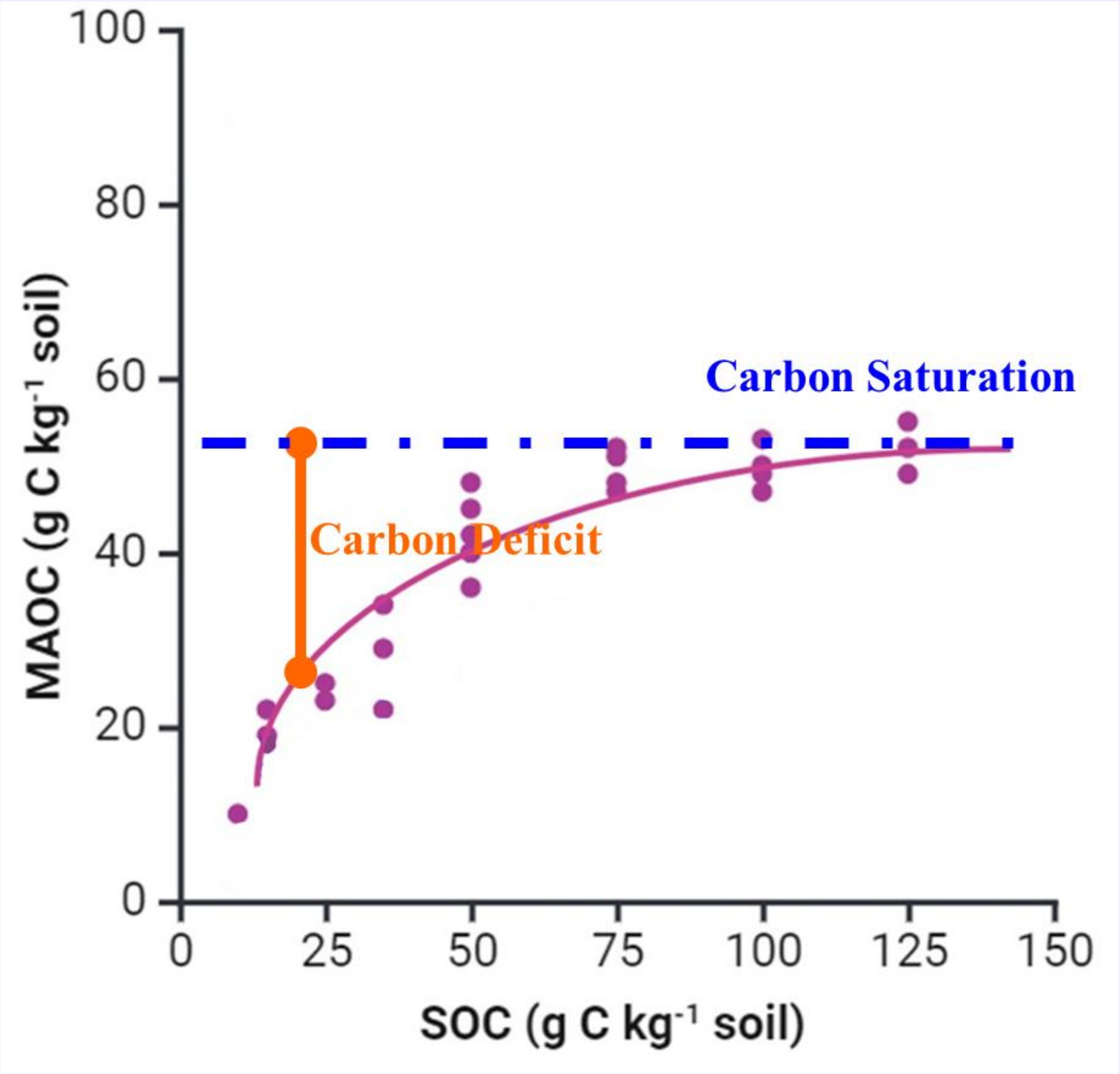


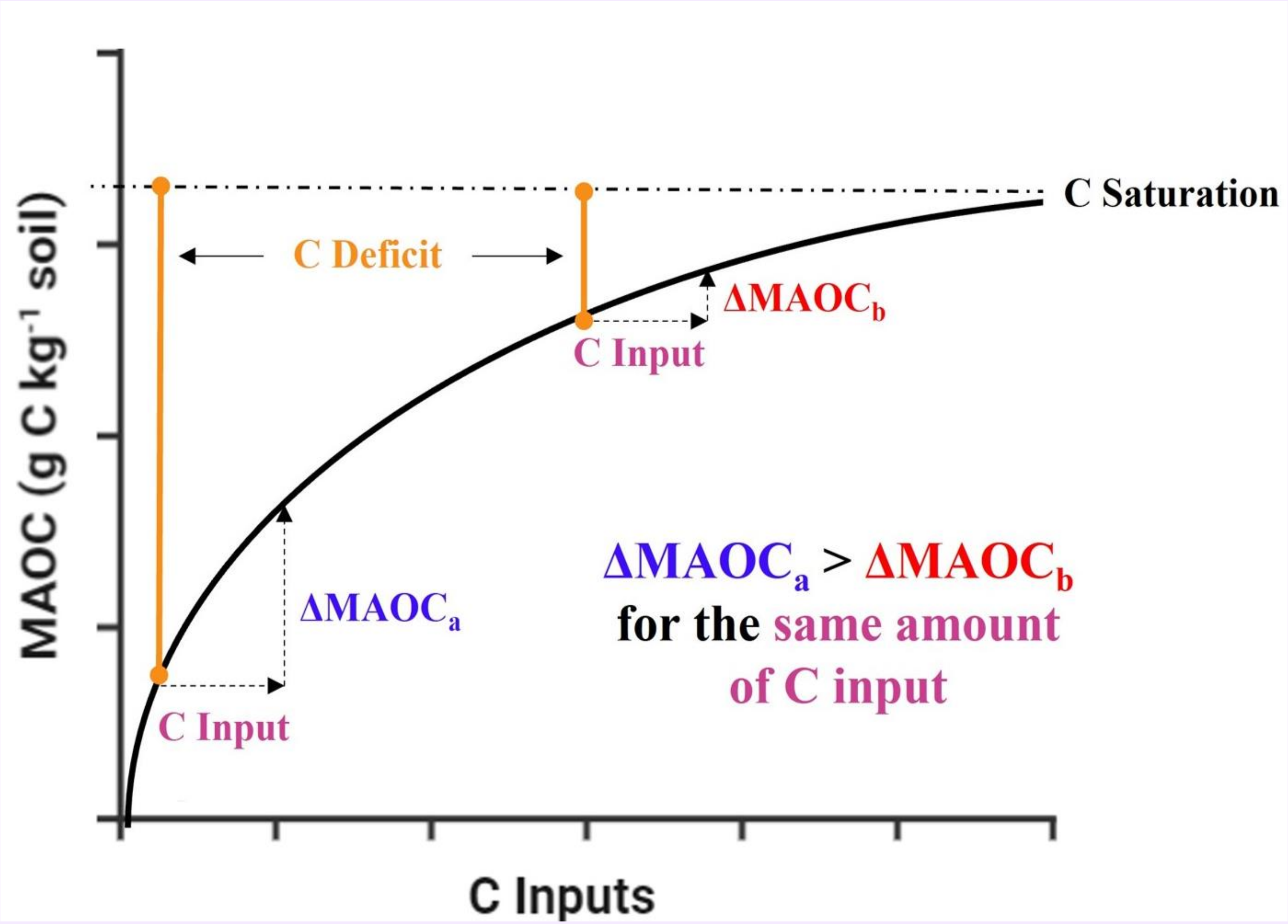
Carbon Saturation Thresholds are Unknown

- We have limited understanding of the total amount of carbon soils can store in the mineral-associated fraction
  - **We do NOT know carbon saturation thresholds for different soils**
    - Without an understanding of carbon saturation, we can't measure the carbon deficit in a given soil



Differential Rates of MAOC Accrual for the Same Carbon Inputs

- The rate of MAOC accrual varies as a function of percent C saturation (or C deficit)
  - Soils with a larger carbon deficit accumulate MAOC more quickly
  - Soils with a lower carbon deficit accumulate MAOC more slowly



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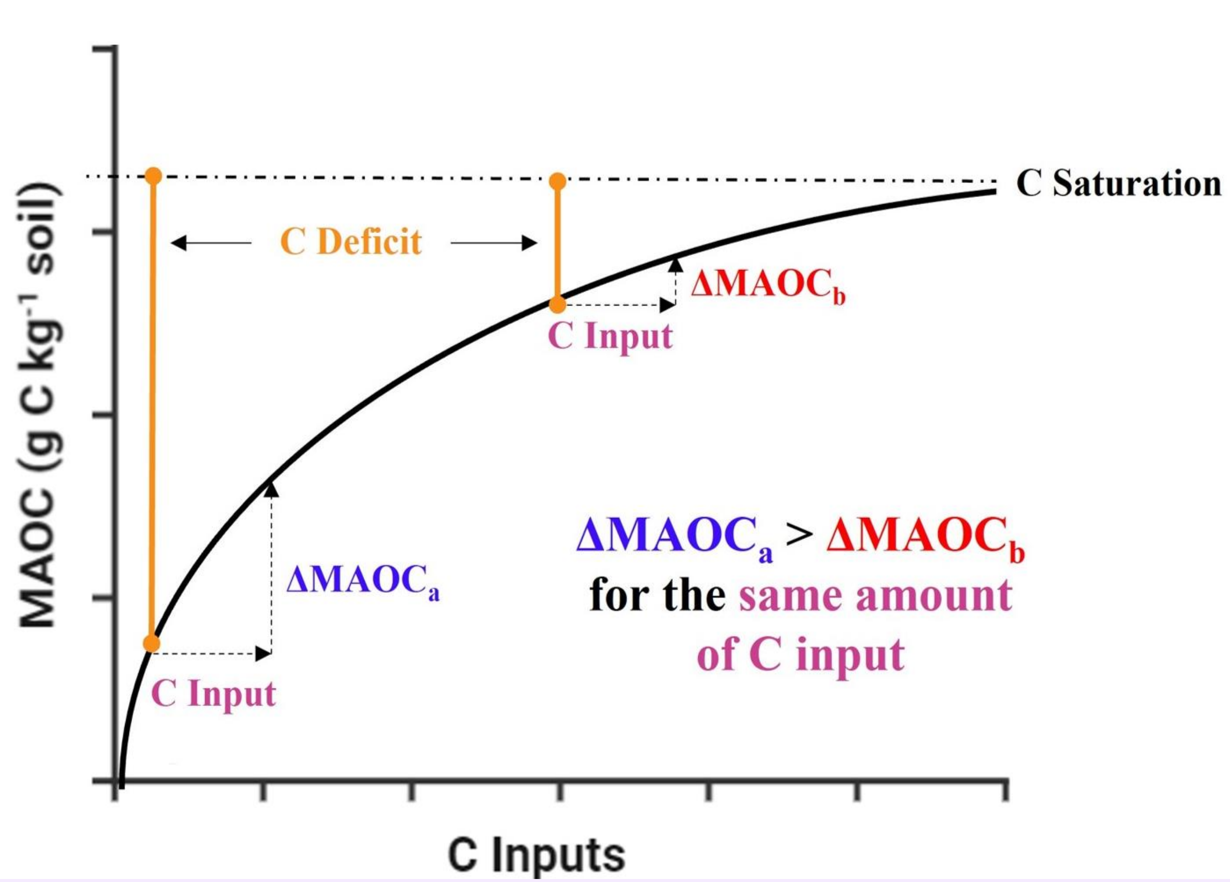
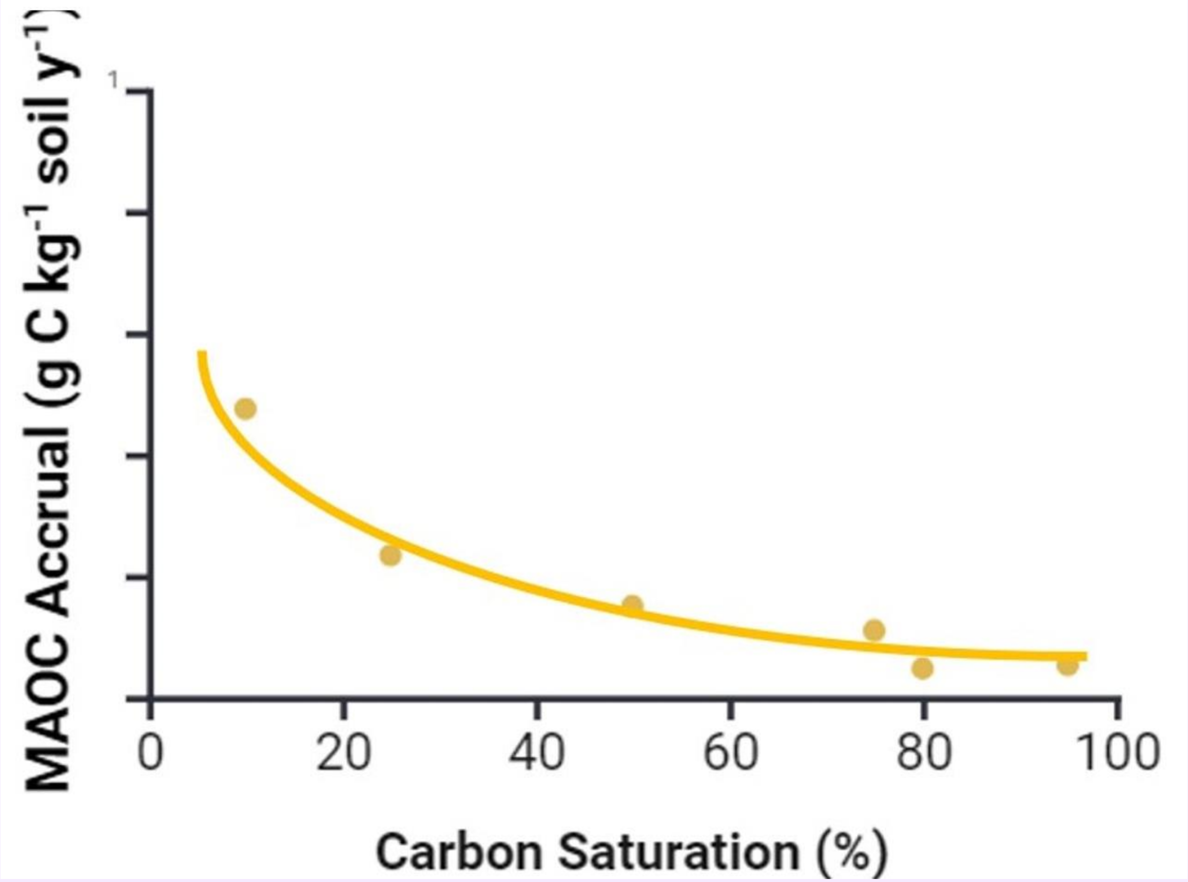
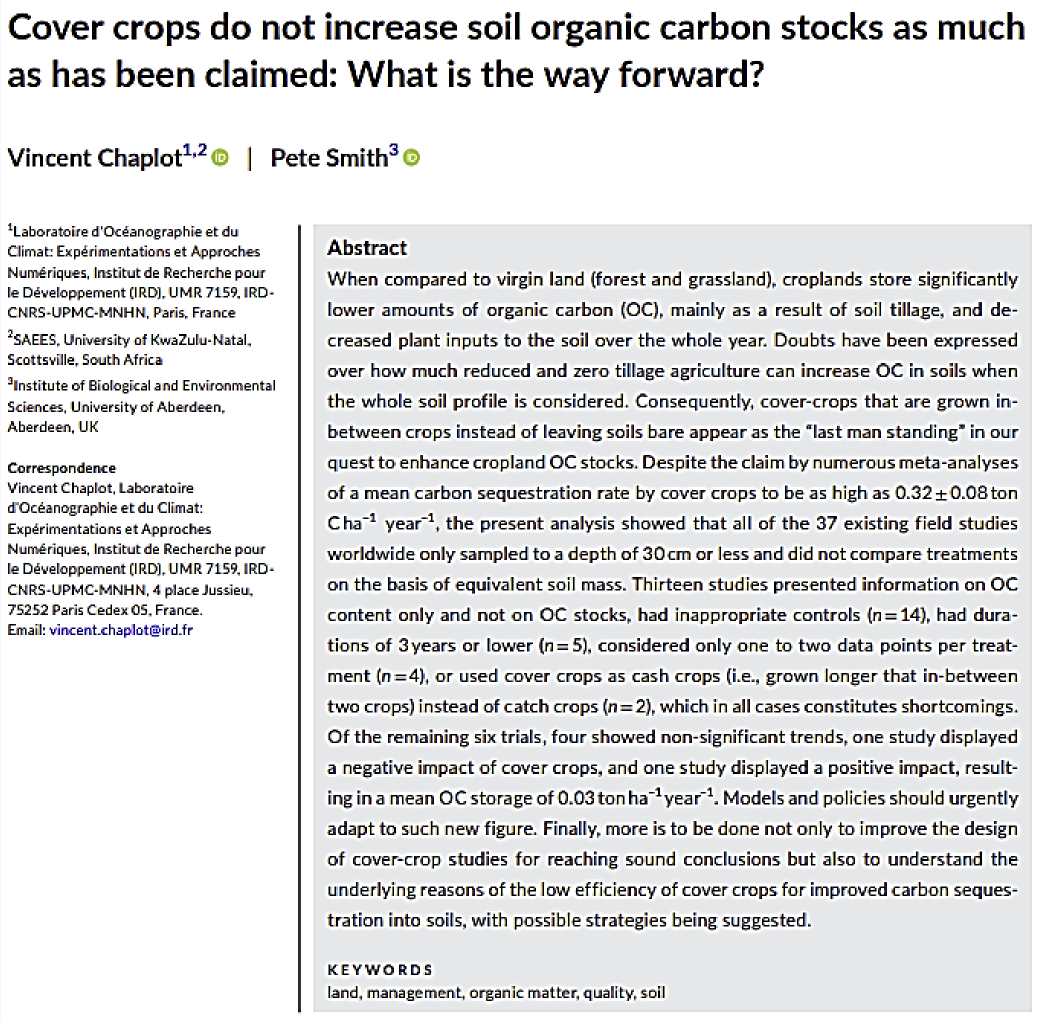




Increasing Carbon Inputs DOES NOT Always Translate to Increases in SOC Stocks



Cover crops do not increase soil organic carbon stocks as much as has been claimed: What is the way forward?

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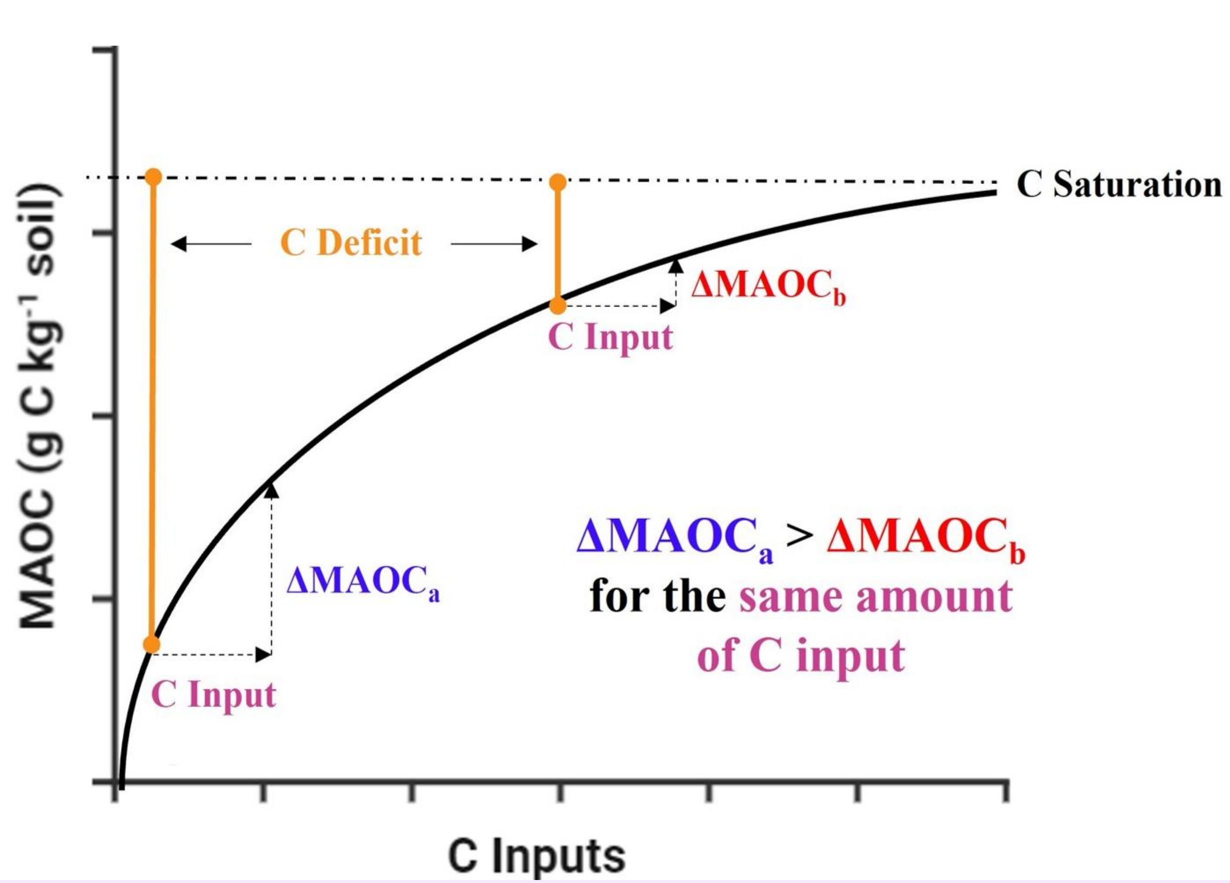
Abstract
When compared to virgin land (forest and grassland), croplands store significantly lower amounts of organic carbon (OC), mainly as a result of soil tillage, and decreased plant inputs to the soil over the whole year. Doubts have been expressed over how much reduced and zero tillage agriculture can increase OC in soils when the whole soil profile is considered. Consequently, cover-crops that are grown in-between crops instead of leaving soils bare appear as the "last man standing" in our quest to enhance cropland OC stocks. Despite the claim by numerous meta-analyses of a mean carbon sequestration rate by cover crops to be as high as 0.32 ± 0.08 ton C ha^{-1} $year^{-1}$, the present analysis showed that all of the 37 existing field studies worldwide only sampled to a depth of 30 cm or less and did not compare treatments on the basis of equivalent soil mass. Thirteen studies presented information on OC content only and not on OC stocks, had inappropriate controls ($n = 14$), had durations of 3 years or lower ($n = 5$), considered only one to two data points per treatment ($n = 4$), or used cover crops as cash crops (i.e., grown longer that in-between two crops) instead of catch crops ($n = 2$), which in all cases constitutes shortcomings. Of the remaining six trials, four showed non-significant trends, one study displayed a negative impact of cover crops, and one study displayed a positive impact, resulting in a mean OC storage of 0.03 ton ha^{-1} $year^{-1}$. Models and policies should urgently adapt to such new figure. Finally, more is to be done not only to improve the design of cover-crop studies for reaching sound conclusions but also to understand the underlying reasons of the low efficiency of cover crops for improved carbon sequestration into soils, with possible strategies being suggested.

KEYWORDS
land, management, organic matter, quality, soil



Mineralogical and environmental constraints are not always equal

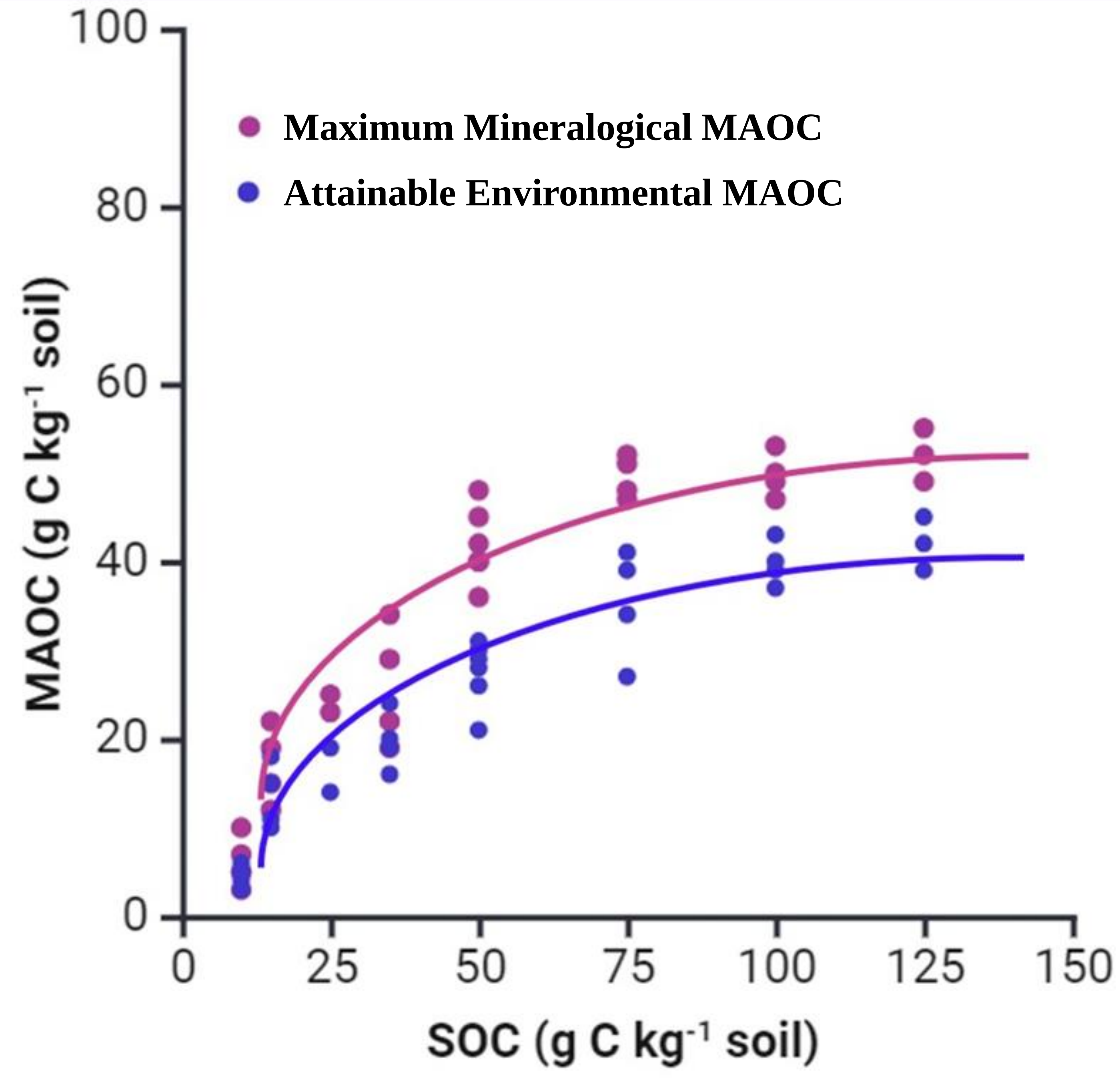
Maximum MAOC

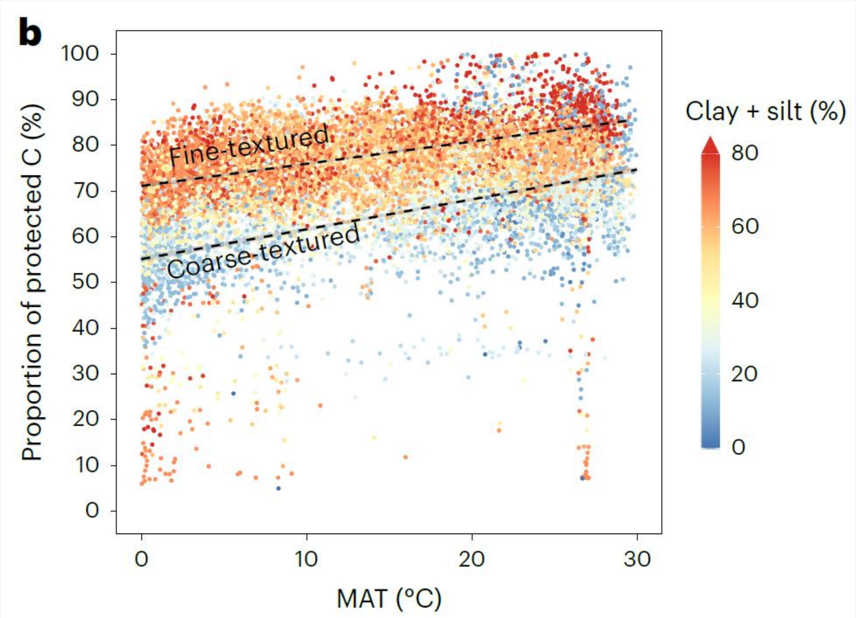
- The maximum amount of MAOC a soil can store based on textural or mineralogical constraints
  - Silt vs. clay content
  - Iron oxides

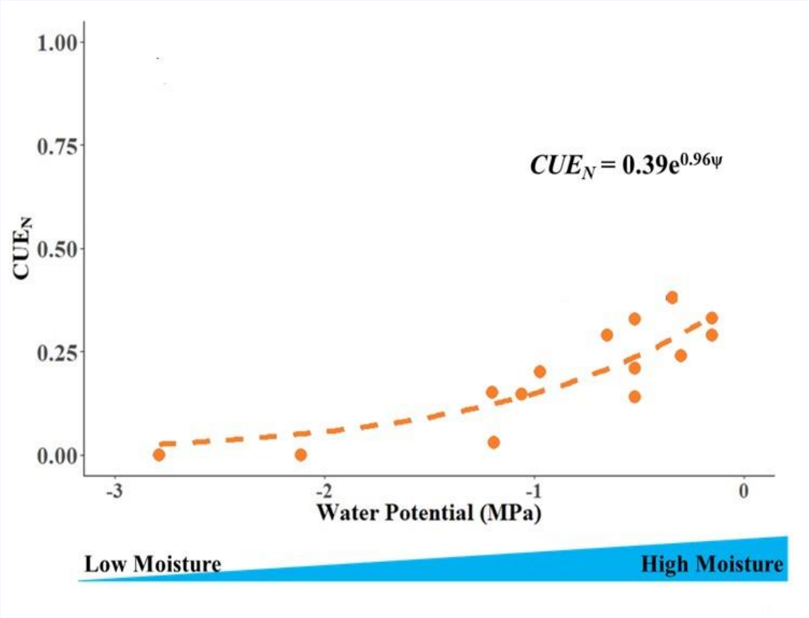
Attainable MAOC

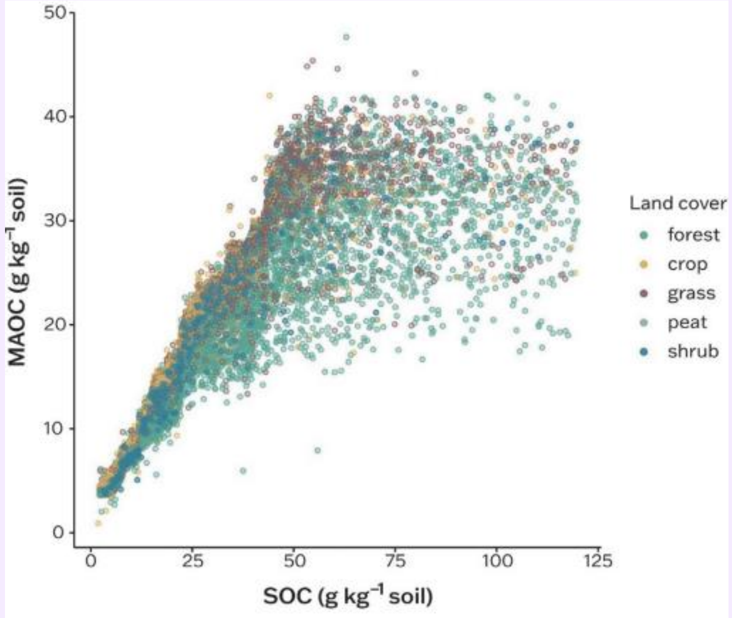
- The maximum amount of MAOC a soil can store based on environmental constraints
  - Temperature
  - Moisture
  - pH
  - Microbial activity and physiology
  - Microbial community composition and structure
  - **Land management**

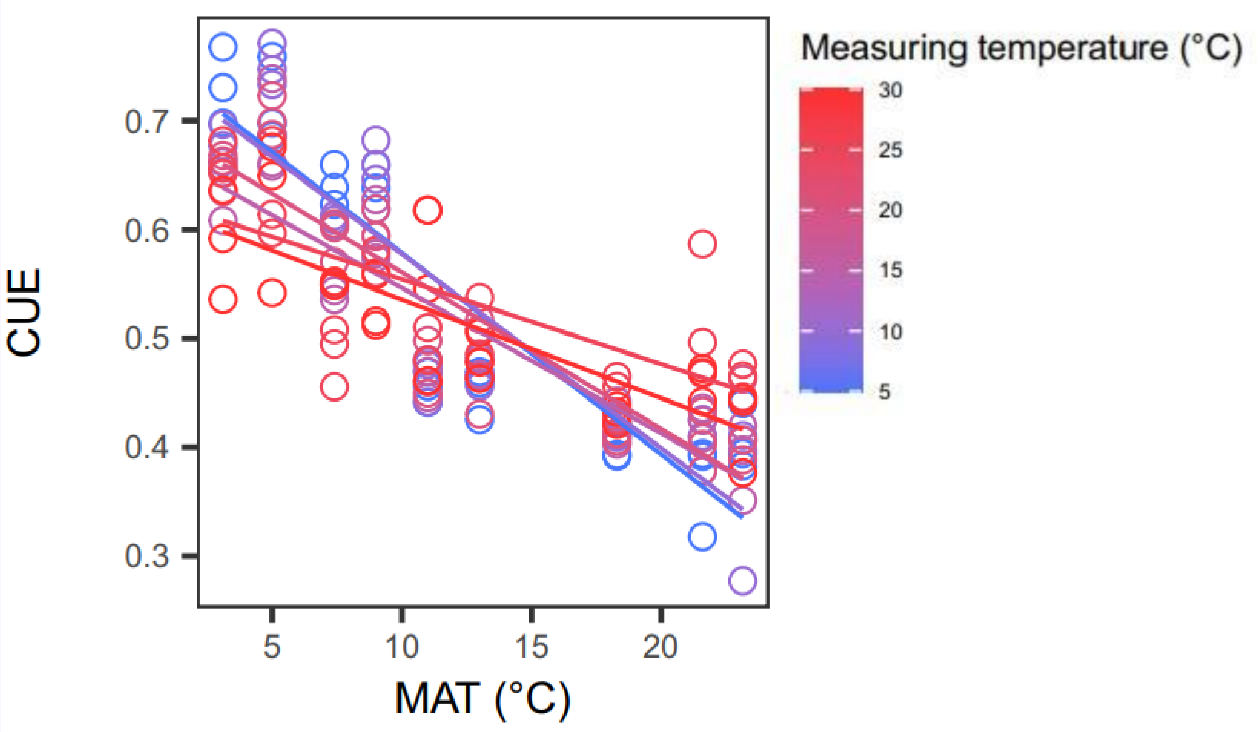
Mineralogical and environmental constraints on C saturation are not always equal

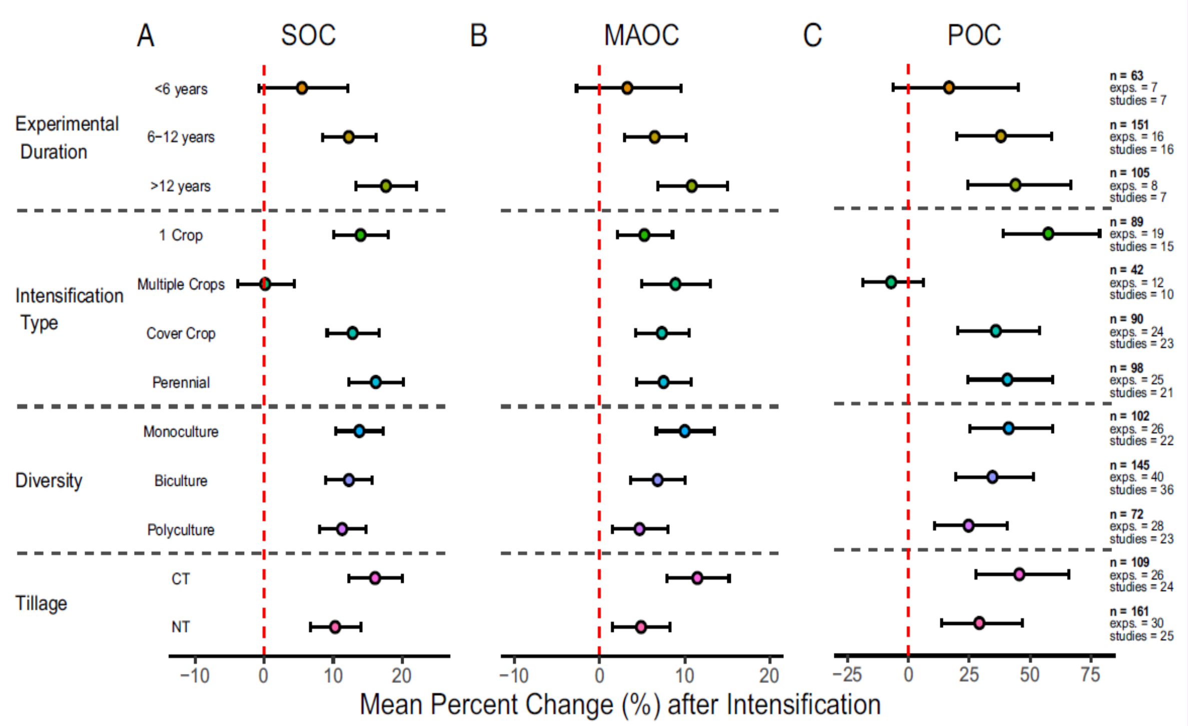



b
Proportion of protected C (%)
Fine-textured
Coarse-textured
MAT (°C)
Clay + silt (%)


$CUE_N = 0.39e^{0.96\psi}$
CUE_N
Water Potential (MPa)
Low Moisture
High Moisture


MAOC (g kg^{-1} soil)
SOC (g kg^{-1} soil)
Land cover
forest
crop
grass
peat
shrub


CUE
MAT (°C)
Measuring temperature (°C)


A
SOC
B
MAOC
C
POC
Experimental Duration
<6 years
6–12 years
>12 years
Intensification Type
1 Crop
Multiple Crops
Cover Crop
Perennial
Diversity
Monoculture
Biculture
Polyculture
Tillage
CT
NT
n = 63 exps. = 7 studies = 7
n = 151 exps. = 16 studies = 16
n = 105 exps. = 8 studies = 7
n = 89 exps. = 19 studies = 15
n = 42 exps. = 12 studies = 10
n = 90 exps. = 24 studies = 23
n = 98 exps. = 25 studies = 21
n = 102 exps. = 26 studies = 22
n = 145 exps. = 40 studies = 36
n = 72 exps. = 28 studies = 23
n = 109 exps. = 26 studies = 24
n = 161 exps. = 30 studies = 25
Mean Percent Change (%) after Intensification

Not All Soil Carbon is Created Equally

1) Soil Organic Carbon

i. Soil carbon cycling
ii. Soil carbon and climate change
iii. Carbon in agricultural systems
iv. New paradigm of soil carbon

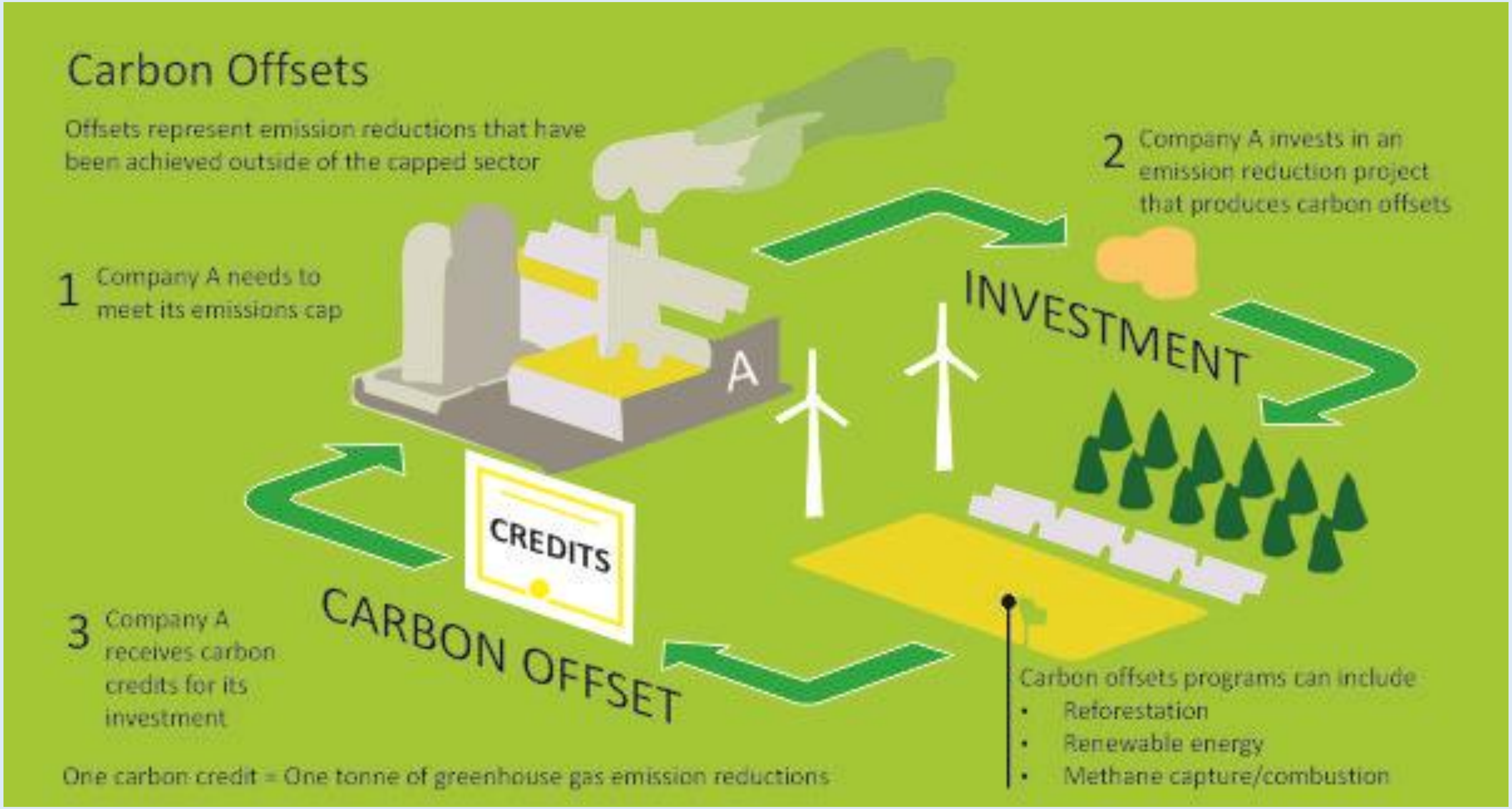
2) The Knowns and Unknowns of Soil C

i. Soil microbes and soil carbon
ii. Soil carbon saturation and deficit
iii. Maximum MAOC vs Attainable MAOC

3) Carbon Credits?

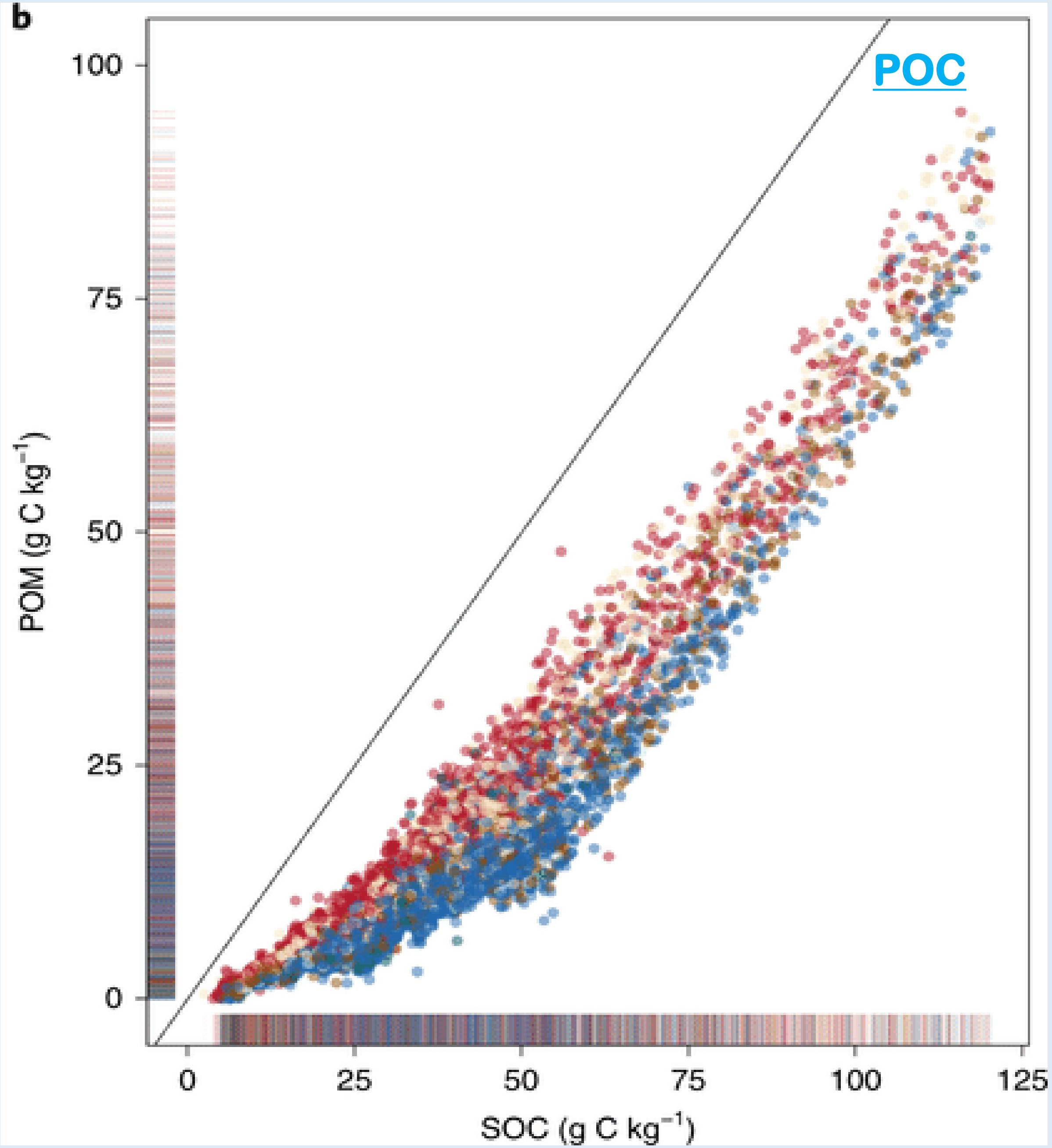
i. Can we monetize C sequestration?

Can we monetize carbon sequestration?



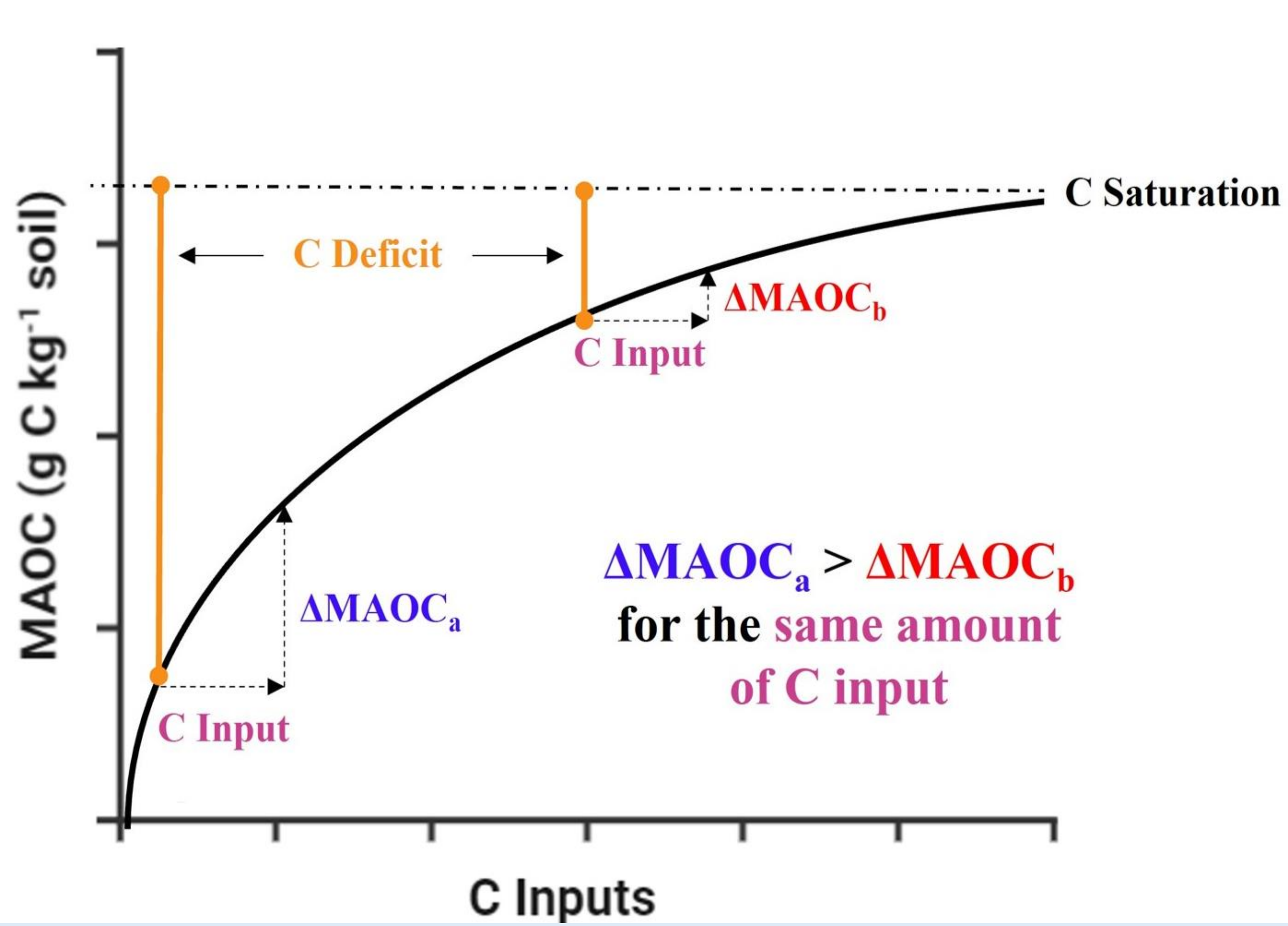
Use of total organic carbon is NOT sustainable for a Carbon Credit Model

- Total organic carbon includes both particulate organic carbon (POC) and mineral-associated organic carbon (MAOC)
  - Particulate organic carbon accumulates indefinitely
    - Producers and ranchers could be paid indefinitely and increasingly for carbon added to soil that is not actually sequestered



Without understanding carbon saturation, we cannot equitably compensate producers and ranchers

- We cannot estimate carbon deficits
  - If credits are based on MAOC accrual rates, then inequities will exist
    - Producers/ranchers closer to saturation will see slower accrual of MAOC, despite potentially having more sequestered carbon on their land



Can we monetize carbon sequestration?