Carbon stocks in soils and soil carbon sequestration

An overview of specific mitigation options and opportunities

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Outline

- Background
    - Soil organic carbon
    - Major Terrestrial Pools of Carbon
- Carbon Exchange in Terrestrial Ecosystems
    - Inputs
    - Outputs - Soil Organic Matter Decomposition
- Soil Carbon Balance
    - Equilibrium SOC values and multiple pools
    - The issue of permanence
- Anthropogenic Impacts on Carbon Cycling
- SOC stocks in ‘natural’ tropical ecosystems. Setting Baselines
- SOC Sequestration Potential. An overview of specific mitigation options and opportunities for rangelands

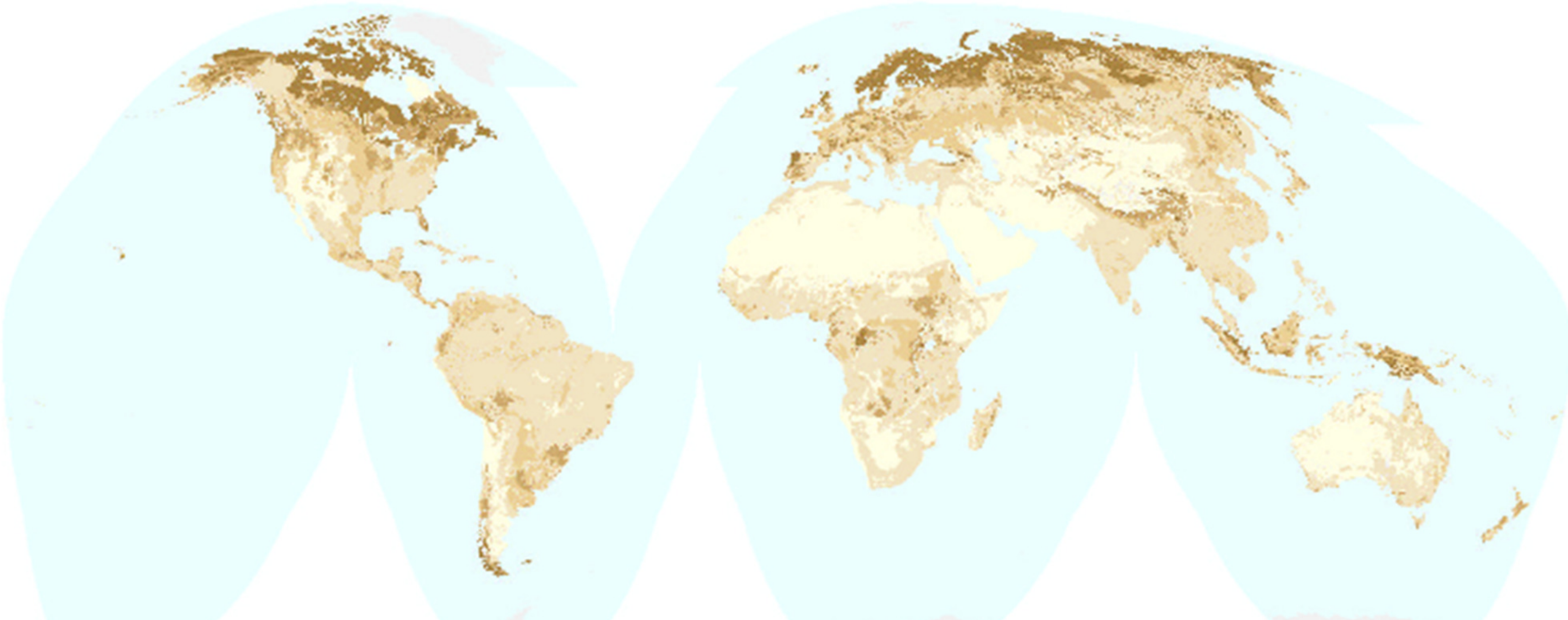
Global Organic Carbon Pools

- Oceans: 40,000 Gt
- Locked deposits (fuels): 4,000 Gt
- Atmosphere: 750 Gt
- Land vegetation: 560 Gt
- Soil and organic matter:

= Big Opportunity for C sequestration

exchanged each year with the atmosphere

Carbon storage in soils



- Unlike biomass, most soil carbon is stored in cold wet areas
- This is because organic matter decays slowly under these conditions, and therefore builds up over time
- In the tropics, carbon is rapidly cycled back to the atmosphere
- In arid zones SOC stocks tend to be low because of high temperatures and limited water availability, as well as there are very little OM inputs into the soil

Major Terrestrial Pools of Soil Carbon

Estimates of soil organic carbon pool (adapted and recalculated from IPCC, 2000; Prentice, 2001)

Ecosystem	Area (10^9 ha)	SOC pool (billion tons C)	SOC density (tons C/ha)
Forests			
· Tropical	1.76	213–216	121–123
· Temperate	1.04	100–153	96–147
· Boreal	1.37	338–471	247–344
Tropical savannas and grasslands	2.25	247–264	110–117
Temperate grassland and scrub land	1.25	176–295	141–236
Tundra	0.95	115–121	121–127
Desert and semi-desert	4.55	159–191	35–42
Cropland	1.60	128–165	80–103
Wetlands	0.35	225	643

Functions / Benefits of SOM pool

- Source and sink of principal **plant nutrients** (e.g., N, P, S, Zn, Mo);
- Source of charge density and responsible for **ion exchange**;
- Absorbent of water at low moisture potentials leading to increase in **plant available water capacity**;
- Promoter of **soil aggregation** that improves soil tilth;
- Cause of high **water infiltration** capacity and low losses due to surface runoff
- Substrate for **energy for soil biota** leading to increase in soil biodiversity;
- Source of strength for soil aggregates leading to **reduction in susceptibility to erosion**;
- Cause of high **nutrient and water use efficiency** because of reduction in losses by drainage, evaporation and volatilization;
- **Buffer** against sudden fluctuations in soil reaction **(pH)** due to application of agricultural chemicals
- **Moderator of soil temperature** through its effect on soil color and albedo.

In addition, there are also off-site functions of SOC which have both economic and environmental pool, significance. Important among these are:

- **Reduces sediment** load in streams and rivers,
- **Filters pollutants** of agricultural chemicals,
- Reactors for **biodegradation of contaminants**, and
- **Buffers the emissions of GHGs from soil to the atmosphere**

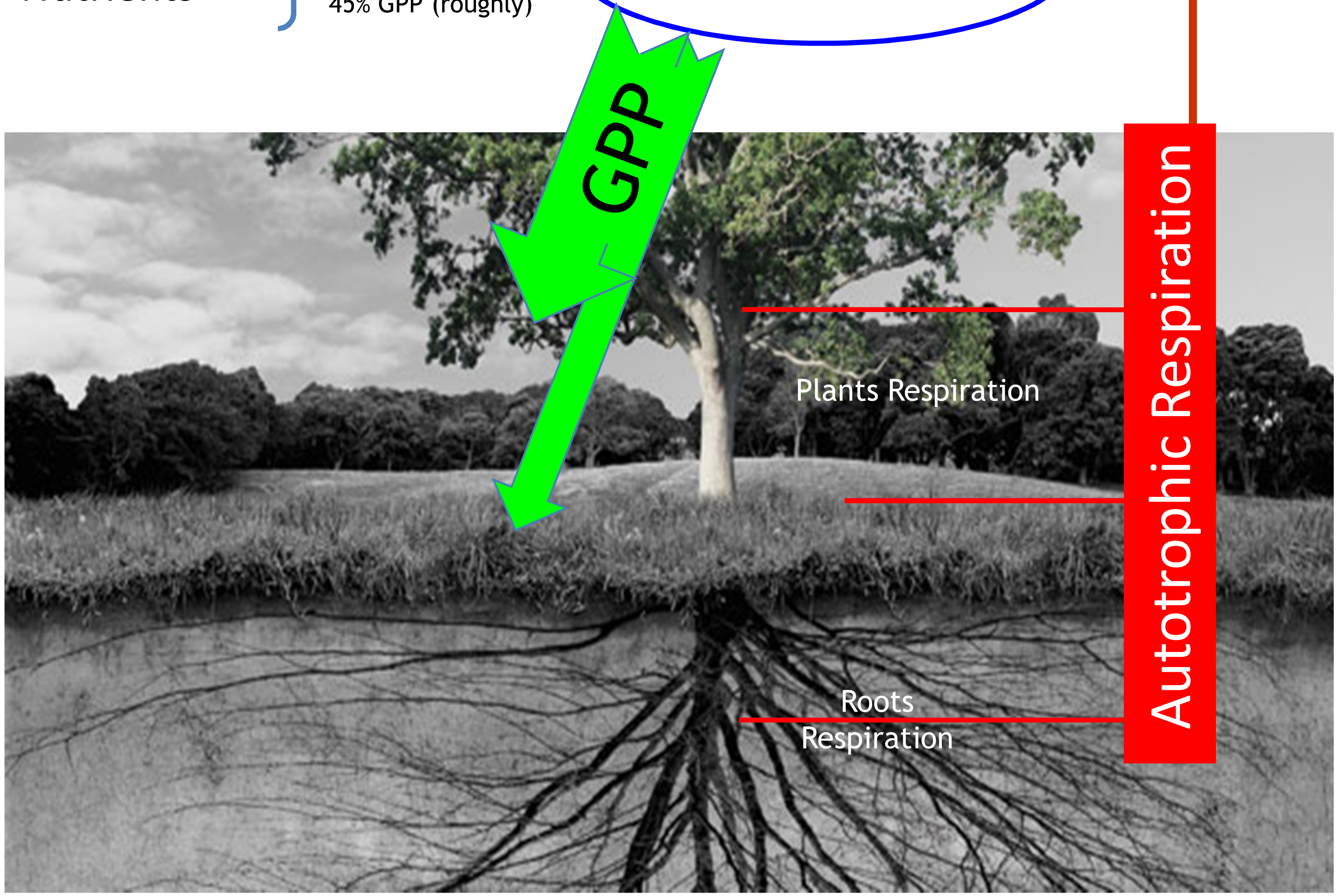
Carbon Exchange
in Terrestrial Ecosystems

Carbon Exchange in Terrestrial Ecosystems

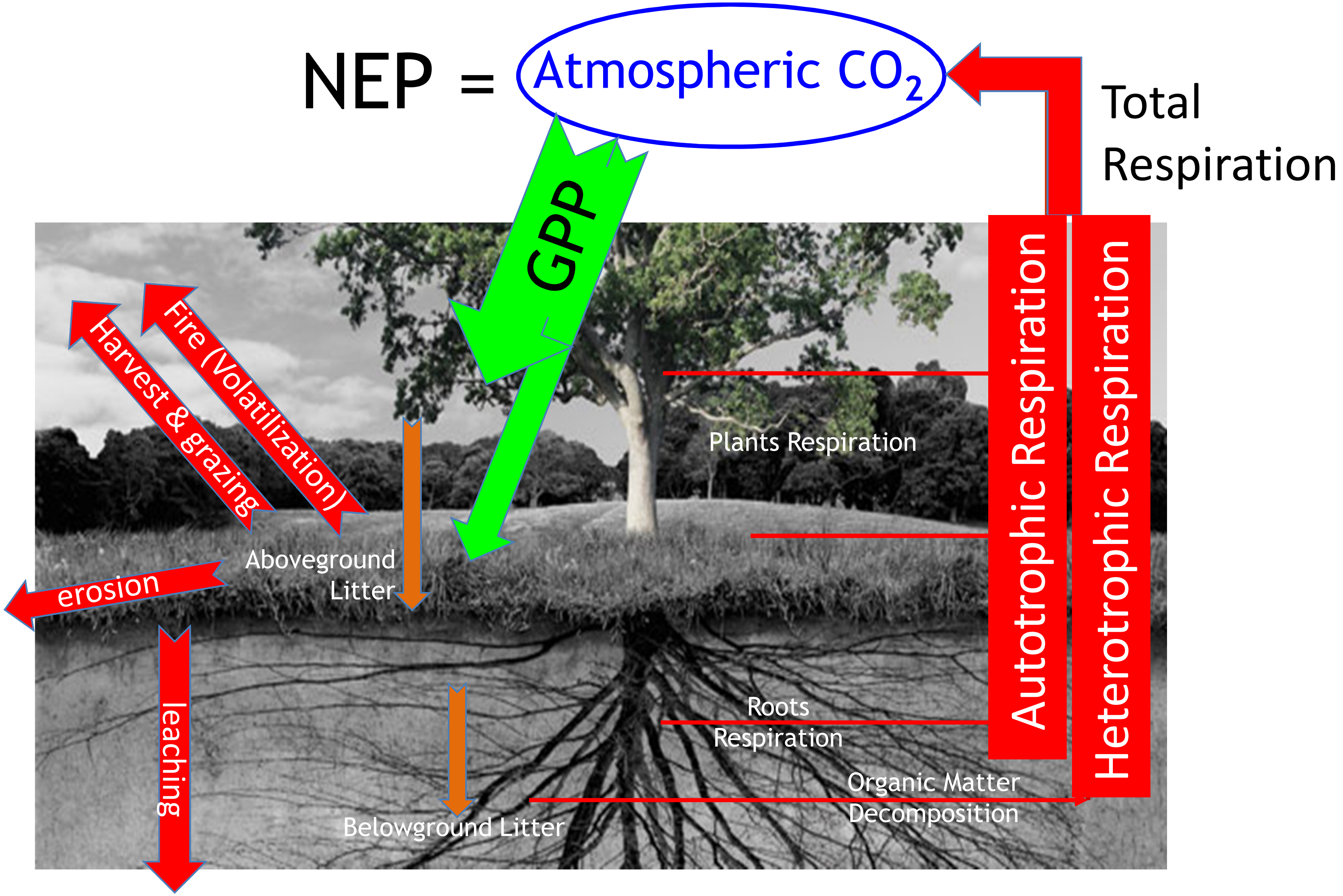
Limitations
Water
Nutrients

NPP = Atmospheric CO_2

45% GPP (roughly)

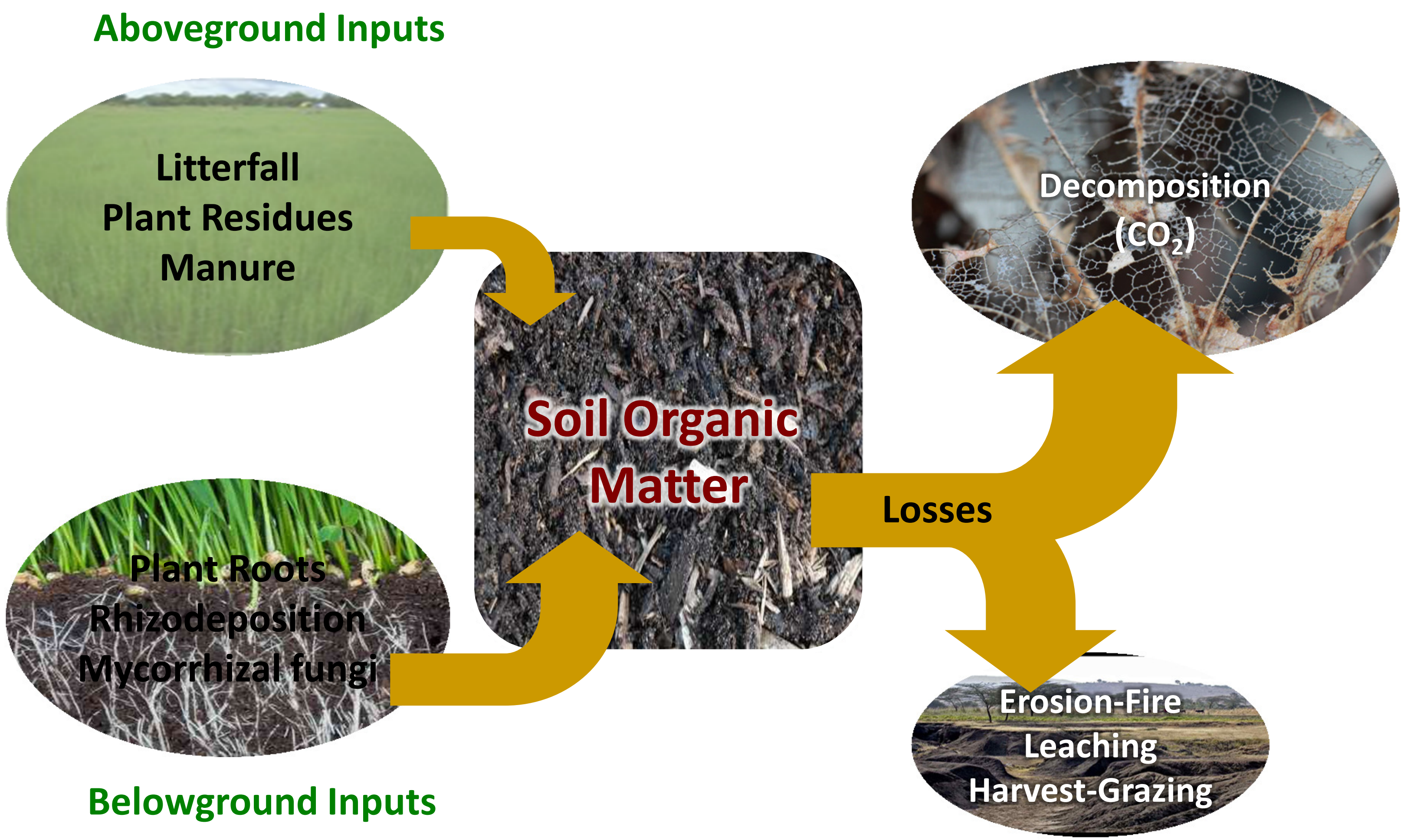


Carbon Exchange in Terrestrial Ecosystems



Soil Organic Matter Cycling

- There is a constant turnover of organic material in soil
- The quantity of SOM depends on the balance between inputs and losses of organic material



SOM Inputs

Aboveground Inputs

Litterfall Plant Residues (Manure)	To significantly persist they need to be incorporated into the mineral soil … and relatively fast

Belowground Inputs

Plant Roots	Very significant contribution to SOC pool Root distribution is often coupled to that of SOC Decay slower than aboveground biomass due to: - spatial location (mineral & environmental conditions) - litter quality
Rhizodeposition	Represents an average 17% NPP (up to 40% ~ stress) Priming effect Affects soil aggregation
Mycorrhizal fungi	It can represent between 4-20% NPP Glomalin (may slow down decomposition) Affects soil aggregation
Soil Fauna	Big contributors to SOM mixing and own decay

SOM Outputs

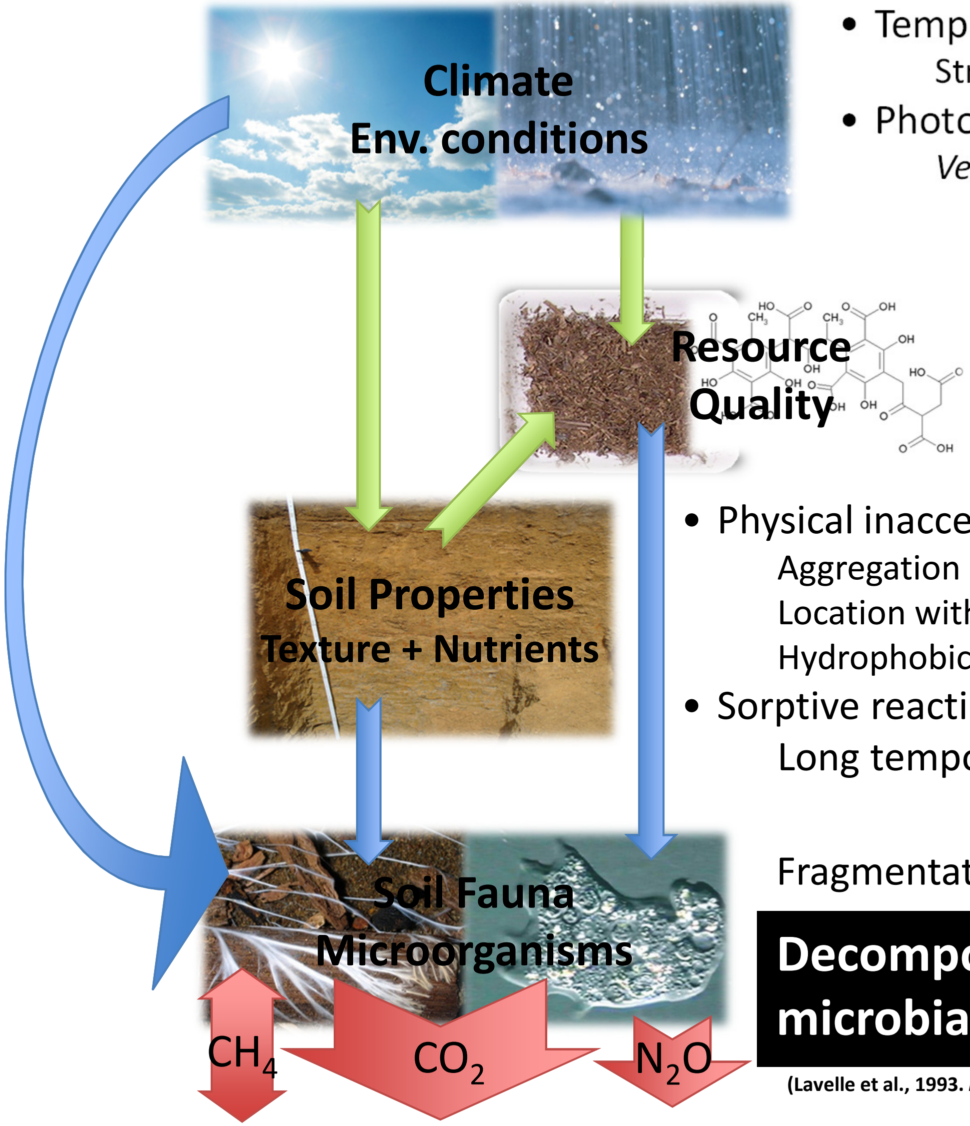
Organic matter decomposition (the big one)

Key ecological process essential for maintaining a supply of most plant nutrients

What controls SOM decomposition?

Organic matter decomposition

Controls on Decomposition and Stabilization



- Temperature and Moisture
  Strong influence on decomposition over large regions
- Photodegradation of litter (UV-Light)
  Very relevant in tropical systems

- Biochemical Recalcitrance
  Cellulose, lignin, pyrogenic carbon, etc.
  Relevant to short temporal scales (months to decades, except for charcoal - if protected)

- Physical inaccessibility of OM to the decomposer
  Aggregation
  Location within soil profile (aeration, nutrients, etc.)
  Hydrophobicity of partly oxidized materials
- Sorptive reactions with minerals & complexation with metals
  Long temporal scales (centuries, millennia)

Fragmentation and mixing of residues by soil fauna

Decomposition is ultimately controlled by microbial activity (and their enzymatic activities)

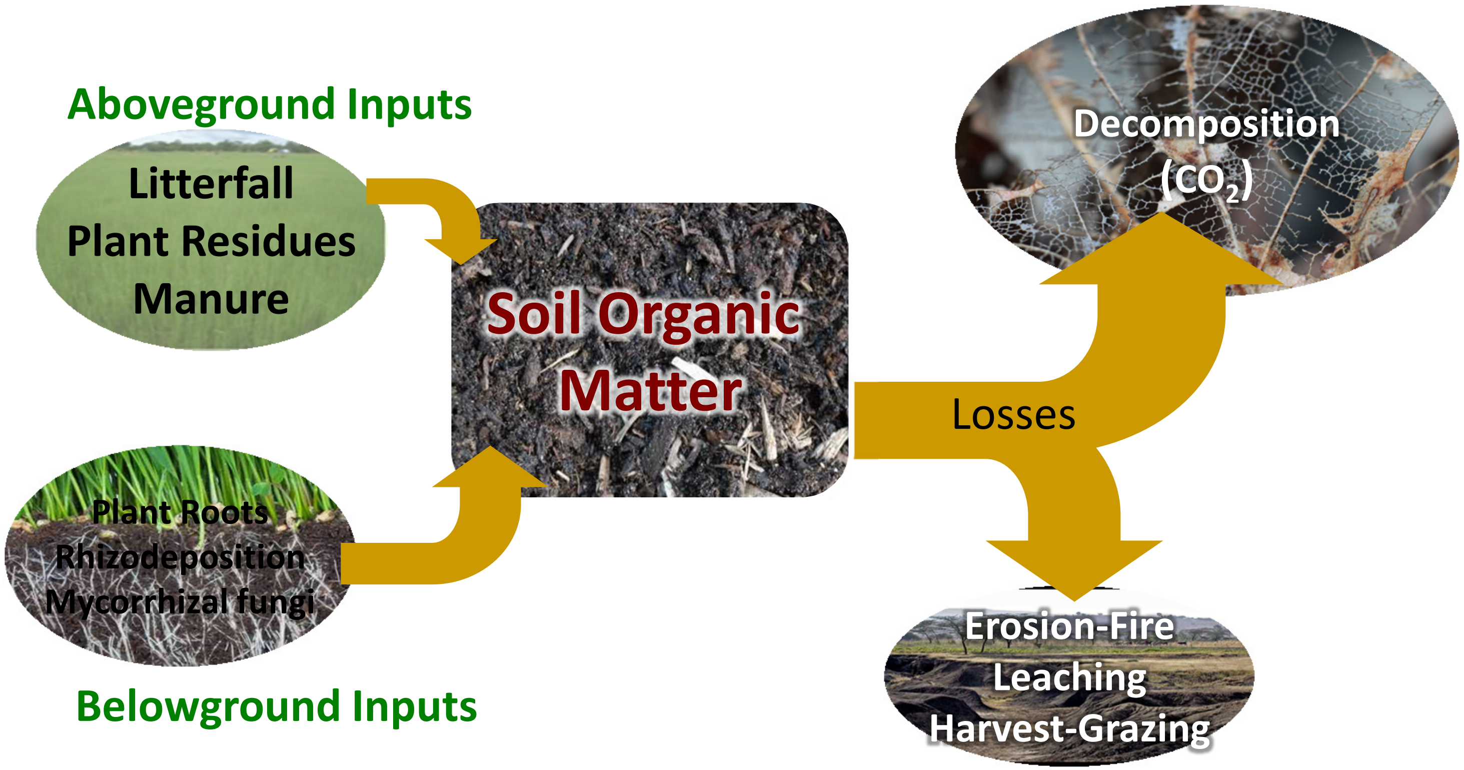
(Lavelle et al., 1993. *Biotropica* **25,** 130-150. **)**

Soil Carbon Balance

Equilibrium SOC values and multiple pools

Soil Organic Matter Cycling

If **inputs increase** and losses remain the same, SOM will increase

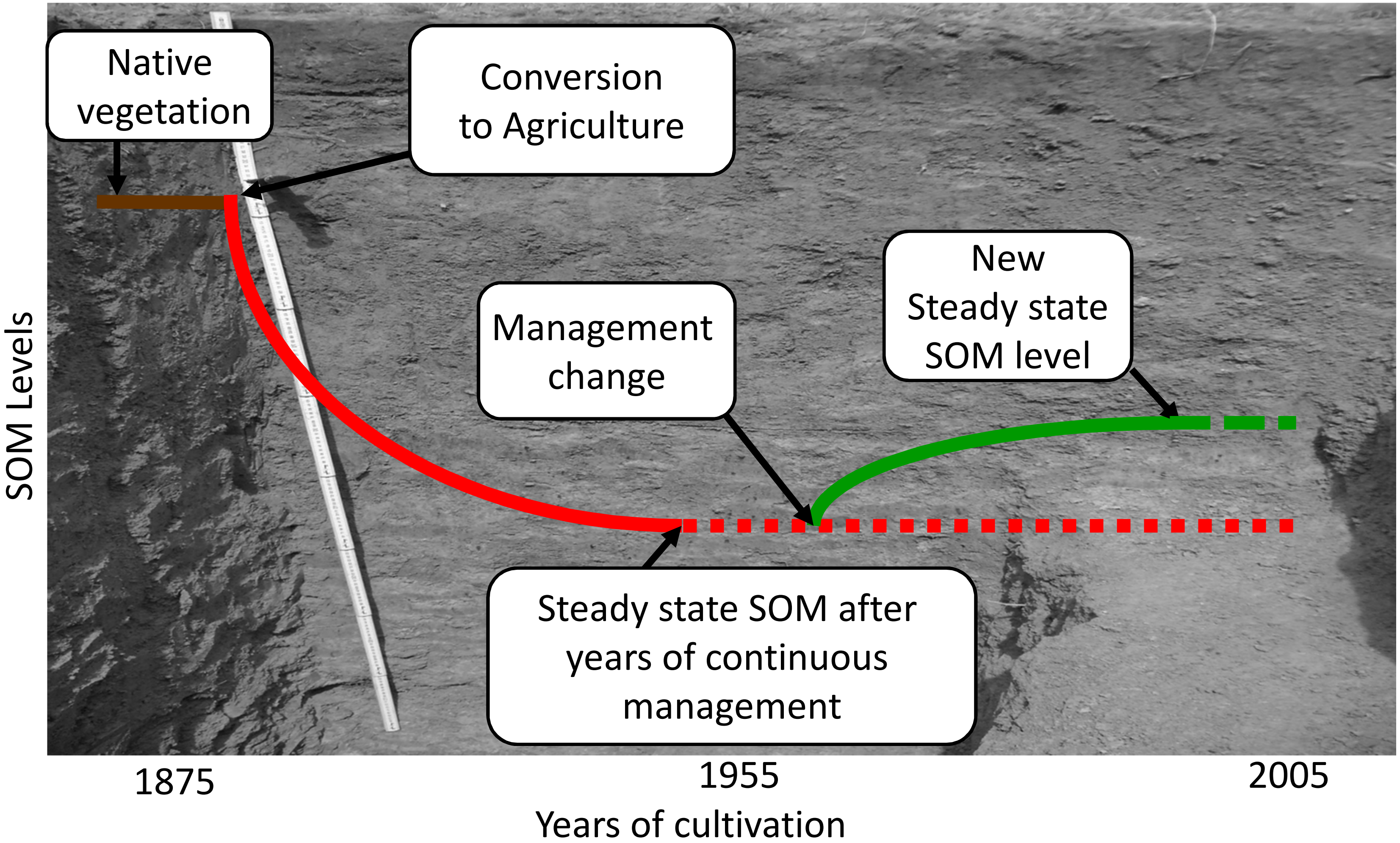


Soil Organic Matter Cycling

If **losses** increase and inputs remain constant, SOM will decrease

When inputs or losses are changed, SOM quantity changes to a different level and a new steady state condition is reached

SOC stocks will not continue to increase or decrease indefinitely

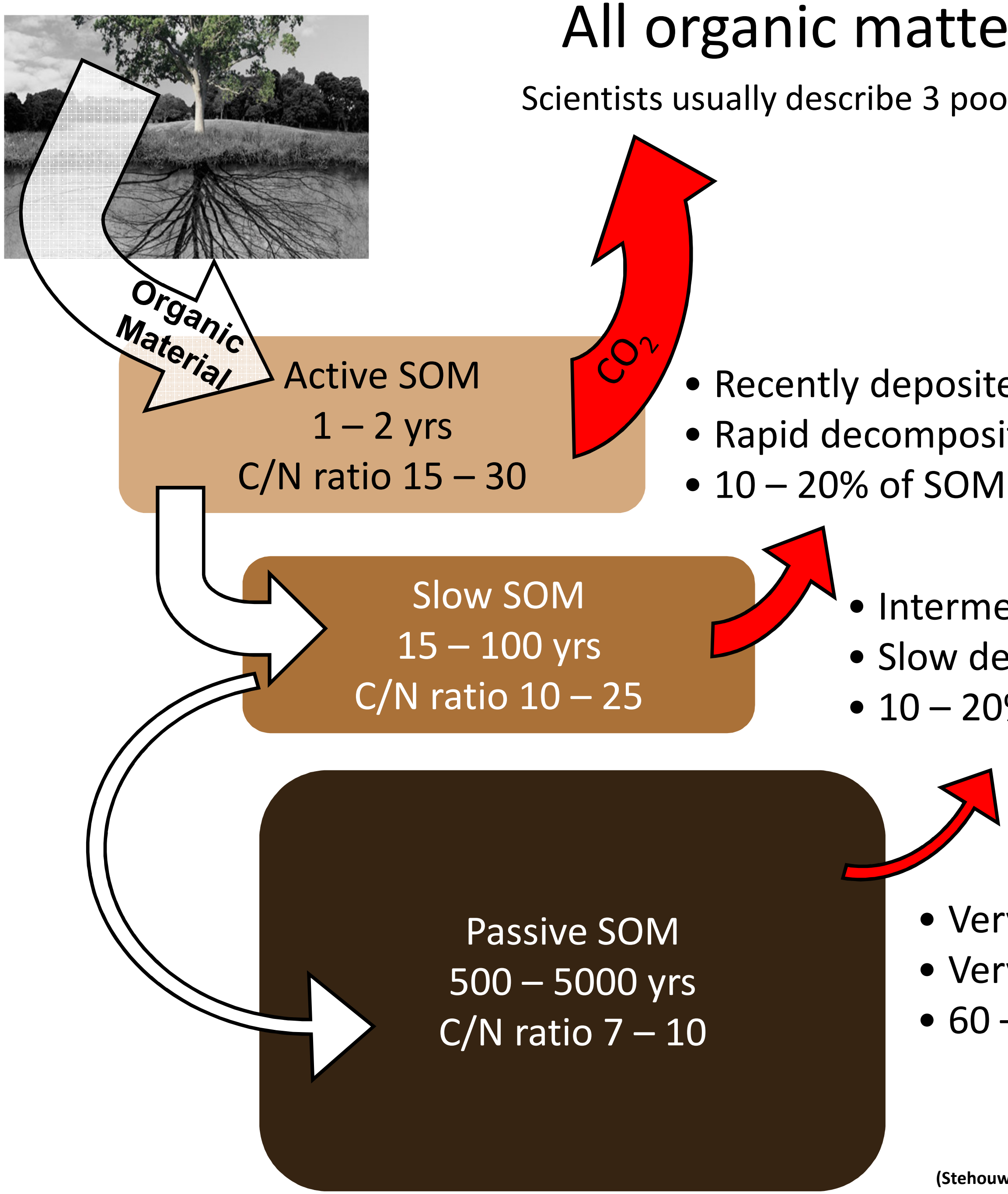


Soil Organic carbon multiple pools

The issue of Permanence

All organic matter in soil is not equal

Scientists usually describe 3 pools of soil organic matter (convenience)



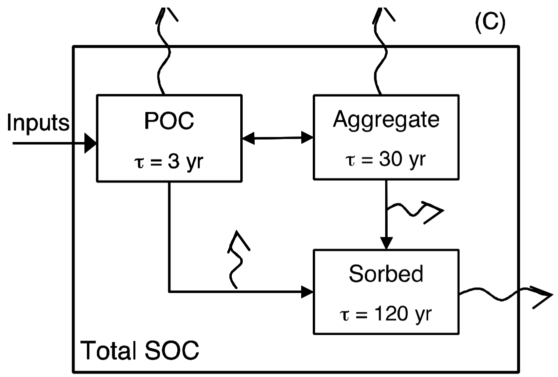
- Recently deposited organic material
- Rapid decomposition
- 10 – 20% of SOM

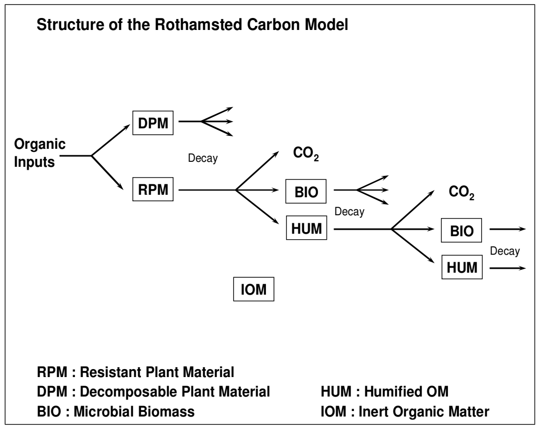
- Intermediate age OM
- Slow decomposition
- 10 – 20% of SOM

- Very stable OM
- Very slow decomposition
- 60 – 80% of SOM

(**Stehouwer.** *Managing to improve soil organic matter*)

The critical issue is in which form carbon is stored in the soil (**permanence**)

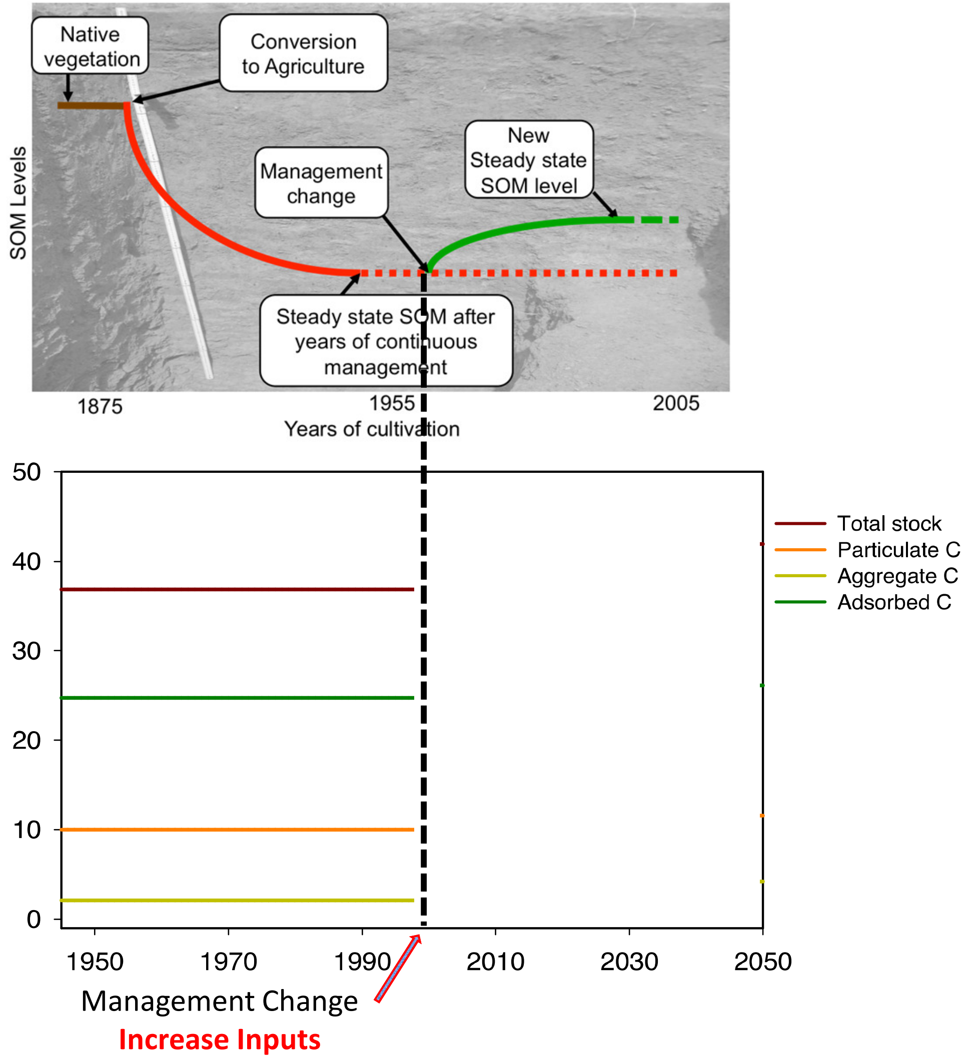




(Coleman & Jenkinson, 1999)

Decay: SOC_{pool}*e^{-abckt}

a: factor for temperature
b: factor for moisture
c: factor for soil cover
k: decay rates
10 for DPM
0.3 for RPM
0.66 for BIO
0.02 for HUM
t: 1/12 for monthly timestep



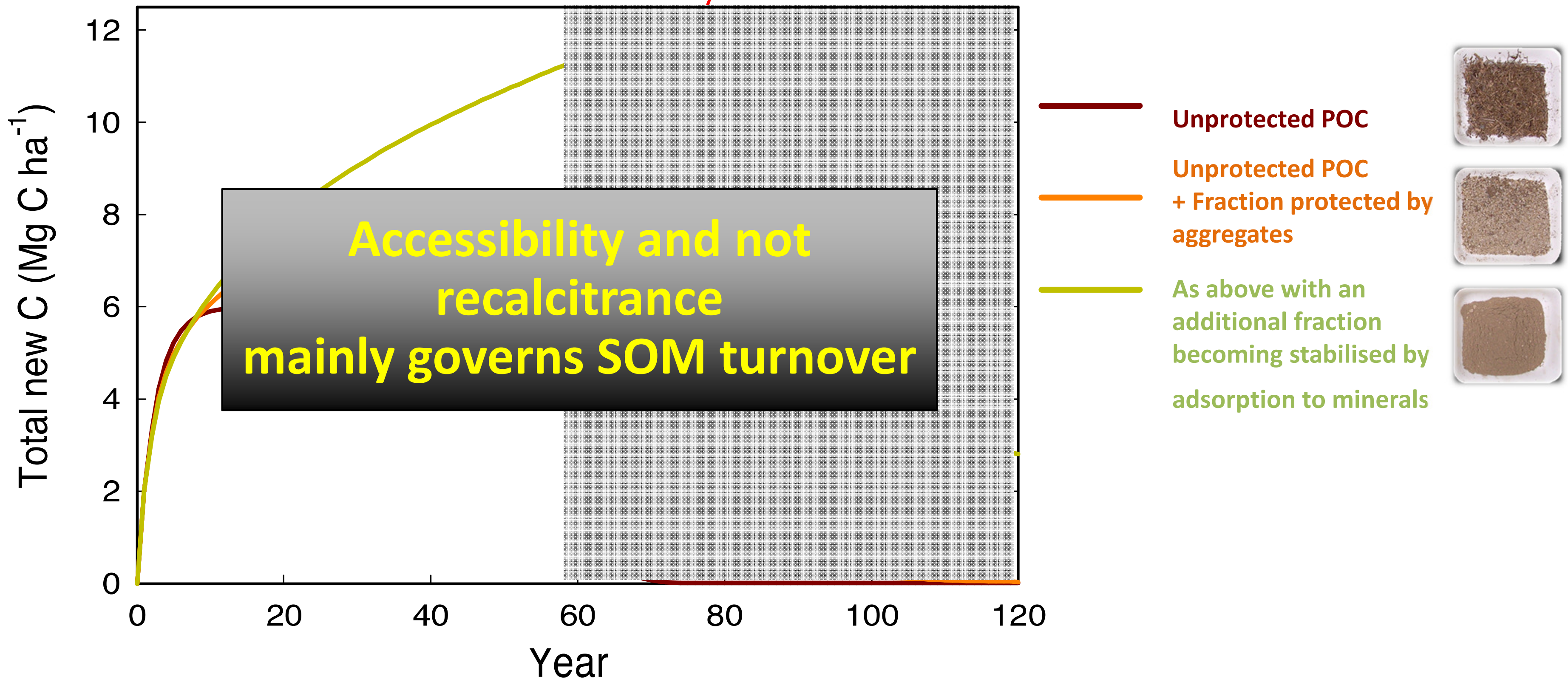
(Sanderman et al. *2010. CSIRO Land and Water report***)**

Permanence of SOC

SOC dynamics - Model Simulations

Total new soil C following a 2 Mg C ha-1 yr-1 **increase in inputs** for 3 scenarios

with a cessation of the new inputs
after 60 years



(**Sanderman et al.** *2010. CSIRO Land and Water report*)

Anthropogenic Impacts on Carbon Cycling

Just a few man-induced ecosystem disturbances

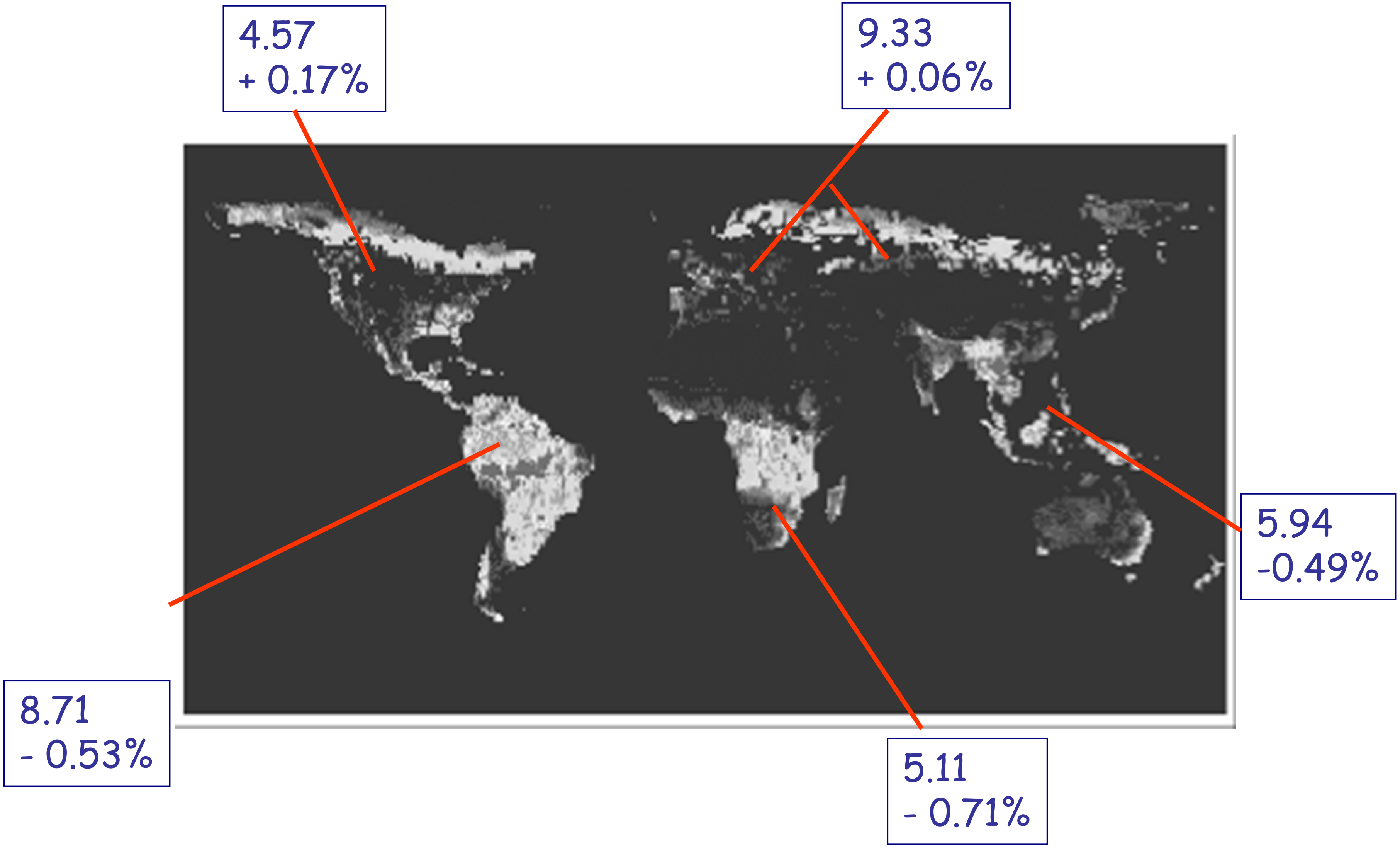
- Overgrazing

-Slash & burn agriculture

- Recurrent Fires

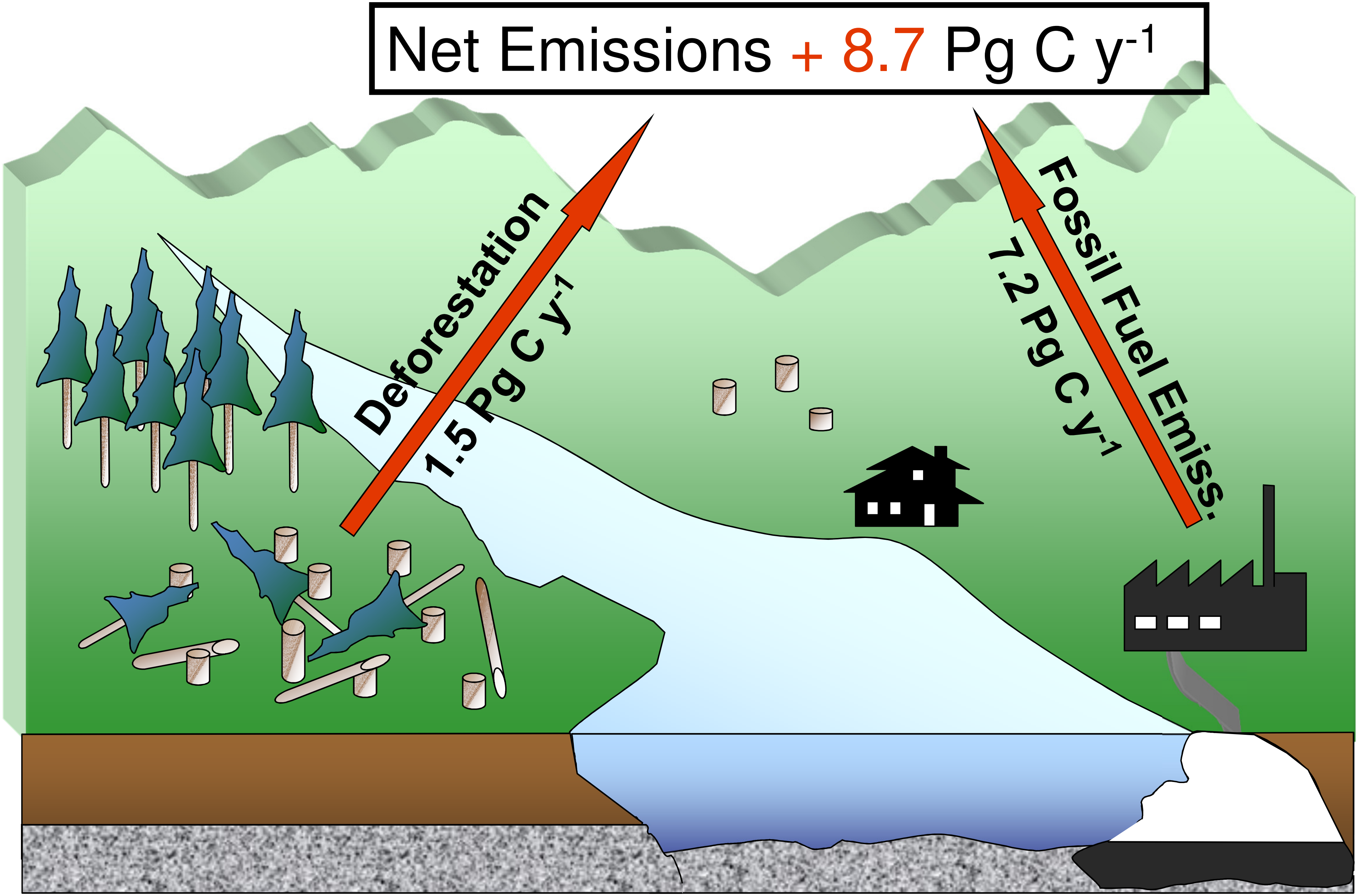
- Unchecked Deforestation

Forest areas, and rates of change



Units: millions of km^2 and annual % change (1995)

Anthropogenic Disruption

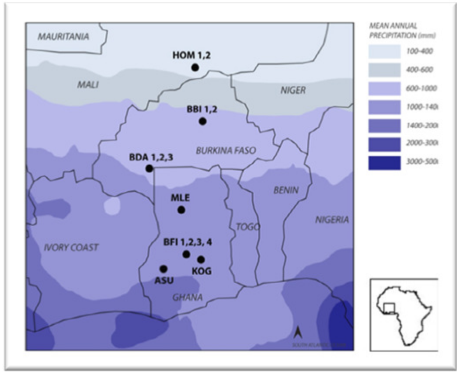


Outlook of SOC stocks in “natural” tropical systems (setting baselines)

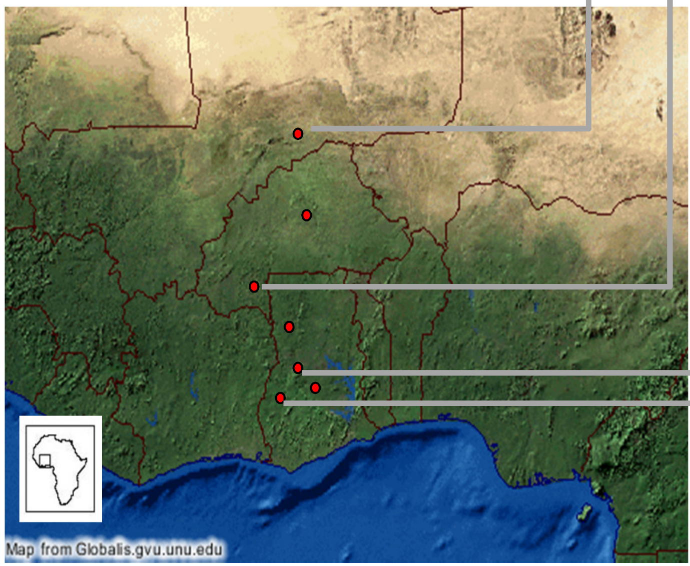
Description of a Climatic Transect West African TROBIT Sites

Description of a Climatic Transect

West African TROBIT Sites



Average annual precipitation (1960-1999)



Sahelian ecosystems (29℃ 240mm)

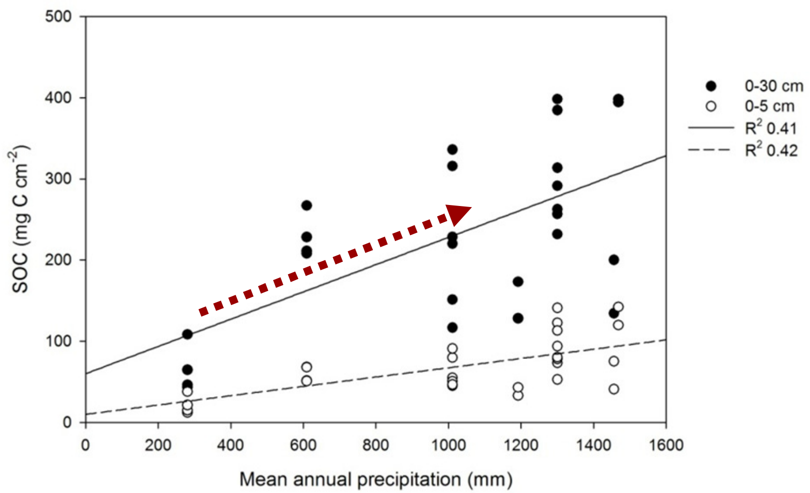
Sudan savanna (27℃ 800mm)

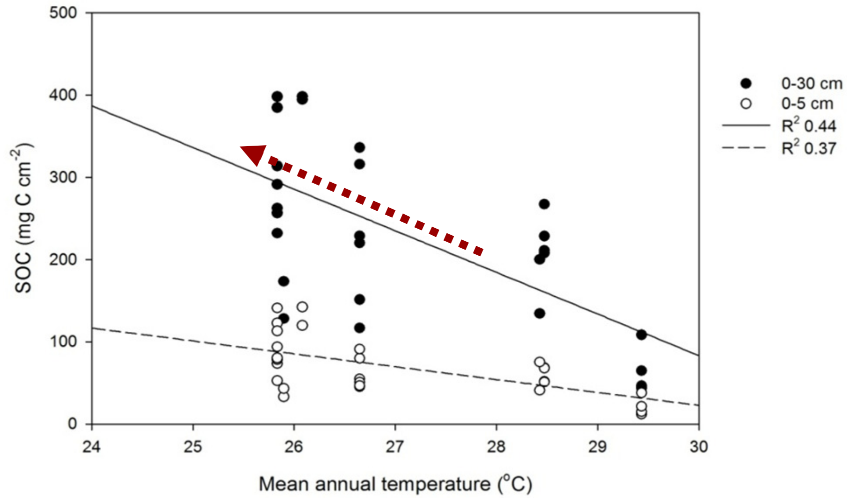
Transition forest (26℃ 1250mm)

Rain Forest (26℃ 1480mm)

(Saiz et al., 2012. ***Global Change Biology*****)**

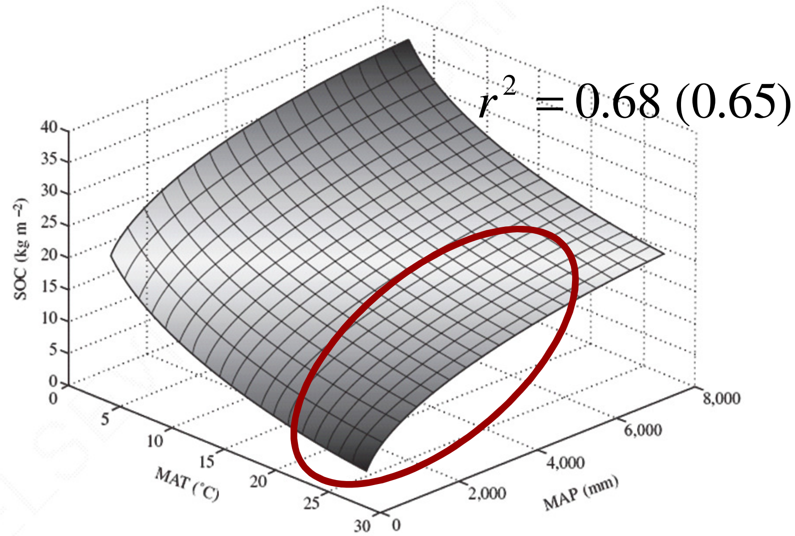
Climate controls on SOC





Empirical regression based on global soil surveys suggests non-linear relationships to **MAP & MAT**

(<u>1m depth interval</u>)



$$SOC = -3.42 + 11.9\log(MAP) - 16.93\log(MAT)$$

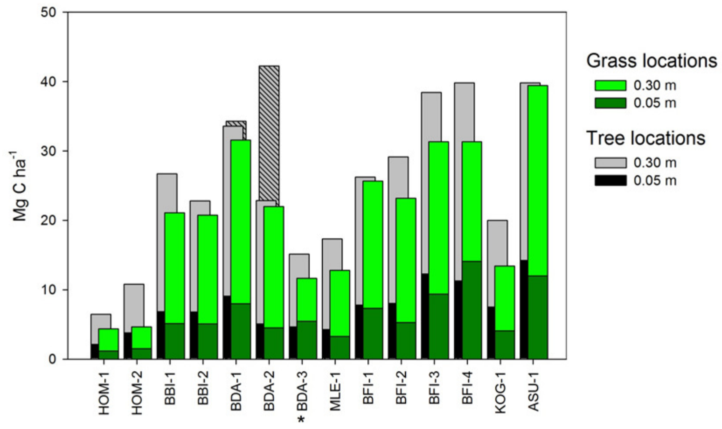
BUT not just climate significantly controls SOC storage

Soil characteristics heavily control SOC

Main soil characteristics and Relative abundance of main minerals present in the soil (<2 mm) extracted from x-ray diffraction (XRD) analysis for the different sites across the transect.

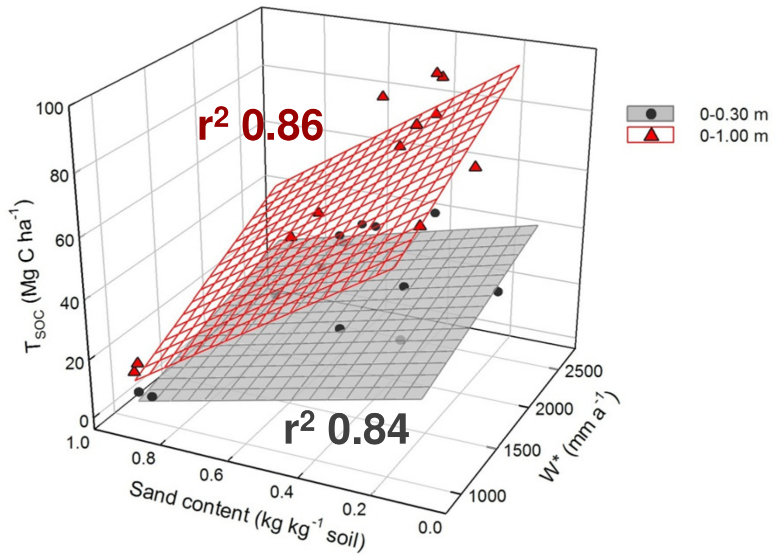
Site	Soil Type WRB	Textural Class FAO (USDA)	Clay content kg kg^{-1}	Sand content kg kg^{-1}	pH	Quartz SiO_2	Kaolinite $Al_2Si_2O_5(OH)_4$	Hematite Fe_2O_3	Goethite FeO(OH)	K-Feldspar $KAlSi_3O_8$
HOM-1	Haplic Arenosol	Coarse (Sandy)	0.03	0.89	6.4	0.94	0.04	0.01	0.00	0.01
HOM-2	Haplic Arenosol	Coarse (Sandy)	0.01	0.93	6.7	0.95	0.04	0.00	0.00	0.01
BBI-1	Haplic Luvisol	Medium (Clay Loam)	0.39	0.31	5.8	0.65	0.28	0.01	0.00	0.04
BBI-2	Pisolithic Plinthosol	Medium (Loam)	0.18	0.49	6.1	0.72	0.23	0.01	0.00	0.04
BDA-1	Haplic Fluvisol	Medium Fine (Silty loam)	0.25	0.11	5.8	0.74	0.18	0.02	0.02	0.03
BDA-2	Acric Stagnic Plinthosol	Medium (Silty loam)	0.1	0.39	5.6	0.85	0.1	0.01	0.03	0.01
BDA-3	Epipetric Stagnic Plinthosol	n/a			5.6	0.79	0.15	0.02	0.02	0.01
MLE-1	Brunic Arenosol	Coarse (Loamy sand)	0.04	0.81	6.1	0.94	0.05	0.00	0.00	0.01
BFI-1	Haplic Alisol	Coarse (Sandy loam)	0.11	0.72	7.0	0.87	0.11	0.02	0.00	0.00
BFI-2	Brunic Arenosol	Coarse (Sandy loam)	0.09	0.71	5.3	0.87	0.11	0.02	0.00	0.00
BFI-3	Haplic Nitosol	Medium (Sandy clay loam)	0.2	0.61	5.7	0.76	0.21	0.03	0.00	0.00
BFI-4	Haplic Nitosol	Medium (Sandy Loam)	0.05	0.65	6.7	0.85	0.13	0.02	0.00	0.00
KOG-1	Haplic Arenosol	Coarse (Loamy sand)	0.03	0.77	5.3	0.97	0.02	0.00	0.00	0.01
ASU-1	Endofluvic Cambisol	Medium (Loam)	0.17	0.43	4.9	0.84	0.12	0.01	0.00	0.02

Functions combining climate and soil characteristics provide acceptable SOC stocks predictions in “natural” tropical ecosystems



Regression values for the functions predicting T_{SOC} using Water availability index-*W** (mm a^{-1}, *x*), and sand and clay content (kg kg^{-1}, *y*) respectively at two different depths.

Depth	0.30 m			1.00 m		
Sand	n=13	r^2 0.84	P <0.0001	n=12	r^2 0.86	P <0.0001
$f = y_o + a*x + b*y$	y_o	a	b	y_o	a	b
Coefficient	16.063	0.010	-27.056	57.918	0.019	-72.901
St Error coeff	6.410	0.002	5.703	16.694	0.006	14.281
t	2.506	4.721	-4.744	3.469	3.273	-5.105
P value	0.031	0.001	0.001	0.007	0.010	0.001
Clay	n=13	r^2 0.70	P=0.0025	n=12	r^2 0.63	P=0.0114
$f = y_o + a*x + b*y$	y_o	a	b	y_o	a	b
Coefficient	-8.971	0.012	45.779	-12.679	0.0268	65.417
St Error coeff	7.008	0.003	17.363	19.278	0.009	36.807
t	-1.280	3.920	2.637	-0.658	3.026	1.777
P value	0.229	0.003	0.025	0.527	0.014	0.109



Soil Organic Carbon Sequestration Potential

An overview of specific mitigation options and opportunities

Historical SOC **losses** due to Land Use conversion for agriculture

78 ±15 Gt C

56 Gt C mineralization

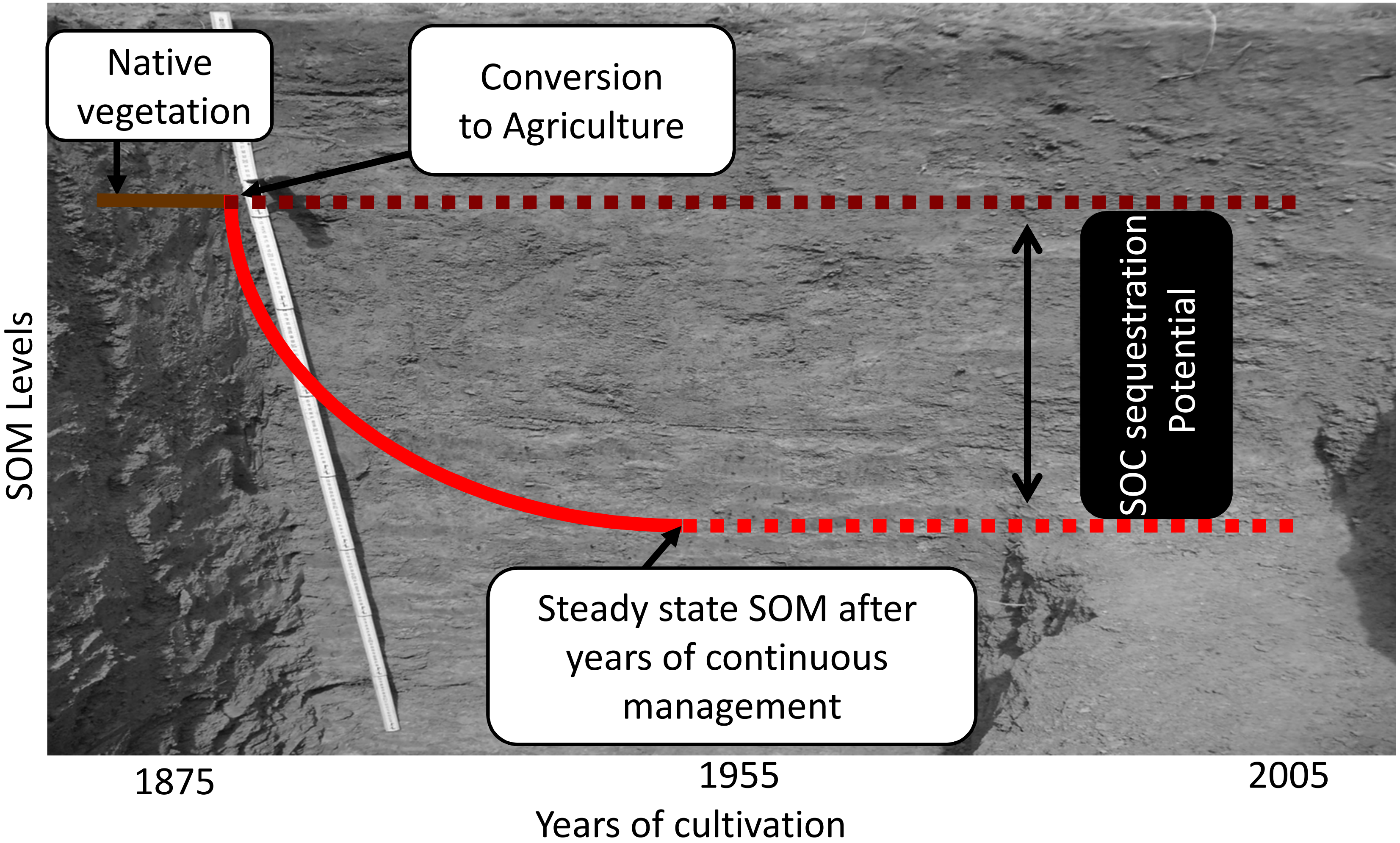
22 Gt C erosion

- 42%

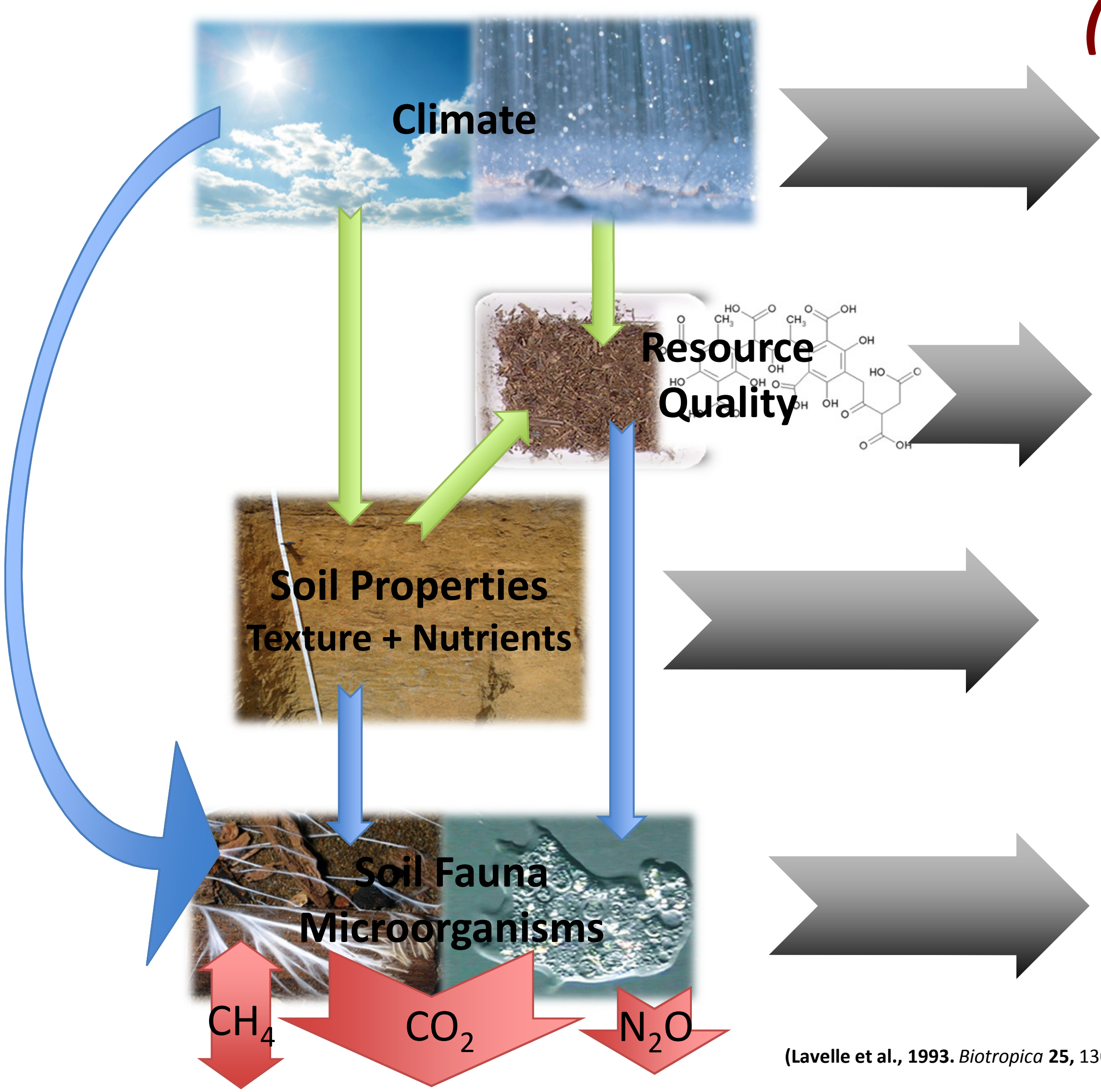
- 59%

SOC Sequestration Potential in Agricultural systems

Disturbance of natural vegetation generally leads to a decrease in SOM levels



Controls on Decomposition and Stabilization



Anthropogenic Controls (i.e. Cultivation)

- Irrigation
- Crop Selection
- Herbicides
- Tillage
- Fertilizers
- Pesticides
- Fungicides

(**Lavelle et al., 1993.** *Biotropica* **25,** 130-150.)

An overview of specific mitigation options and opportunities (rangelands)

(Adapted from **Sanderman et al.** *2010. CSIRO Land and Water report*)

Management	*SOC Benefit*	*Rate of C gain (Mg C ha^{-1} y^{-1})*	*Confidence (Qualitative assessment)*	*Justification*	*Other GHG and impacts*
a) **Increased Productivity**		0.51	Low	Potential trade-off between increased C return to soil and increased decomposition rates	+ N_2O Reduced erosion if grazing management appropriate
Irrigation					Salinization risks Associated fossil fuel emissions
Fertilization					++ N_2O, off site nutrient impacts, acidification
b) **Rotational Grazing**		0.22	Low	Increased productivity, inc. root turnover and incorporation of residues by trampling but lacking field evidence	Increases sustainability & plant biodiversity - CH_4 emissions due to better diet quality
c) Shift to perennial species		1.1-3.3	Medium	Plants can utilize water throughout year, increased belowground allocation but few studies to date	Still big uncertainty wrt N_2O and CH_4 emissions Biodiversity loss from native pastures
d) Retirement & restoration degraded land		0.1-1.1	High	Annual production, minus natural loss, is now returned to soil; active management to replant native species often results in large C gains	Long term studies needed to certify true gains
e) Fire management		0.5-1.2	Medium	Greater C return to the soil should increase SOC stocks	Tradeoff between charcoal production and degradation
f) Biochar application			Medium-High	**Incipient** **Needs to be fully tested!**	?

Thank you