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forward together
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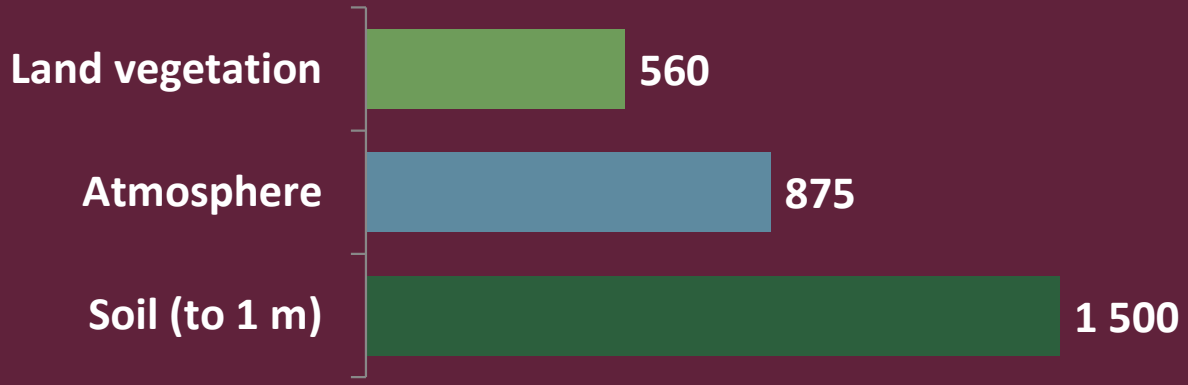
The Carbon Cycle: What we should Learn from it?

CE Clarke and AG Hardie Department of Soil Science

Talk Outline

- What Carbon does for Soils?
- The Carbon Cycle
  - Soil Carbon Chemistry: Pools of Carbon in Soils
  - Storage pathways
  - Photosynthesis
  - Carbon inputs into soils
- South African Context
- Carbon for Credits
- What can we learn from the Carbon Cycle

Carbon in the soil: What is the Hype about?



Approx. billion tonnes of carbon

So even a small percentage change in soil carbon is huge in absolute terms — the basis of the "4 per 1000" idea, and of carbon farming.

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Carbon in the soil: SOM what the hype SHOULD be about?

Functions of SOM in the Soil

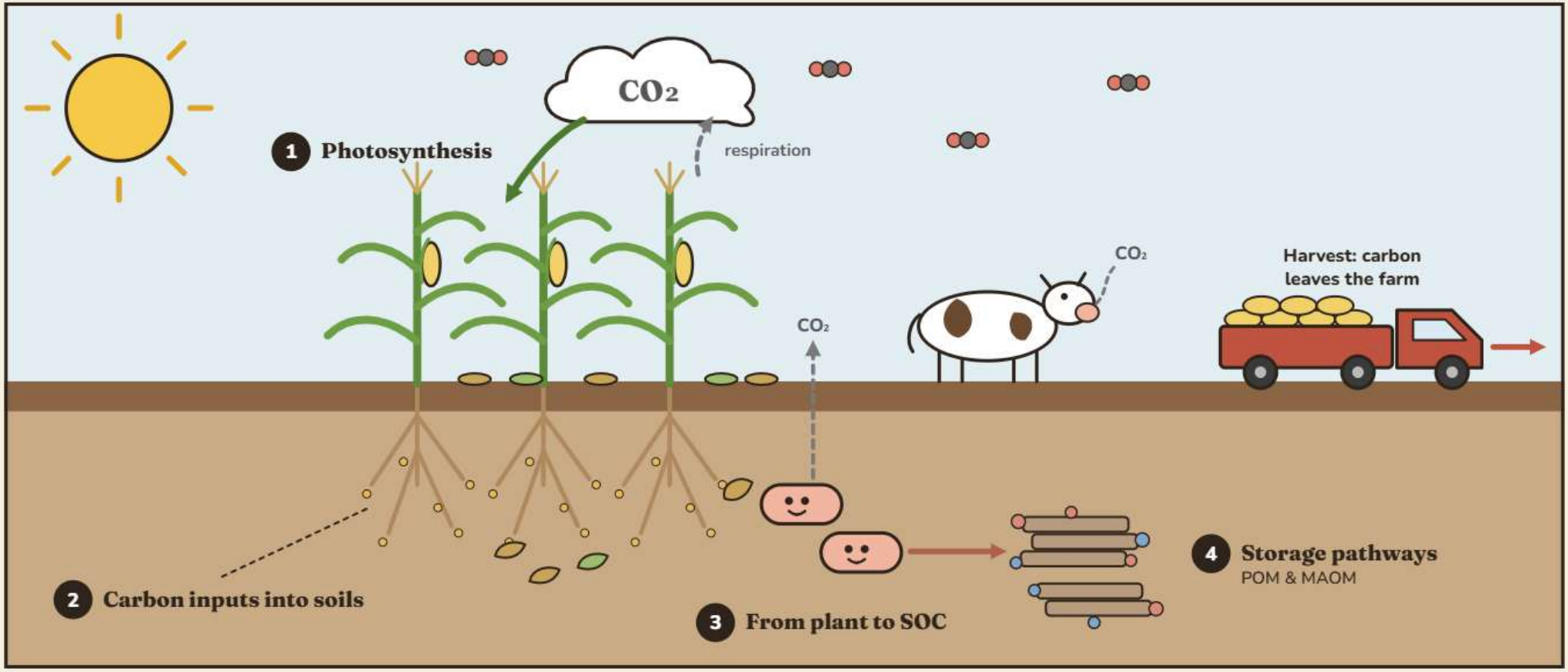
- All the attributes we would assign to a healthy soil
  - Nutrient cycling
  - Nutrient availability
  - Chemical buffering (eg Al toxicity)
  - Water holding capacity
  - Microbial diversity
  - Structural stability



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The Carbon Cycle

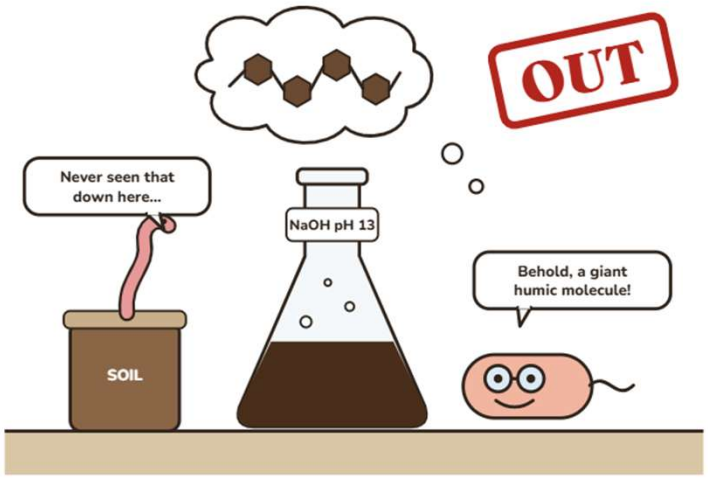
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Soil Carbon Chemistry has Changed since we were at University

Out: humic & fulvic acids. In: POM & MAOM.

Soil scientists have retired the idea that soil carbon is made of giant, stable “humic” molecules. What matters is whether organic matter is protected.

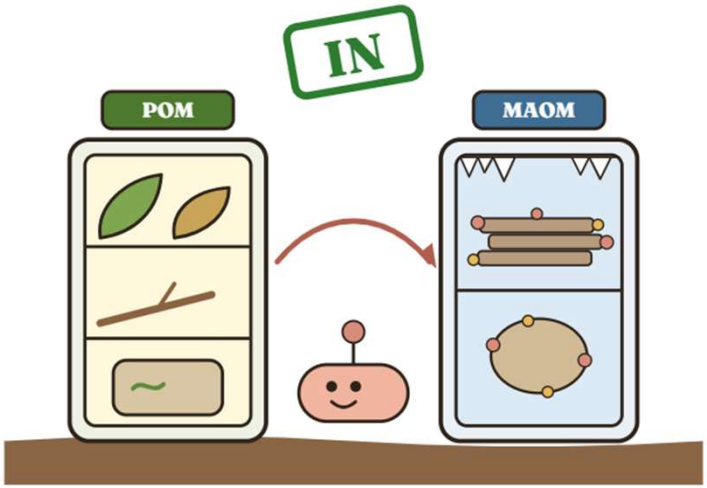


The old story: humification

Plant matter was thought to be “humified” into huge, dark, complex molecules.

They supposedly lasted because microbes couldn’t break them down.

The evidence: brown extracts made with strong alkali, largely a lab artefact.



The current view: protection

Organic matter is a continuum of ever-smaller pieces that microbes keep processing.

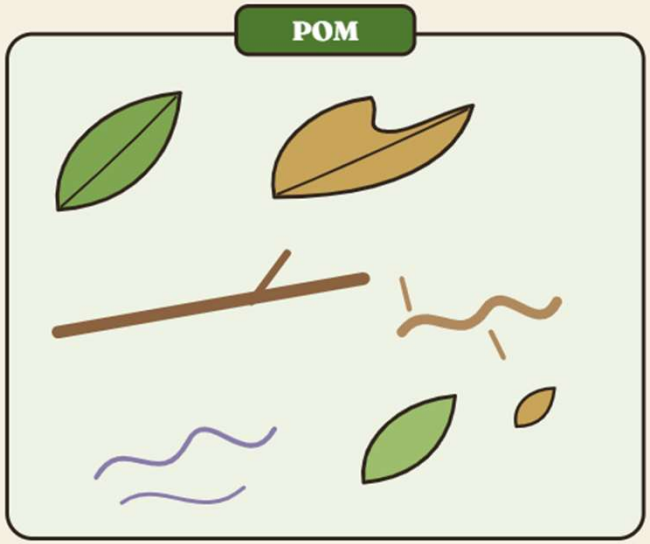
It lasts when it’s protected: stuck to minerals (MAOM) or sealed in aggregates (POM).

The evidence: imaging and spectroscopy of soil in its natural state.

Current Understanding of SOC is one of preservation

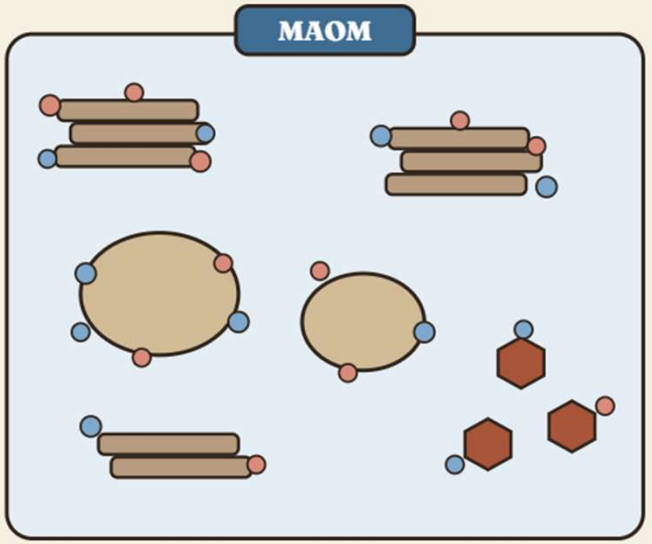
Two kinds of soil carbon

POM (particulate organic matter) is plant debris in the soil. MAOM (mineral-associated organic matter) is carbon stuck to mineral surfaces, and it lasts far longer.



Particulate organic matter

plant and fungal fragments; years to decades
lost when the soil is disturbed



Mineral-associated organic matter

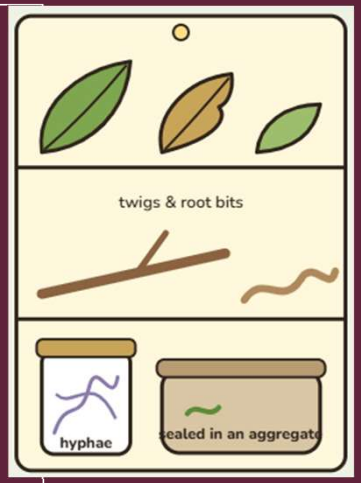
carbon on clay, silt and oxides; decades to centuries
must come off the mineral first

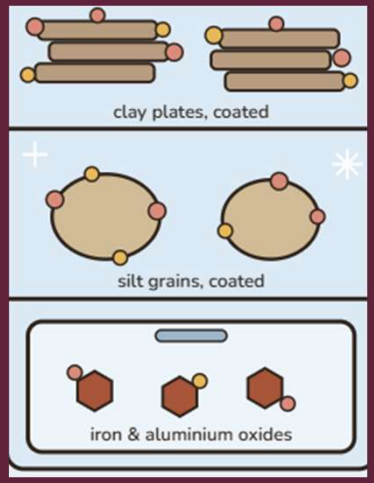
necromass-derived plant-derived (DOC)

Carbon Pools In Soils: Not all C is equal

POM

- **Active** C Pool (years to decades)
- **Accessible** to microbes
- **Recognisable** (under a microscope) fragments of litter and roots
- **Light**: Contains Plant and Fungal remains
- **High C:N** Ratio (typical of litter)

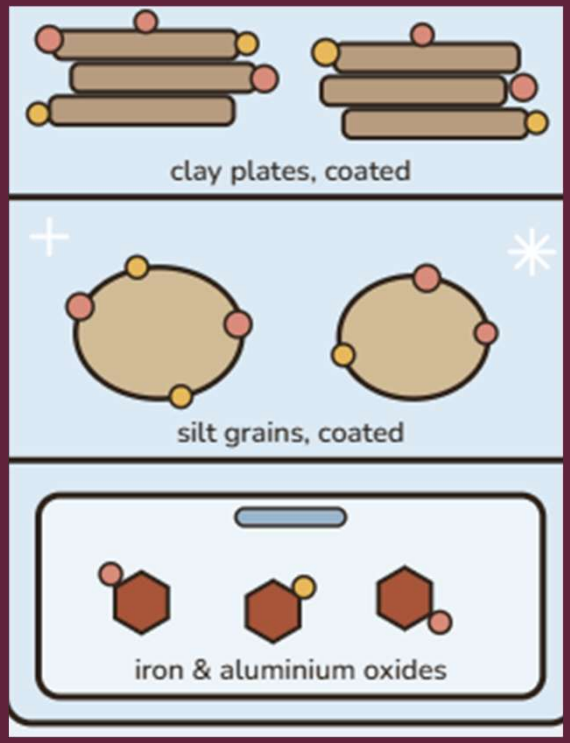




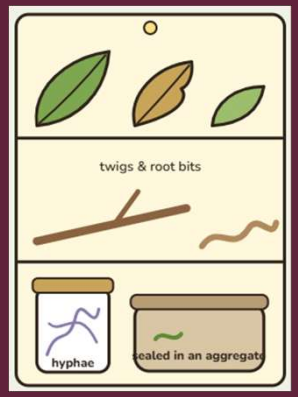
MAOM

- Carbon that has adsorbed onto **mineral surfaces**
- **Stable** (inaccessible to microbes) – decades to centruries
- **Heavy:** bound to minerals
- **Low C:N** ratio (same stoichiometry as microbes)

Soil Carbon Pool Sizes



>



MAOM makes up the majority of SOC

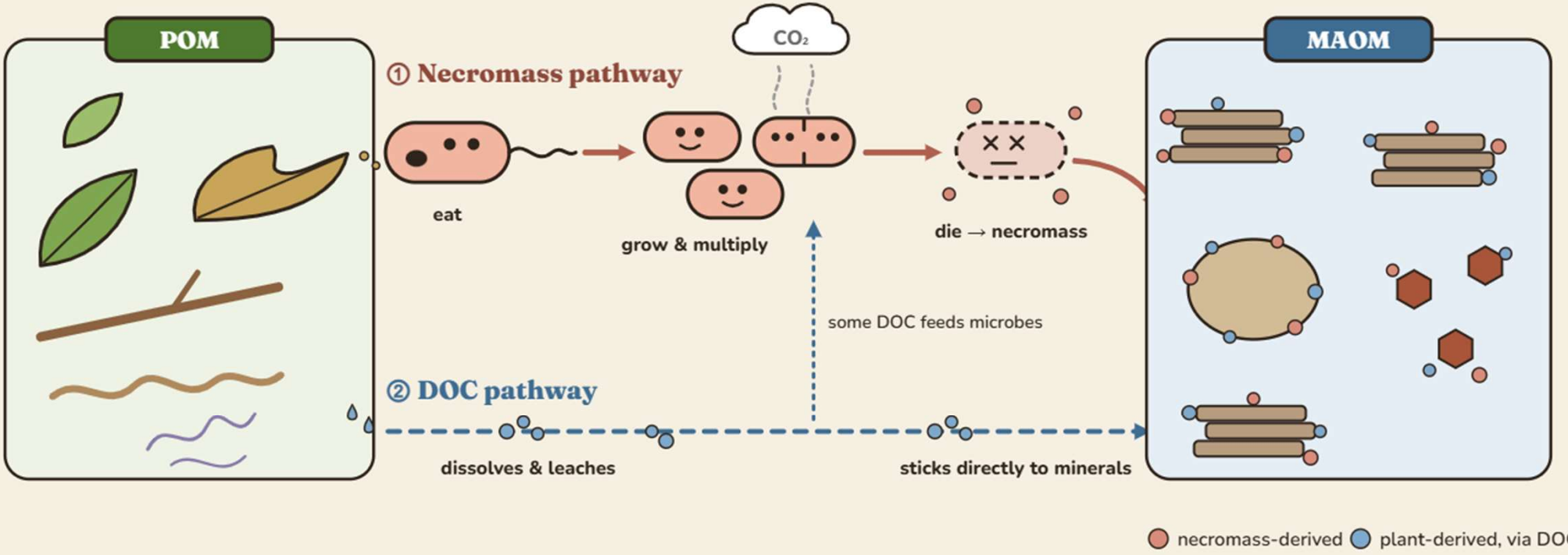
72-79% of SOC – Croplands (Lugato et al 2021)

70-72% of SOC -Grasslands

POM makes up smaller proportion and is most sensitive to management

Proportion decreases with conversion of grassland to cropland (Lugato et al 2021)

Formation of Stable MAOM



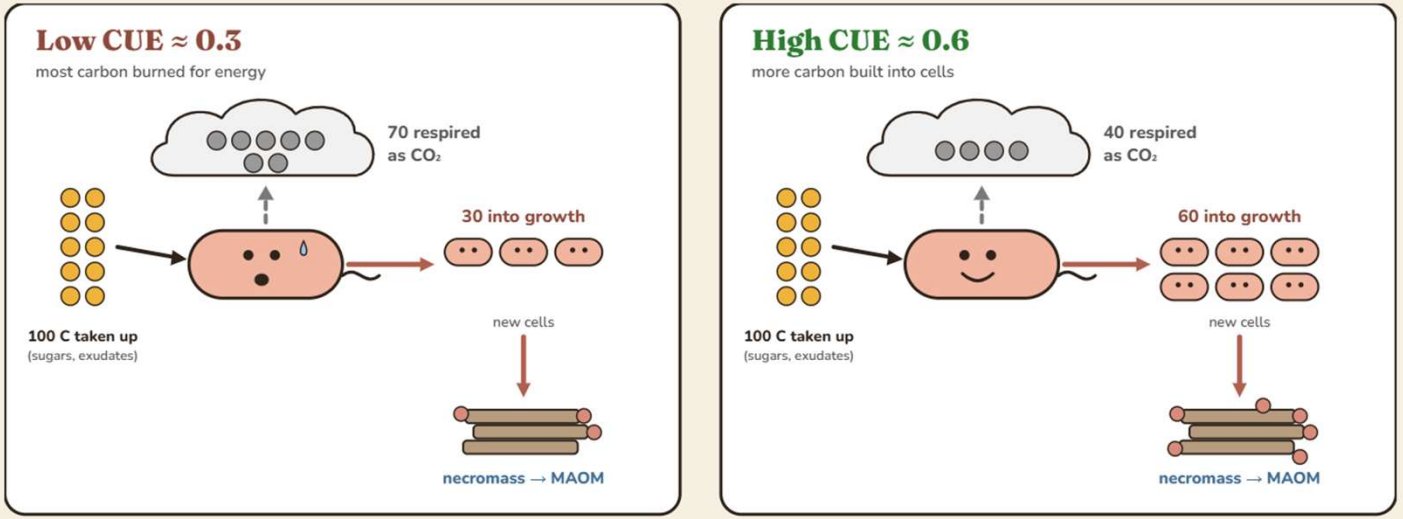
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Formation of Stable MAOM

- **Historically**: More recalcitrant the OM the longer it would persist in the soil and increase SOM – via formation of large macromolecules
- **Modern Theory**: SOM is built through microbial necromass that form associations with mineral surfaces. **The easier a substrate can be converted into microbial biomass the greater its contribution to SOM**
- Proof of the modern theory:
  - **Stoichiometry**
    - C:N ratio of topsoils = 8-13 (In general SOM has a remarkably stable stoichiometry despite wide range in land use and environments)
    - C:N ratio of plant residues = 20-120
    - C:N ratio of microbes = 5-10

Carbon Use Efficiency: Major Driver of SOM Accumulation

CUE = carbon used for growth ÷ carbon taken up. The rest is respired as CO_2. Same meal, but the efficient microbe leaves twice as much carbon behind for the soil.



each dot = 10 units of carbon. Illustrative values: measured soil CUE typically falls between about 0.2 and 0.6.

What controls CUE?

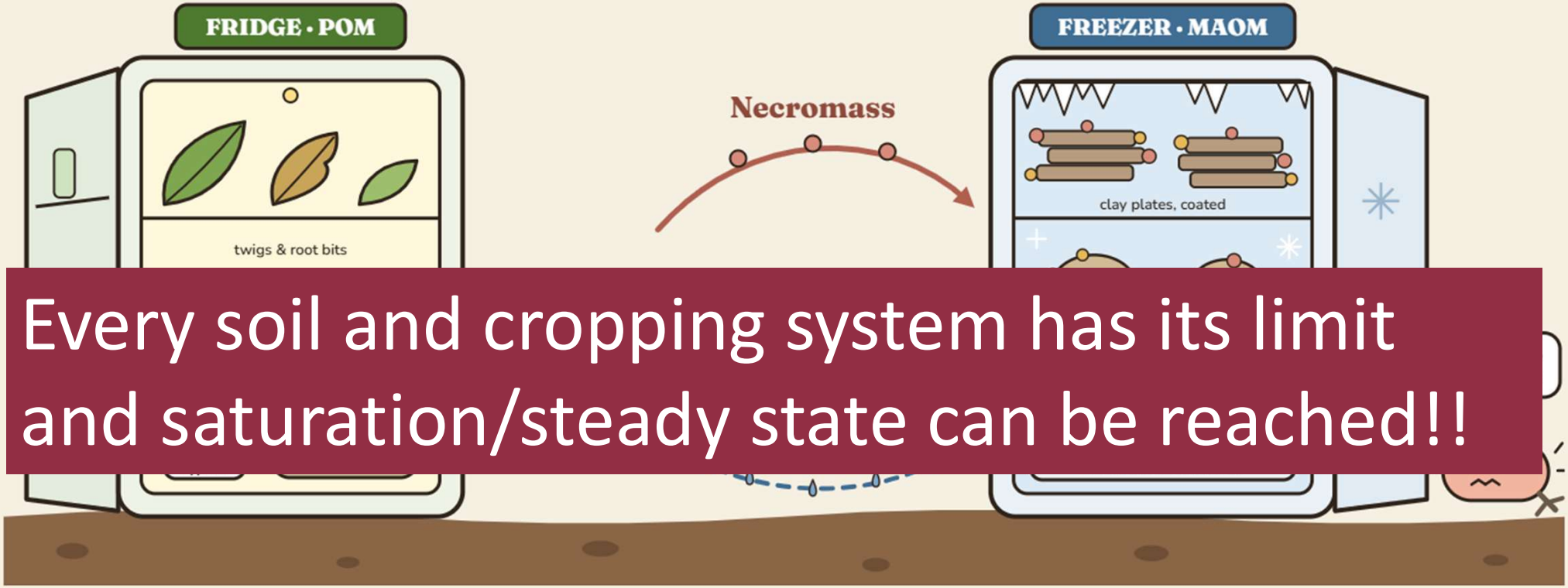
Substrate C:N
- ▲ **raises:** balanced food, near 24:1
- ▼ **lowers:** high C:N residues: surplus carbon is respired

Nitrogen & phosphorus
- ▲ **raises:** adequate N and P
- ▼ **lowers:** nutrient shortage

Temperature
- ▲ **raises:** moderate temperatures
- ▼ **lowers:** warming, though microbes partly acclimate

Moisture
- ▲ **raises:** steady, moist soil
- ▼ **lowers:** drought and dry–wet cycles: stress costs energy

SOC has a cap: MAOM needs mineral storage



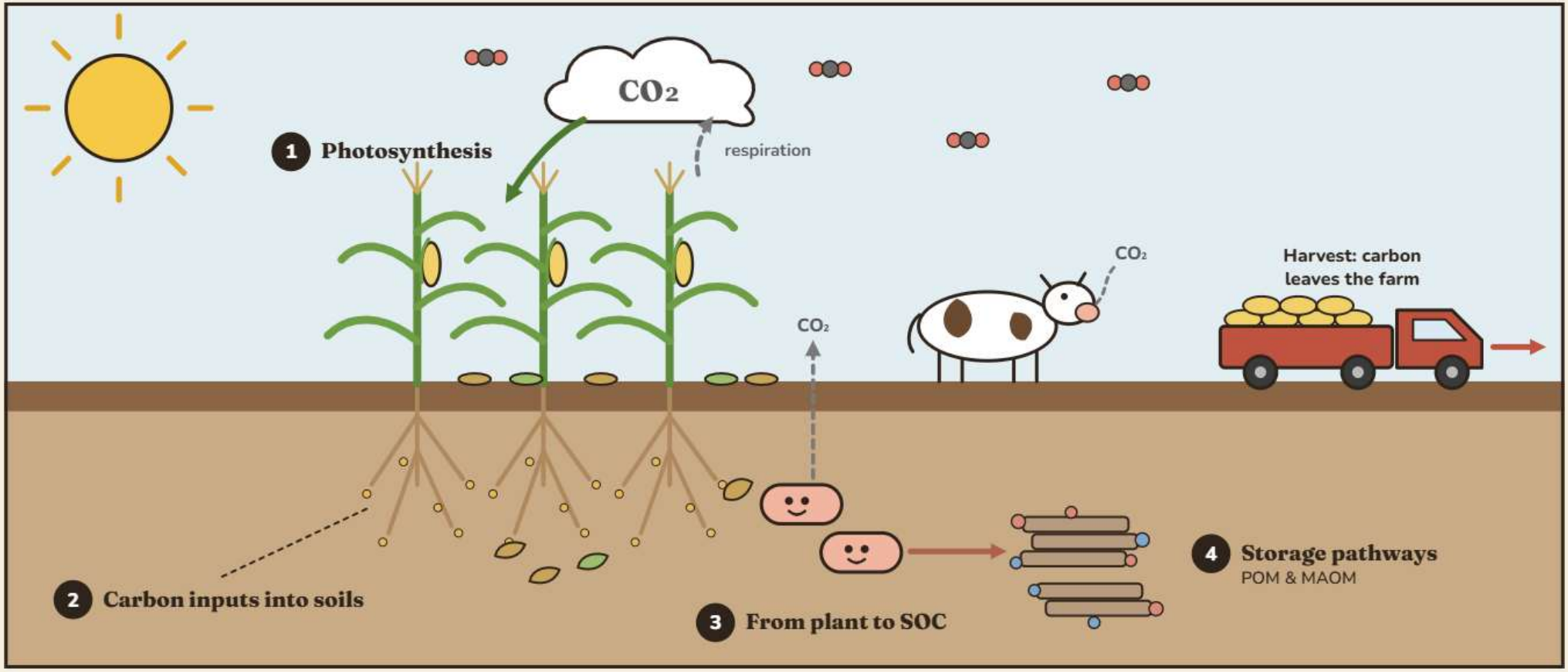
Every soil and cropping system has its limit and saturation/steady state can be reached!!

POM can will accumulate until it reaches steady state with the cropping system
Soils have an upper limit of MAOM storage: Clayey soils have more available surface area for OM stabilization than light textured soils.

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The Carbon Cycle

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Photosynthesis: Agricultures Carbon Pump

$$6\,CO_2 + 6\,H_2O + \text{nutrients} + \text{sunlight} \rightarrow C_6H_{12}O_6 + 6\,O_2$$

Crops fix roughly 10% C of the land's primary production

Farmers are responsible for the largest deliberate C capture on the planet – what happens to this C after it has been captured



Photosynthesis: Agricultural C Balance

$$6\,CO_2 + 6\,H_2O + \text{nutrients} + \text{sunlight} \rightarrow C_6H_{12}O_6 + 6\,O_2$$

Crop production can be both part of the **solution** to climate change and part of the problem and part of this depends on the **management of nutrients**

Part of the solution

- **Balanced plant nutrition** drives the biomass that captures carbon in the first place — no productivity, no sequestration.
- **Stabilising carbon** in soil physically requires nutrients, making soil fertility the enabler of carbon farming. Kirkby et al showed balanced supply of nutrients increased MAOM 2-8-fold, but was lost when inputs stopped

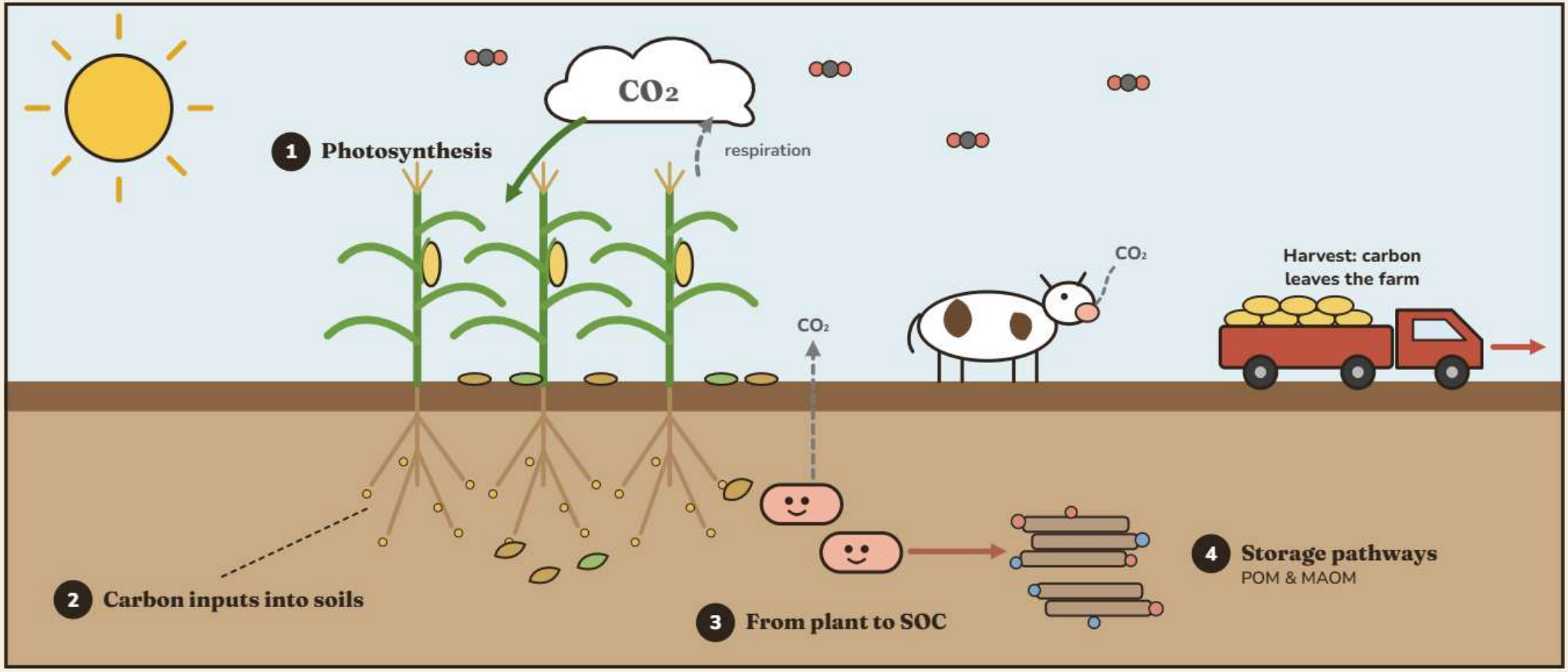
Part of the problem

- Nitrogen fertilizer is linked to an estimated **2–3% of global greenhouse-gas emissions across its life cycle.**
- **Nitrogen emissions from is the largest proportion of this?** – N_2O emissions from cropland in SA is poorly understood, but excess N application more likely to increase N_2O emissions

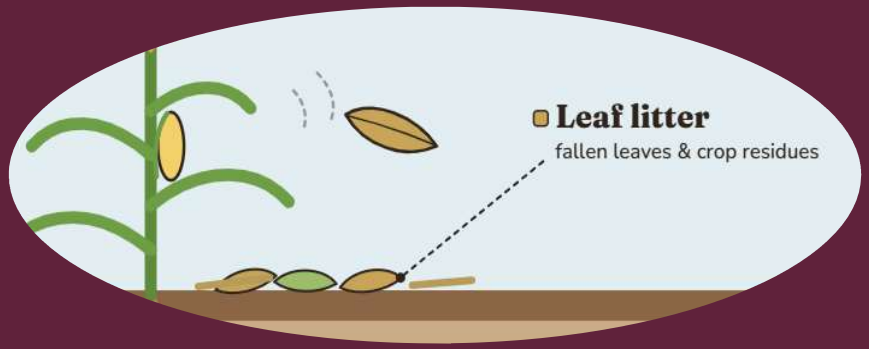
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The Carbon Cycle

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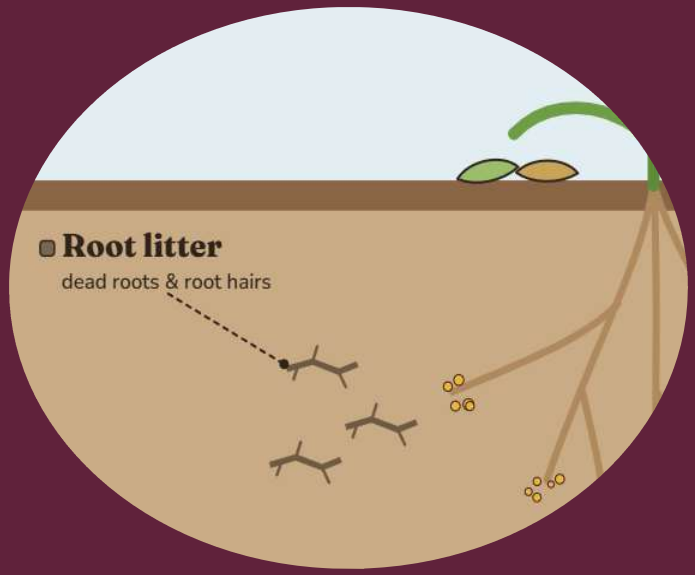


Additions to Soils: Above Ground Litter



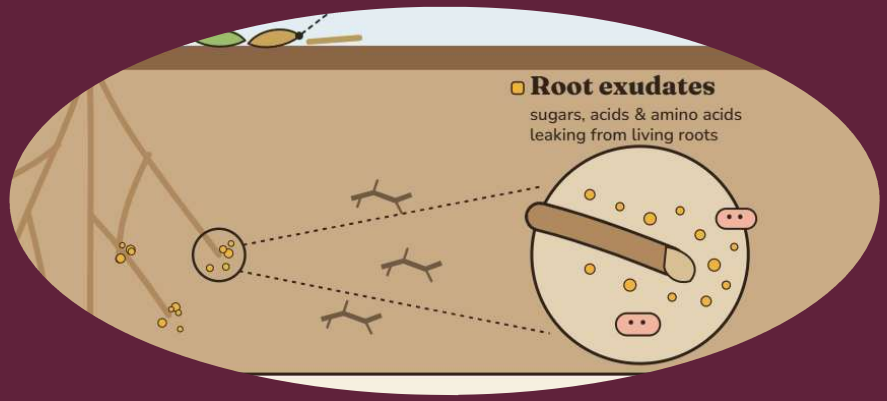
- Crop residues
- High C:N ratio
- Soluble components (sugars, amino acids leach and can contribute to MAOM)
- Surface exposed
- Lignin rich material remain and can form POM : POM is highly sensitive to management (tillage, burning)

Additions to Soils: Roots



- Root litter is produced below the soil surface: Unlike above ground litter it does not need to travel to enter soil
- Root C often has a longer storage time in the soil
  - Occur below active microbes (breaks down more slowly)
  - Associated with aggregates (physical protection)
  - Location next to mineral surfaces means (delivered right to the freezer door)
- Improving root systems can increase SOC

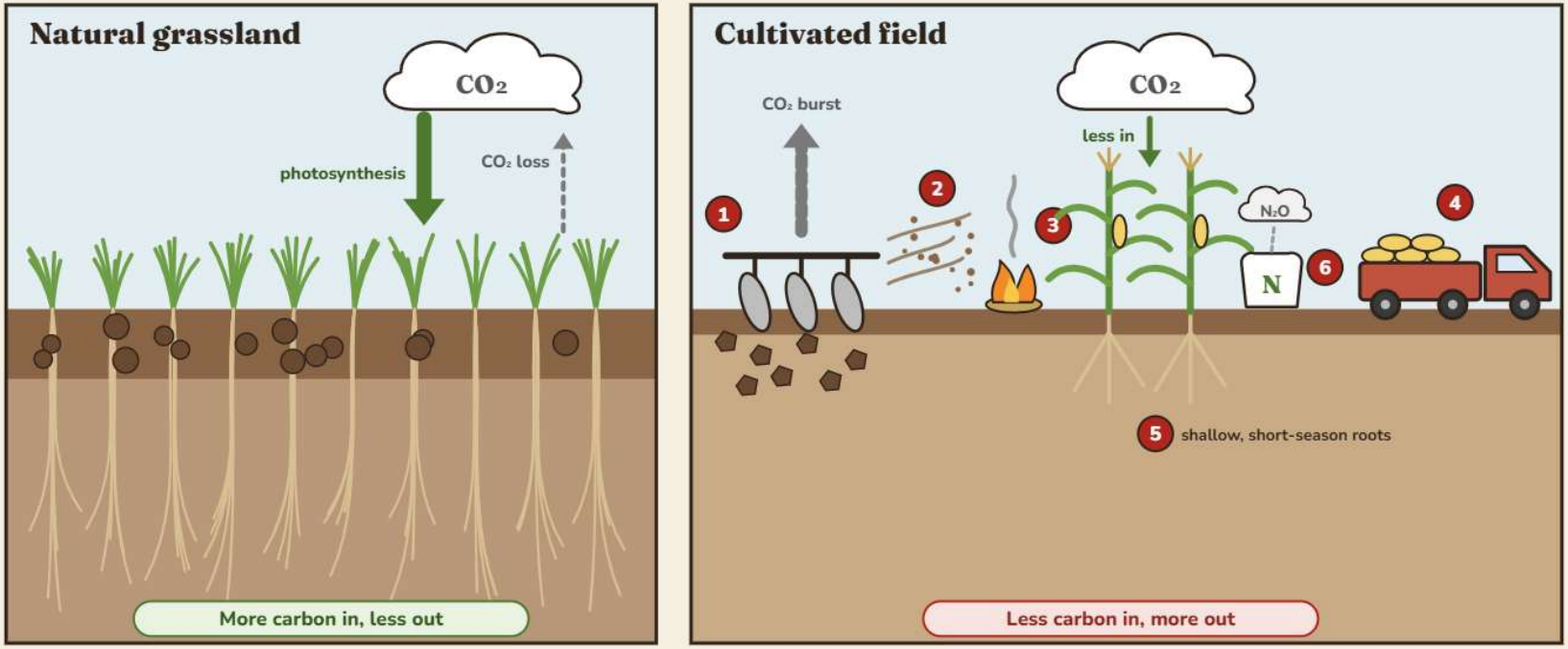
Additions to Soils: Root Exudates



- Produced to secure nutrients
- Cereals between 5-20% of C is allocated to rhizodeposits (Kuzyakov and Domanski, 2000)
- Depends on range of factors, including nutrient availability
- Exudates result in high CUE and MAOM formation
- Generally, plants invest proportionally less C to exudates when N and P are sufficient
- But correct nutrition enhances total plant biomass therefore absolute C from both roots and exudates are greater in optimally-fertilized crops

How do agricultural practices disrupt this cycle?

Converting grassland to cropland cuts carbon inputs and speeds up losses, so soil carbon declines until a new, lower balance is reached.



1. **Tillage:** breaks aggregates and exposes protected POM to microbes: a burst of CO_2.
2. **Bare soil:** wind and water erode carbon-rich topsoil.
3. **Residue burning or grazing:** removes carbon that would have fed the soil.
4. **Harvest:** exports much of the fixed carbon off the farm.
5. **Annual crops:** short seasons and shallow roots mean fewer root inputs than perennial grasses.
6. **Excess nitrogen:** lost as N_2O and wasted when not matched to crop demand.

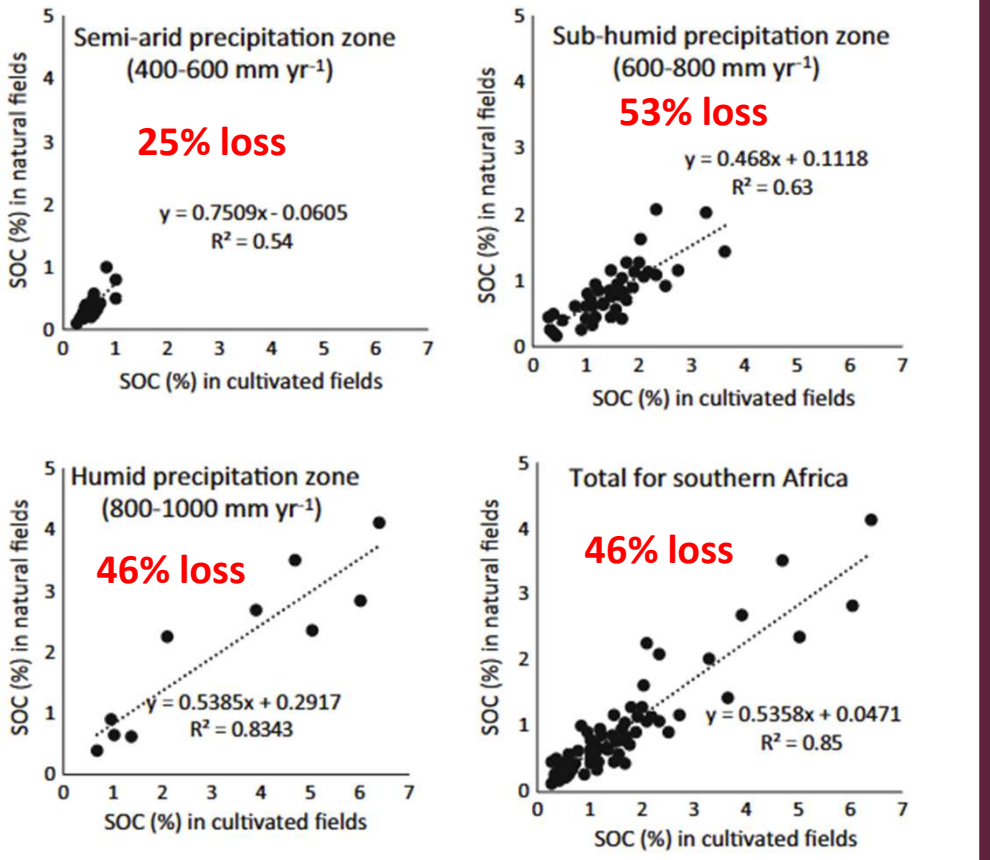
SA Context: How much C have we lost?

Nutr Cycl Agroecosyst (2016) 104:107–123
DOI 10.1007/s10705-016-9763-4

REVIEW ARTICLE

Review and meta-analysis of organic matter in cultivated soils in southern Africa

C. M. Swanepoel · M. van der Laan · H. L. Weepener · C. C. du Preez · J. G. Annandale



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Can we recover those losses?

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Mixed Results – Few long-term trials

- Smith et al. (2019) –Crop rotation+ grazing 10 years 0-2 tonnes C/ha/year
- Swanepoel et al. (2018): No-till Maize 8 years 0-0.4 tonne/ha/year
- Sithole et al. (2019) **Bergville maize 13 years:** 0 tonne/ha/year
- Kotze et al 2025 **High Density Grazing 11 years:** 0-1 tonne/ha year
- Realistically **SOC recovery will be slow in SA**
- Global studies suggest 0.2-0.3 tonne C/ha/year

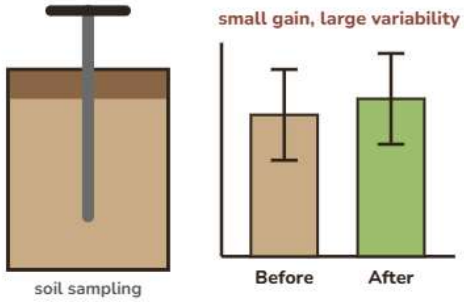
Sanity Check on the 4 per 1000?

- The calculation is based on global soil carbon stocks (0-30 cm), which sit in natural ecosystems boreal forests, permafrost, grasslands, wetlands and farmlands
- Call for action: Soils for Food Security and Climate, suggest that the agricultural land is the battle ground for C capture
- Cropland + permanent pasture = 0.7tC/ha/year
- Cropland = 2tC/ha/year impossible!
- But it's a nice thought and is a major driver of C markets focused on soil

C Credits: If we build carbon in our soils, can we sell it?

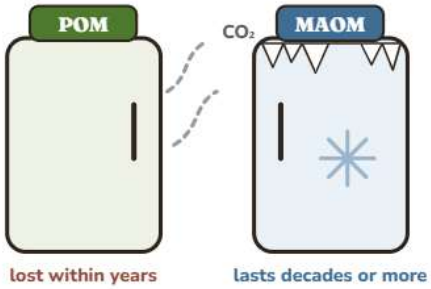
Any credible carbon credit has to pass three tests. The science we have covered explains why each one is hard to pass.

1 Is it real?



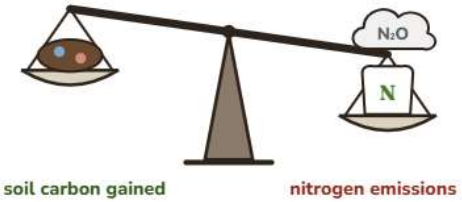
Gains are small (about 0.2–0.5 t C/ha per year) and soils vary a lot, so proving a change takes careful, repeated sampling.

2 Is it permanent?



Schemes measure total soil carbon and cover reversals with buffer reserves. But carbon gained as POM can be lost within years; MAOM lasts far longer.

3 Is it a net gain?

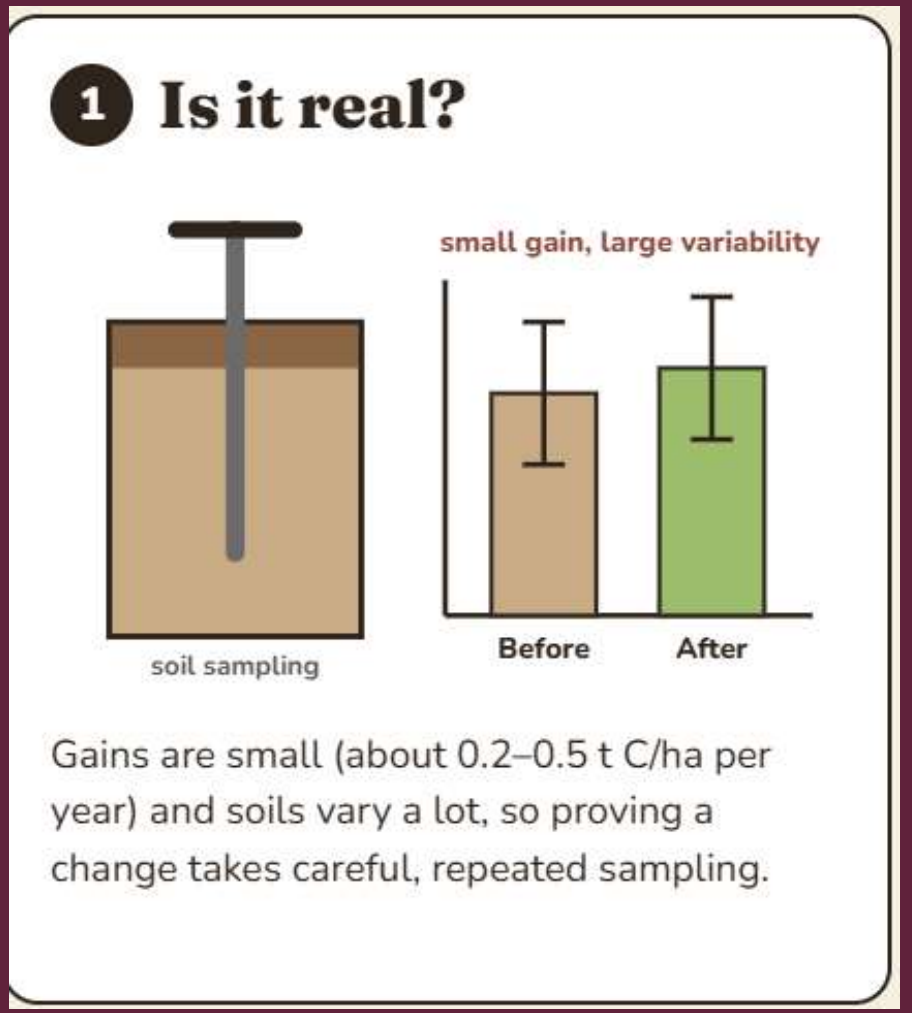


N_2O from the field and emissions from making fertiliser can cancel out modest carbon gains.

Credit schemes count total soil carbon, not POM or MAOM. The fractions still explain why gains are slow, uncertain and easily reversed.

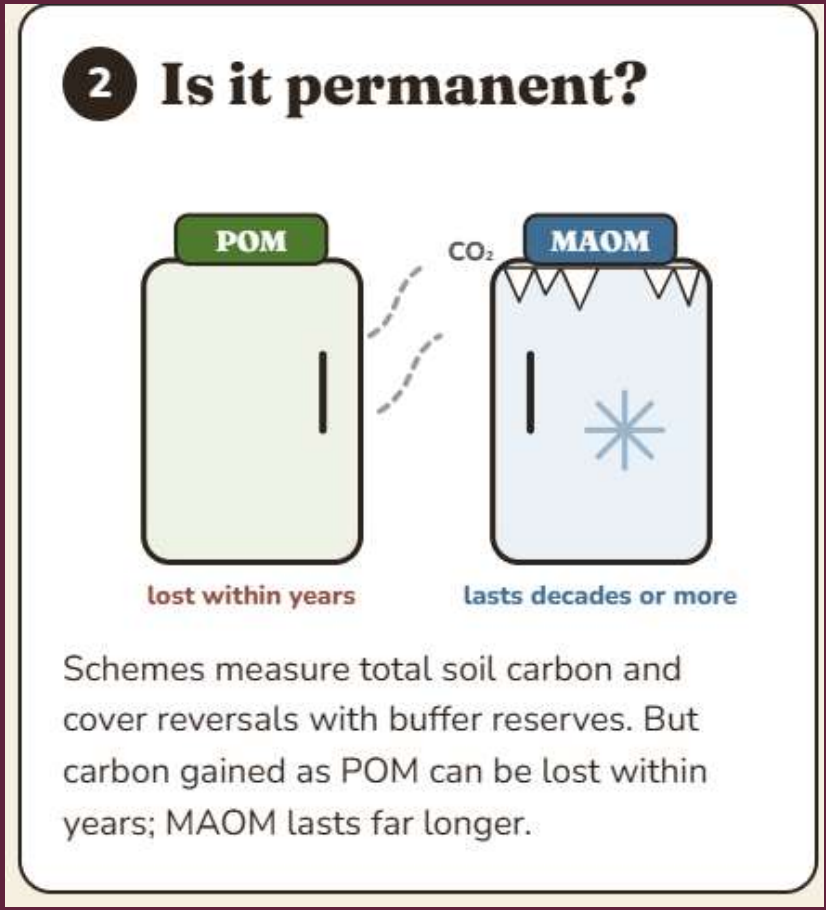
Is it real? How do we measure C?

- Measure and then remeasure- change in carbon over time, high soil variability, sampling variability and analytical variability



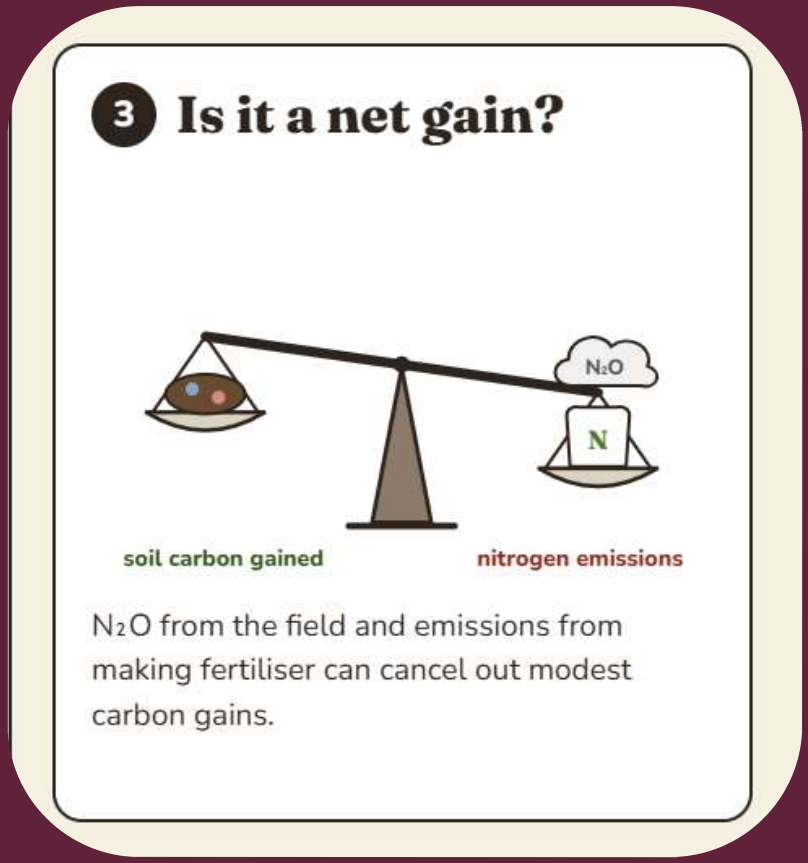
Is it permanent?

- Carbon capture needs to be shown as permanent i.e. 100 years
- Most management related gains will be in the form of POM
- POM is fragile and can be lost in a few seasons of poor management (tillage, fire)
- On-going commitment-can't take foot of the pedal



Is it a net Gain, leakage?

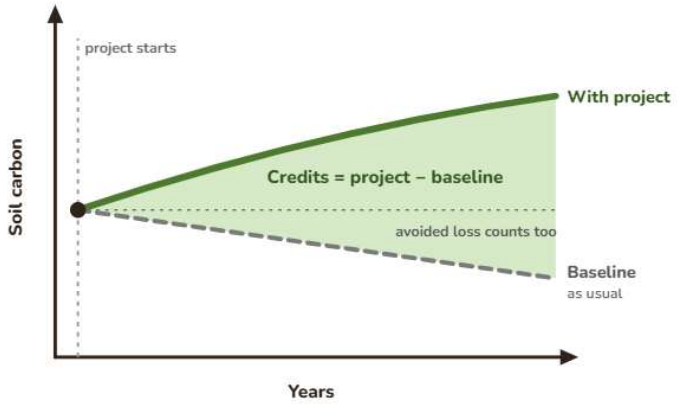
- Are you producing other GHG's in enriching your soil C
- N emissions, methane through cattle
- Total C footprint



Additionality: Would it have happened anyway?

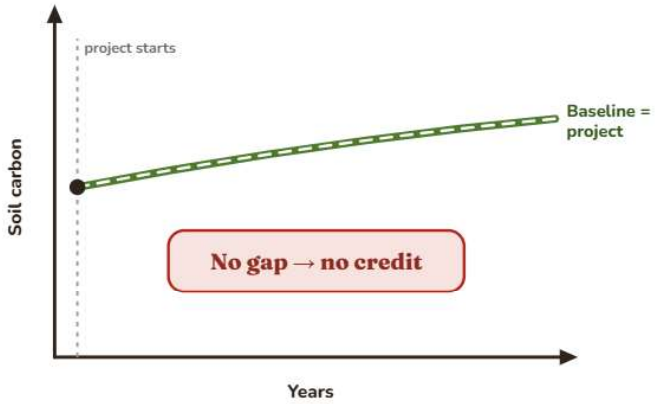
A carbon credit pays only for the difference a project makes, compared with what would have happened without it.

✓ Additional



The farm changed practice, for example to cover crops and reduced tillage, because the carbon payment made it worthwhile.

✗ Not additional



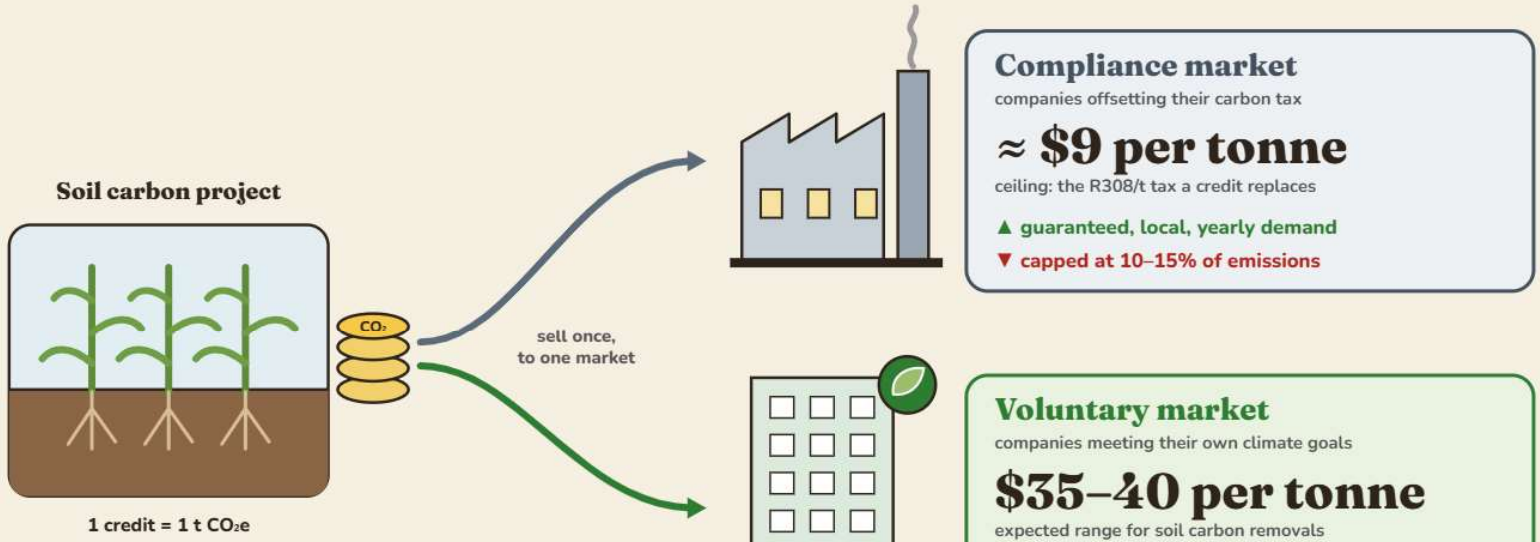
The farm already used these practices, or would have adopted them anyway because they pay. The credit changes nothing.

The awkward part: farmers who adopted good practices early are often not eligible for credits.

Pricing for Carbon: Compliance vs Voluntary

One credit, two markets

Credits are measured to the same standards (Verra, Gold Standard, CDM) either way. The difference is who buys them, and why.



Projects choose between a lower, reliable price and a higher, uncertain one. For soil carbon today, the voluntary market pays more; the carbon tax is a fallback.

My Back of the envelope calculation

- Take a rate of 0.2 tonne C/ha/year
- = 0.74 tonne/CO_2e/ha/year
- VCM price of $35 per tonne CO_2e
- = $25 (R480) per ha per year before costs
- It's not going to make you rich……
- But having more C in your soil COULD make you richer and less stressed?

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Carbon for soil, not soil for carbon

What carbon does for your soil is worth far more than what a credit pays for it.

What carbon does for your soil



Water

Holds more plant-available water and lets rain soak in.



Nutrients

Releases N, P and S as organic matter turns over.



Structure

Stable aggregates resist crusting, compaction and erosion.



Resilience

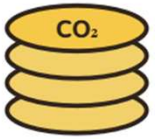
Steadier yields through dry spells and heat.



Biology

Feeds the microbes that cycle nutrients and build MAOM.

What a credit pays



$26–30

per hectare per year, gross, before fees, buffer and sampling

From the back-of-the-envelope calculation.

Build carbon for the soil's sake. If you are doing it anyway, measure it, and treat the credit as a bonus.

Lessons I learnt from the Carbon Cycle

Lesson 1: Soils have two pools of carbon that are connected via a microbial pump

Lesson 2: The efficiency of this pump is governed by litter quality and nutrient availability

Lesson 3: Soils have a saturation potential for stable carbon, each soil type/cropping system has a different capacity for SOC accumulation

Lesson 4: The POM fraction will be the most responsive to management changes and requires constant care

Lesson 5: Plant nutrition has a pivotal role to play in GHG removals balancing biomass production with nitrogen fertilizer based emissions

Lesson 6: Claiming carbon credits requires demonstrated long term changes that do not cause offsets elsewhere

Lesson 7: Fertilizer industry has a major role to play in helping producers to maximise their credits

Lesson 8: Crop producers should grow their carbon for their own resilience, the credit is a bonus