Greenhouse gas emissions from soils and animal manure

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CIMMYT training
10 December 2024

Mazingira Centre
ILRI INTERNATIONAL LIVESTOCK RESEARCH INSTITUTE
CGIAR INITIATIVE ON Livestock and Climate
CGIAR Mitigate+: Research for Low-Emission Food Systems

Learning objectives

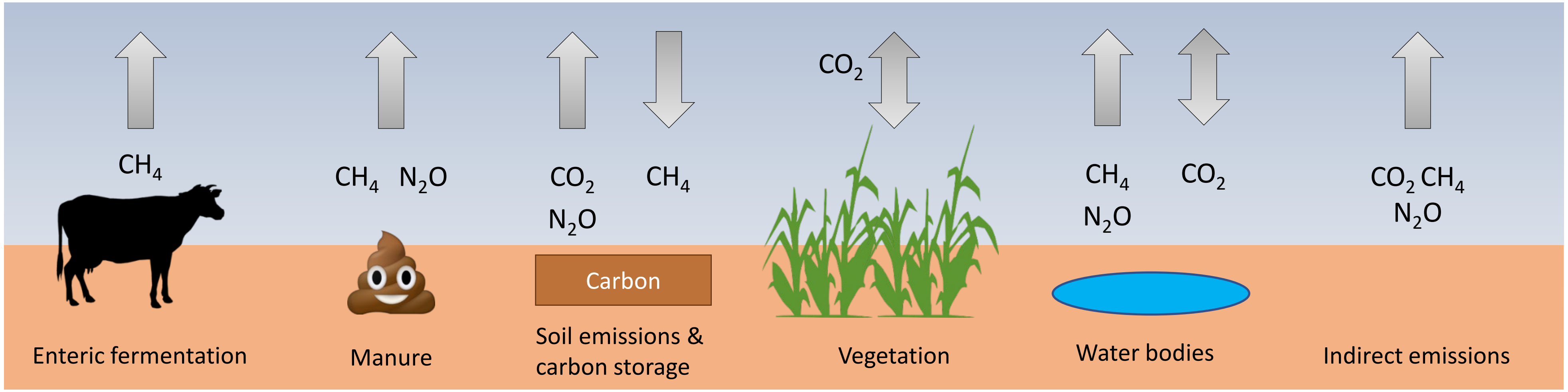
At the end of this lecture, you should be able to…

1) explain how soils control the production, consumption and exchange of the greenhouse gases CO_2, CH_4 and N_2O
2) understand the most important parameters affecting soil and manure GHG exchange, and why they are important
3) know common techniques to measure GHG exchange from soils and manure and know their advantages & disadvantages

Outline

1) Background
2) Processes (biotic & abiotic) & controls
3) Measurements & flux calculation
4) Practice (lab demonstration)

Greenhouse gas emissions from livestock systems



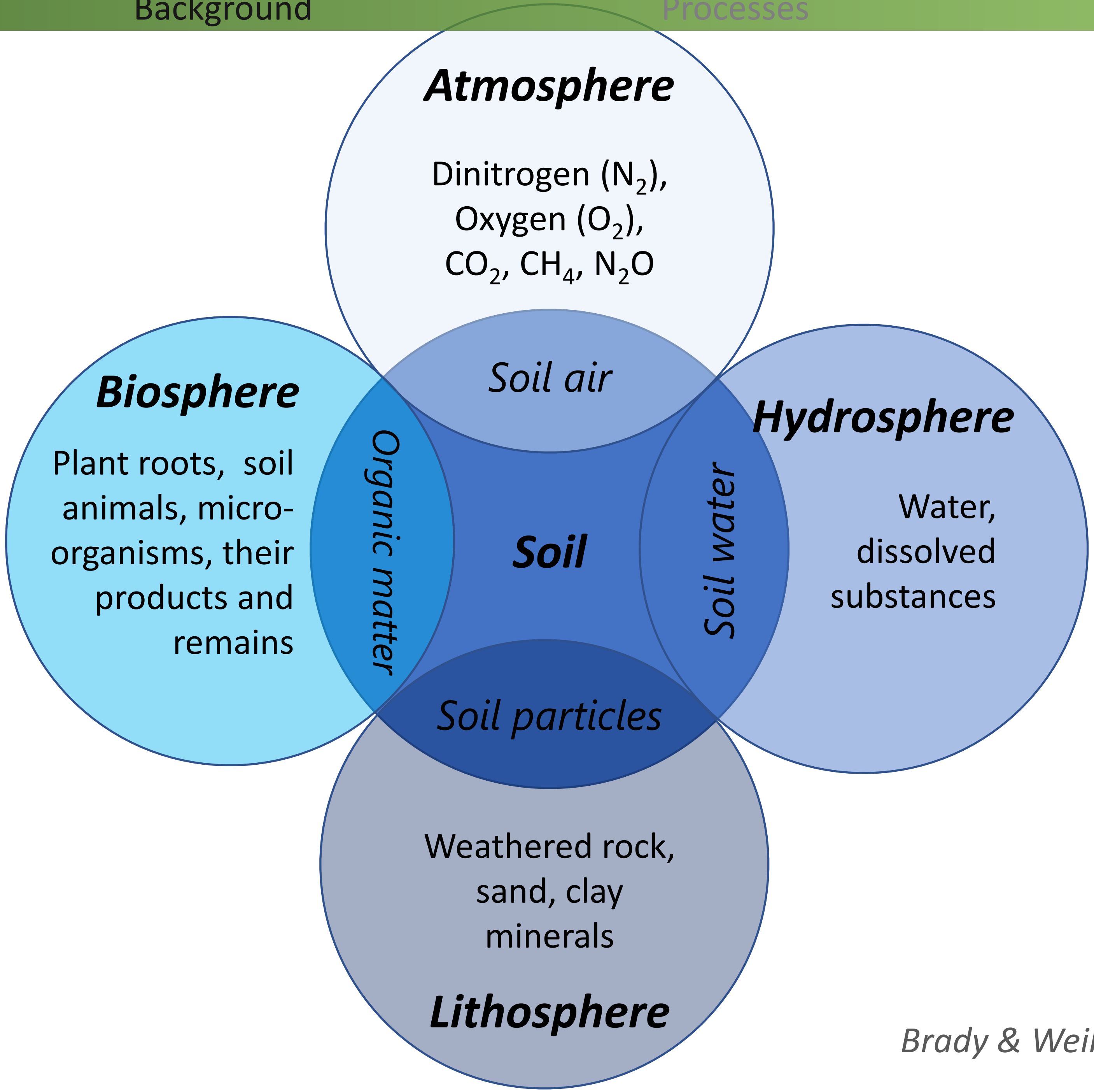
What is „soil“?

Definition

“The upper layer of terrestrial earth crust in which plants grow. Downwards, soils are delineated by solid or loose rocks and upwards by the vegetation cover and the atmosphere.”

Ok, so it’s the stuff between rocks and vegetation…

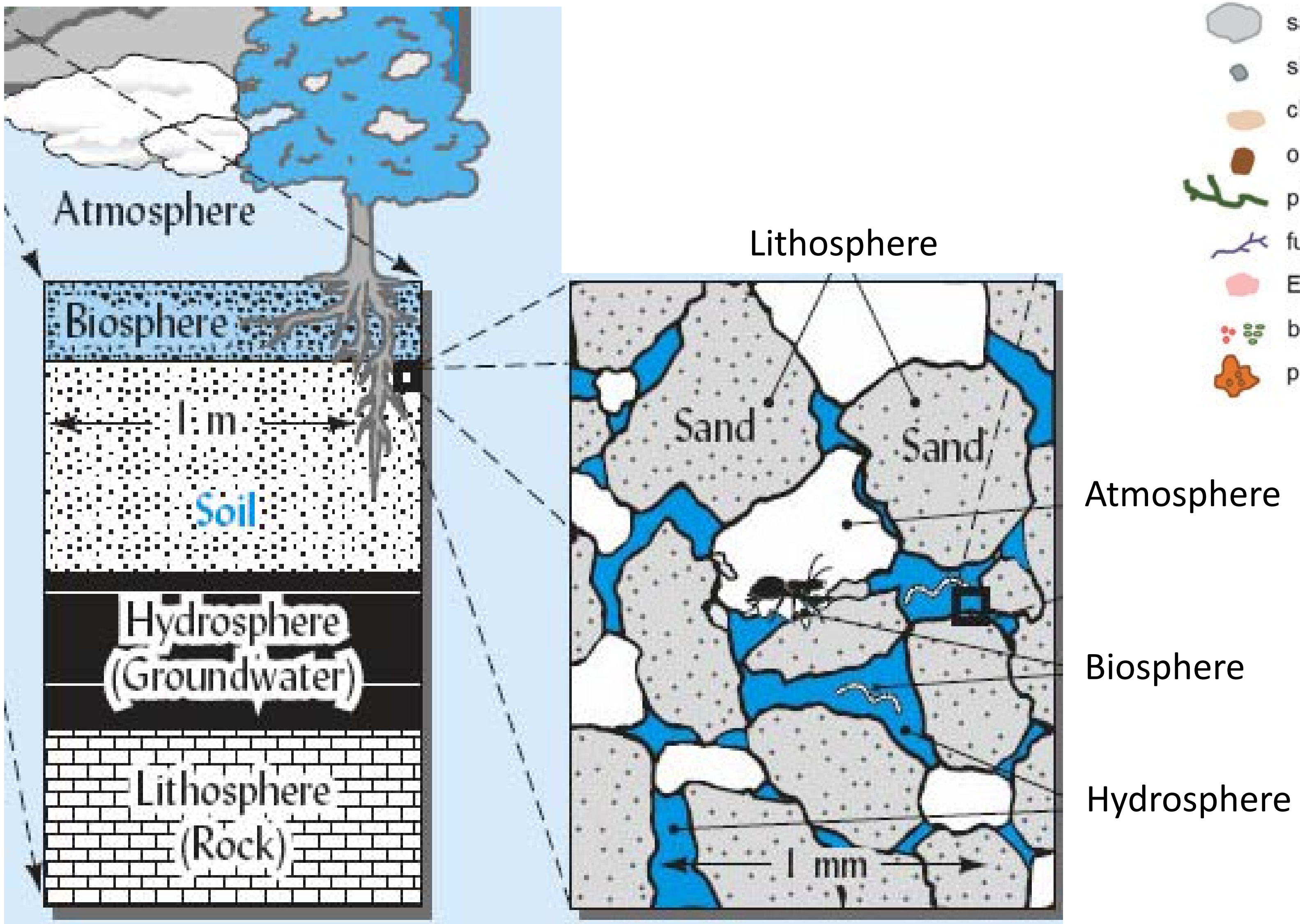
Pedosphere



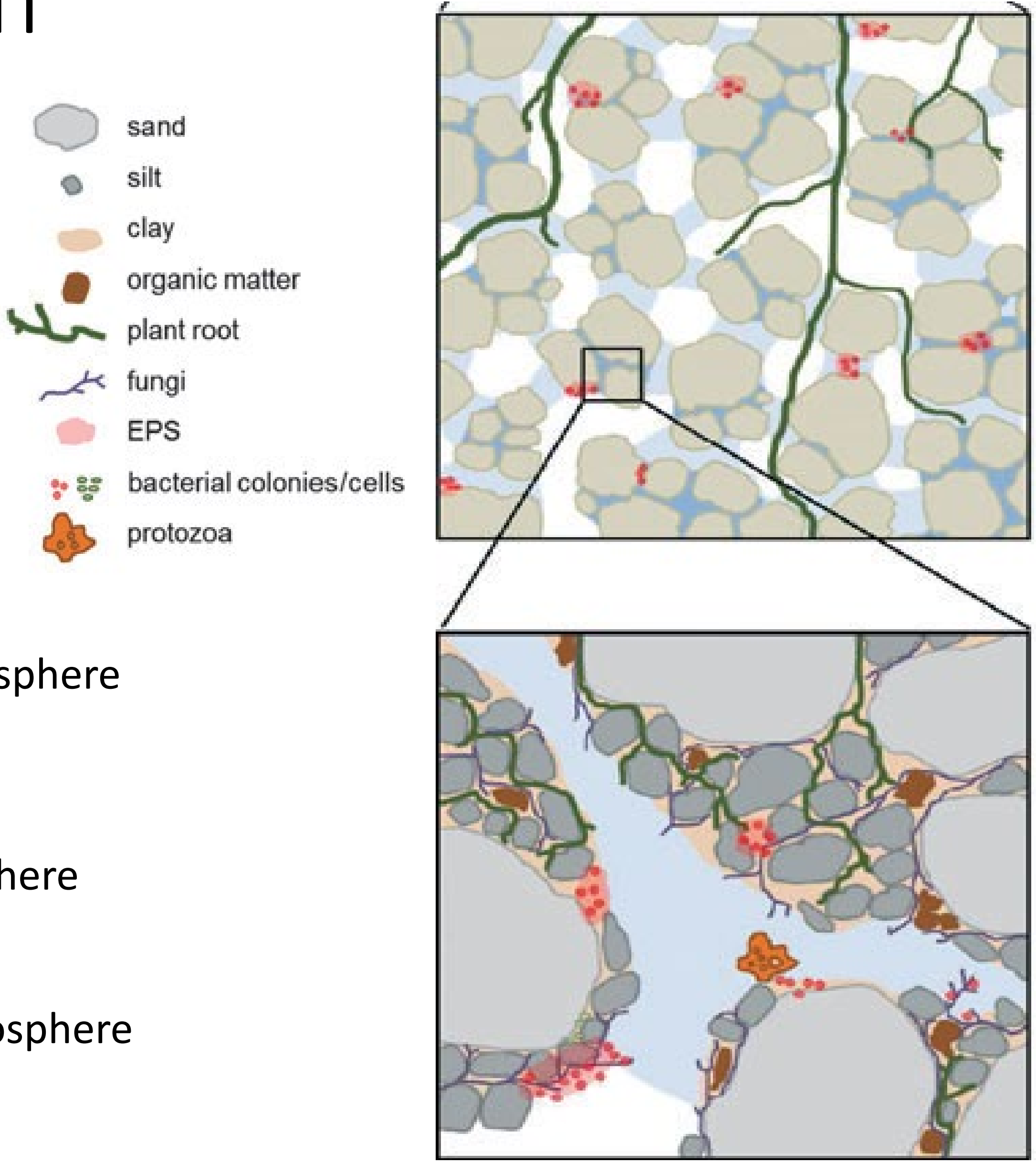
Pedosphere = interface between atmosphere, hydrosphere, lithosphere and biosphere

Brady & Weil, Elements of the Nature and Properties of soils, 2010

Soil – a 3-dimensional system

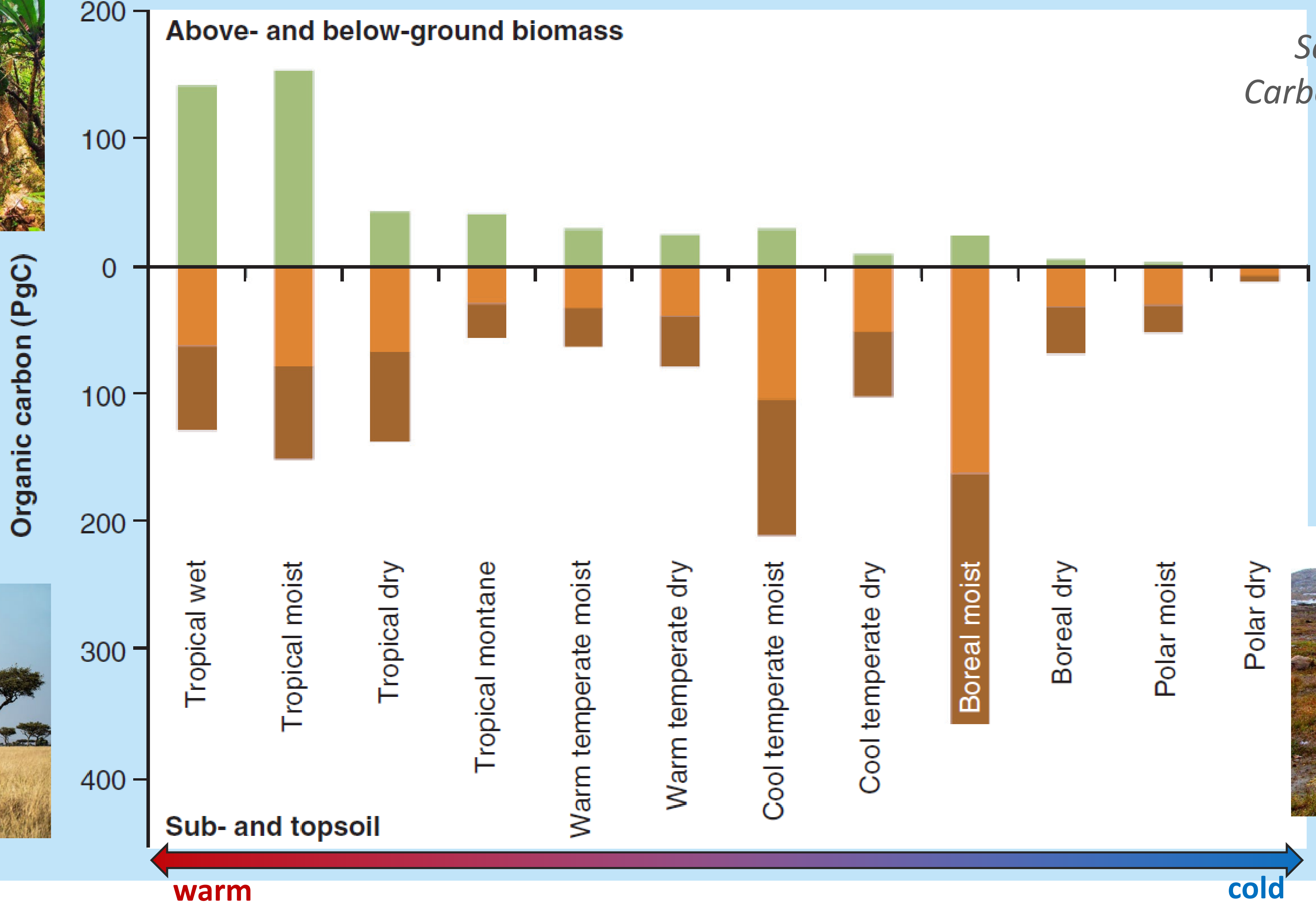


Brady & Weil, Elements of the Nature and Properties of soils, 2010



Vos et al., 2013 FEMS Microb. Rev.

Soil carbon according to geographic location

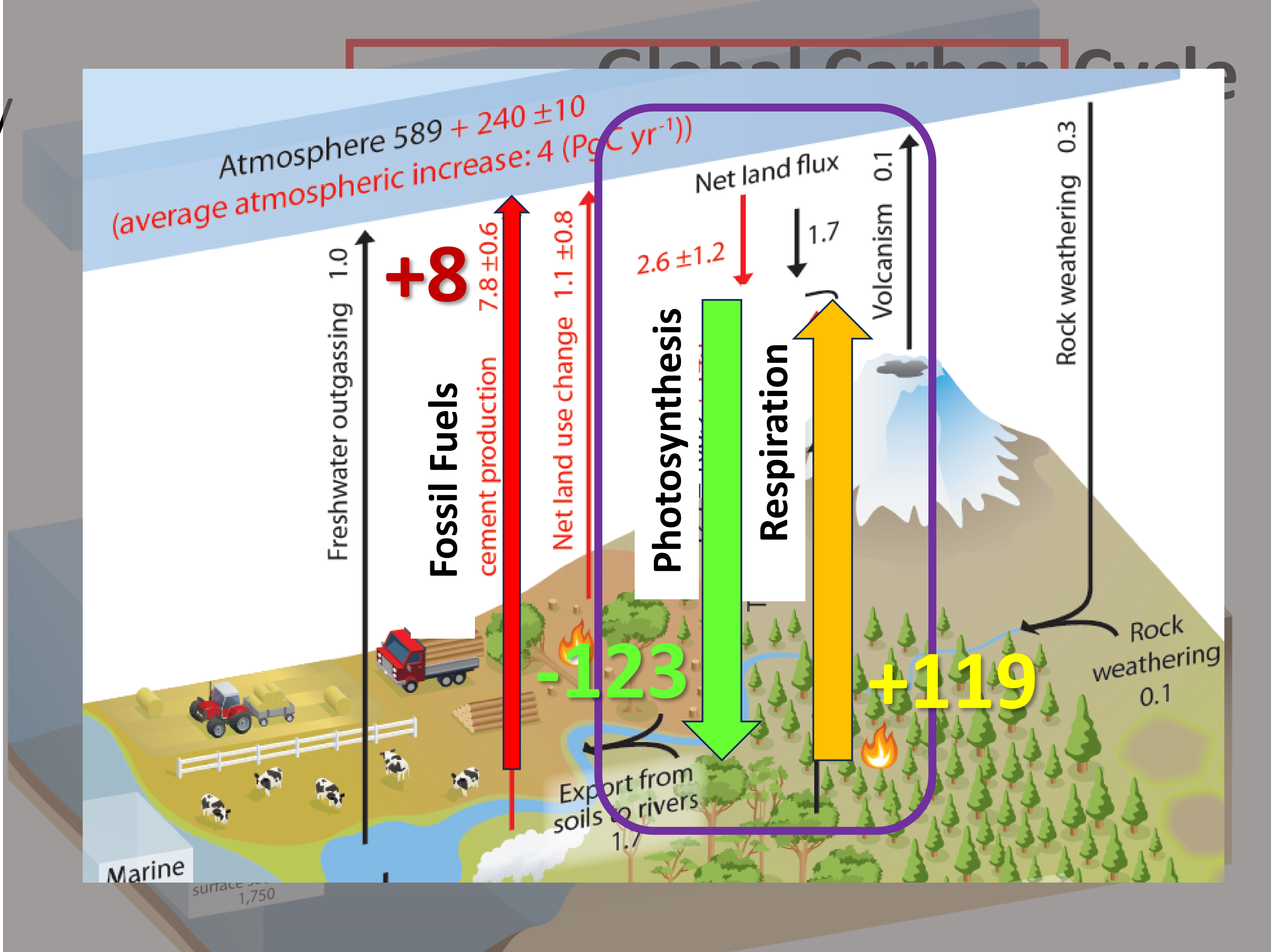


Scharlemann et al, Carbon Management, 2014

Soils not only store C…

… they control the terrestrial C cycle

… they are a major source of CO_2



Boxes = pools
Arrows = fluxes
Black = natural
Red = human
Units = PgC or PgC yr^{-1}

IPCC, 2013

Soils not only store C…

… they control the terrestrial C cycle

… they are a major source of CO_2

… they are sources and sinks of CH_4

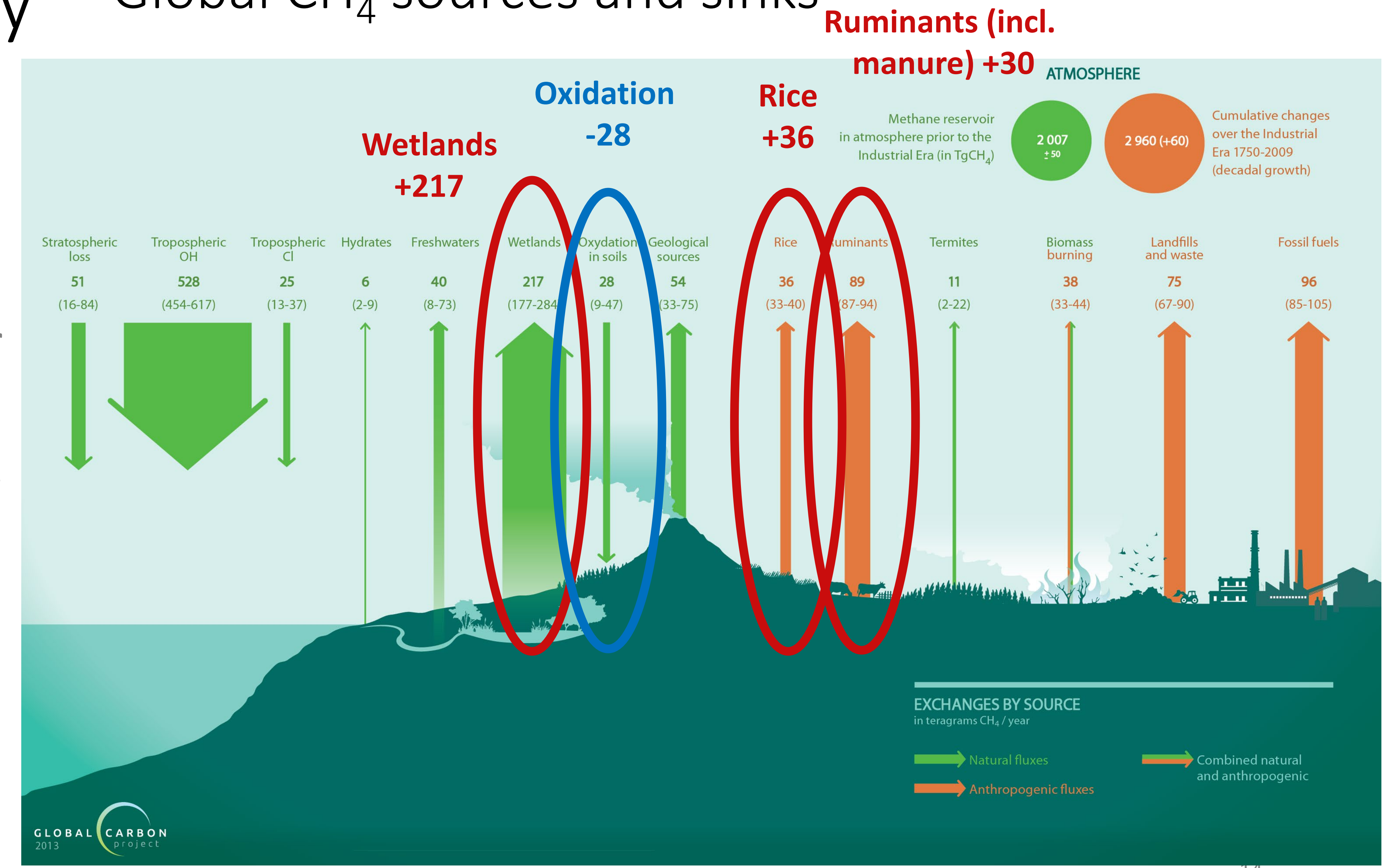
Green = natural

Red = human

Units = $TgCH_4\ yr^{-1}$

Global Carbon Project, 2013 (Data 2000-2009)

Global CH_4 sources and sinks



Soils not only store C…

… they control the terrestrial C cycle

… they are a major source of CO_2

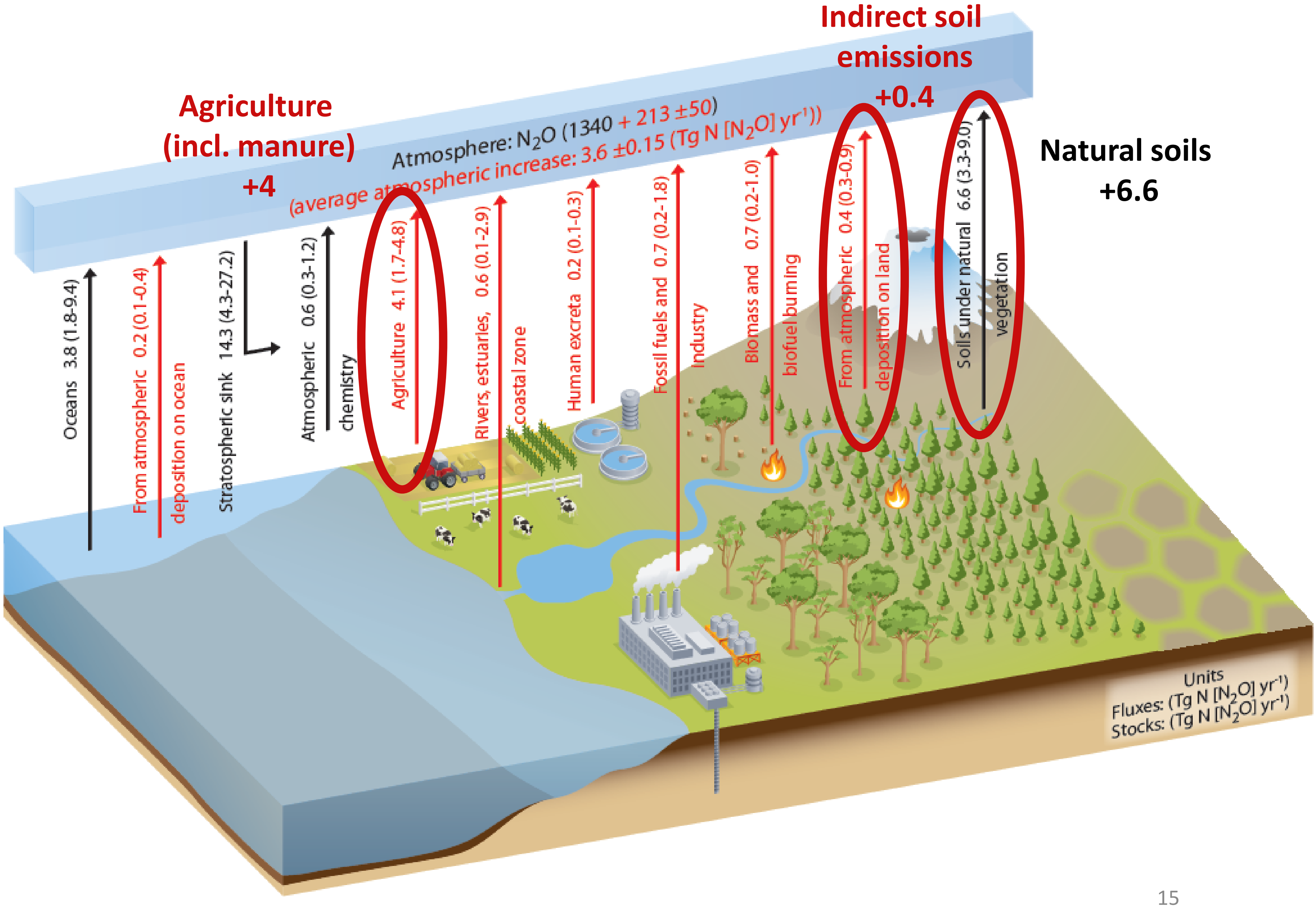
… they are sources and sinks of CH_4

… they are sources (and sinks) of N_2O

Black = natural

Red = human

Units = TgN or TgN yr^{-1}



IPCC, 2013

Global GHG sources and the contribution of soils

Greenhouse Gas	Soils	Anthropogenic Sources (excluding soils*)	Natural Sources (excluding soils)	TOTAL	Soil Contribution to Global GHG Emissions (%)	References
CO_2 (Pg C a^{-1})	98	11.2	100.5	210	47	a, b, c
CH_4 (Tg C a^{-1})	191	221	97	509	38	d
N_2O (Tg N a^{-1})	9.3**	5.5	4.0	18.8	49	e
Total GWP*** ($Pg\ CO_2$-eq a^{-1})	379	53	377	809	47	

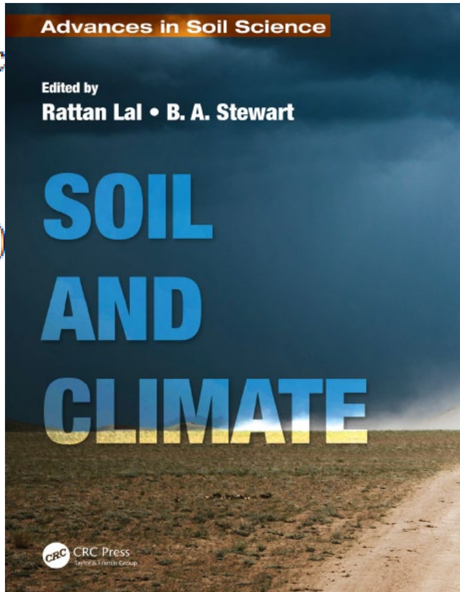
* CH_4 emissions from rice cultivation and N_2O emissions from agricultural soils were excluded from anthropogenic

** Includes indirect N_2O emissions due to fertilization.

*** Assuming a global warming potential of 34 and 298 for CH_4 and N_2O, respectively (Myhre et al. 2013).

Estimates sources: (a) Bond-Lamberty and Thomson (2010); (b) Le Quéré et al. (2016); (c) Ciais et al. (2013); (d) et al. (2016); (e) (Syakila and Kroeze (2011).

Zechmeister-Boltenstern, Diaz-Pines et al., 2018. Soil—The Hidden Part of Climate. In Lal and Stewart (eds), Soil and Climate. CRC Press.



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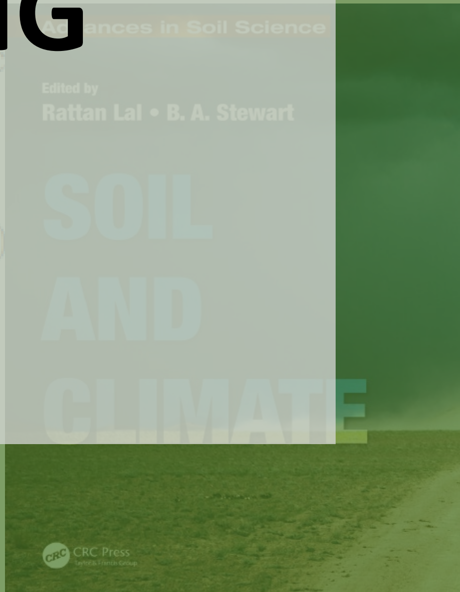
Take-home message: Soils and manure contribute significantly to global GHG emissions

Zechmeister-Boltenstern, Diaz-Pines et al., 2018. Soil—The Hidden Part of Climate. In Lal and Stewart (eds), Soil and Climate. CRC Press.

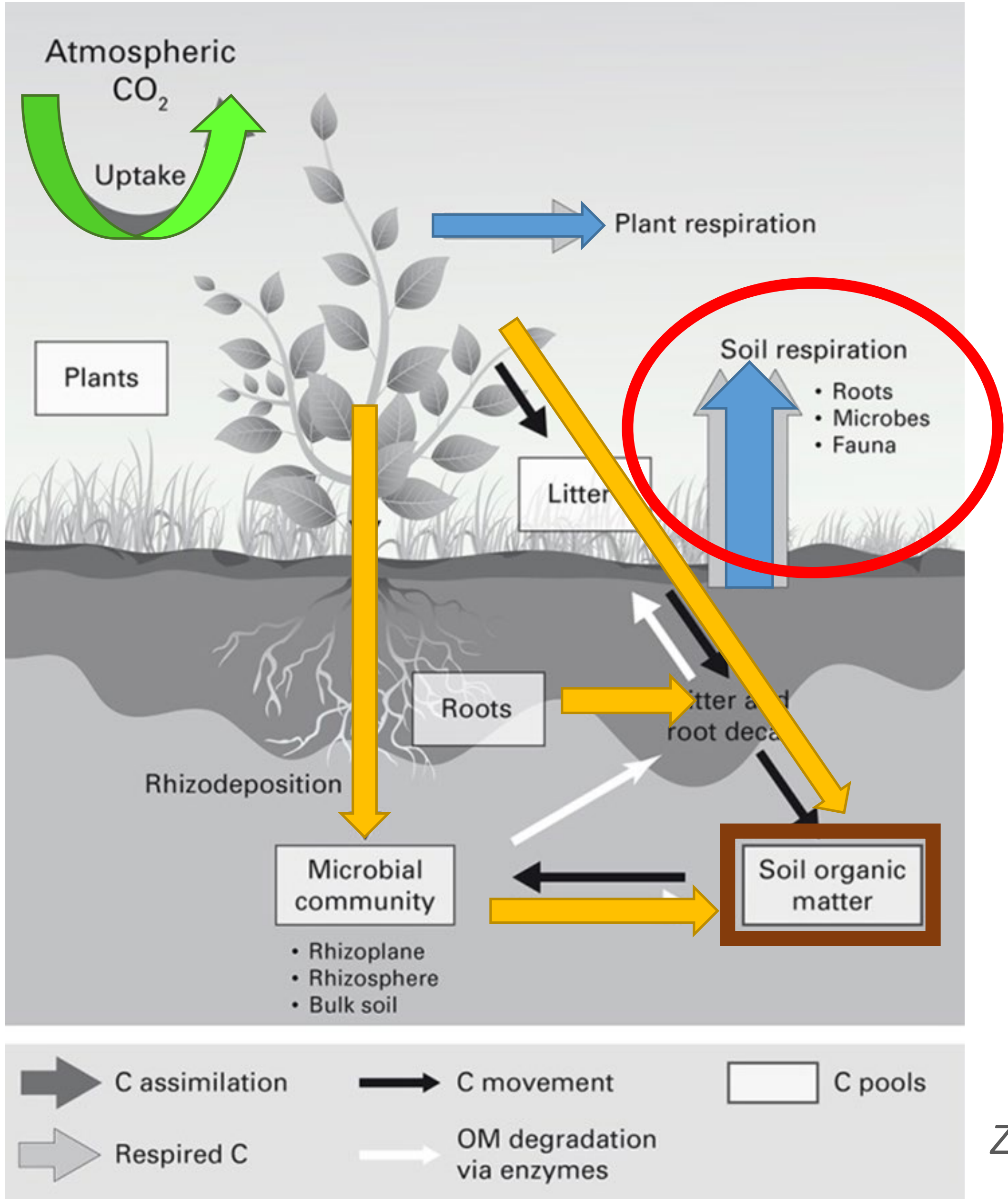


Outline

1) Background (why are soils important?)
2) **Biotic & abiotic processes of GHG emissions**
3) Measurements & flux calculation
4) Practice (field work, hands-on data)

Soil C cycle

(or: how does the C get into the soil?)



Zechmeister-Boltenstern, Diaz-Pines et al., 2018. Soil—The Hidden Part of Climate. In Lal and Stewart (eds), Soil and Climate. CRC Press.

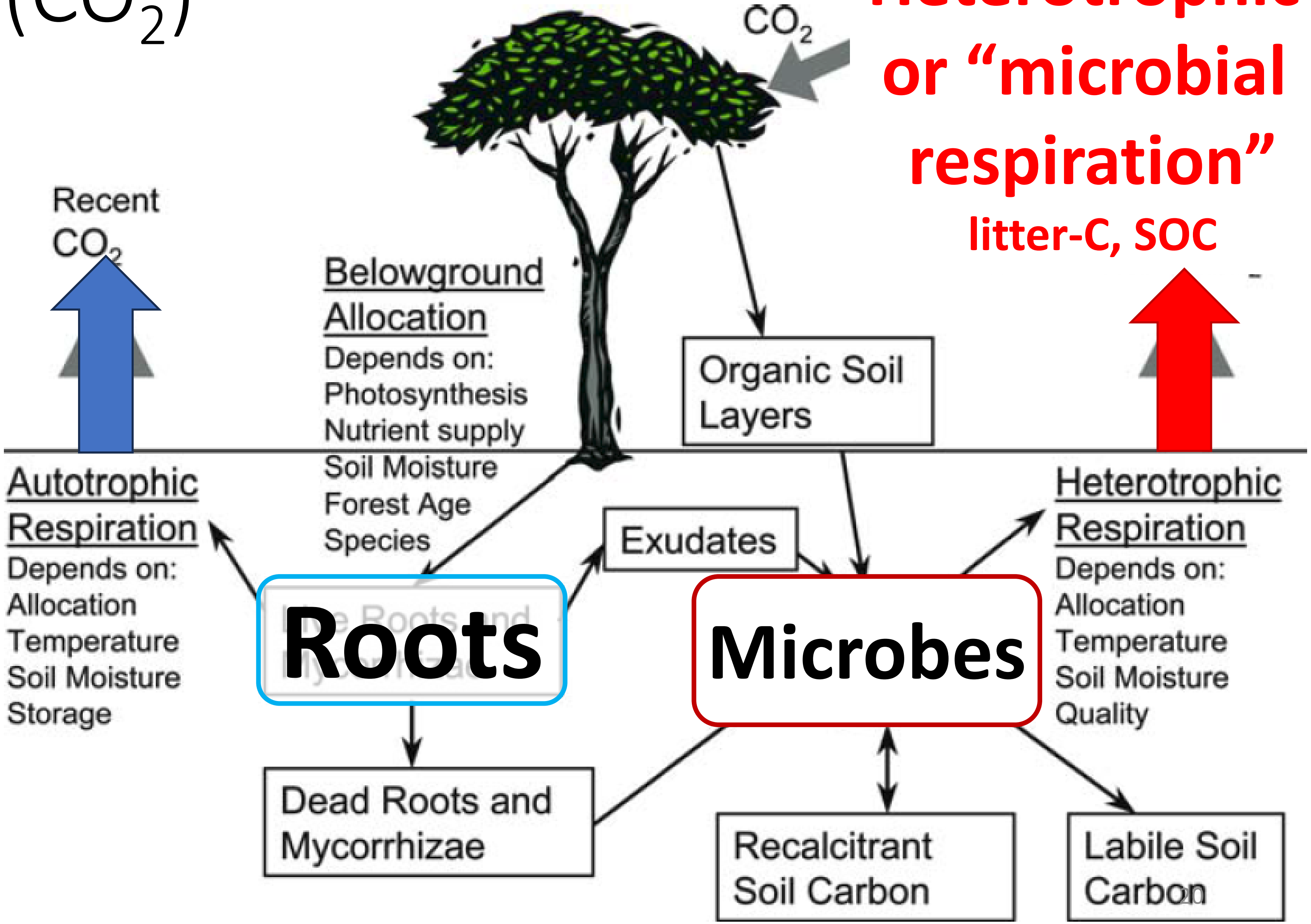
Soil respiration (CO_2)

Heterotrophic or “microbial respiration”

litter-C, SOC

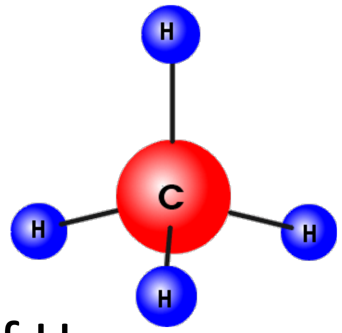
Autotrophic or “root respiration”

photosynthetic C



Ryan & Law, Biogeochemistry, 2005

Methanogenesis (CH_4 production)



- 2 Pathways:
  - **Hydrogenotrophic**: Reduction of CO_2 to CH_4 coupled to oxidation of H_2

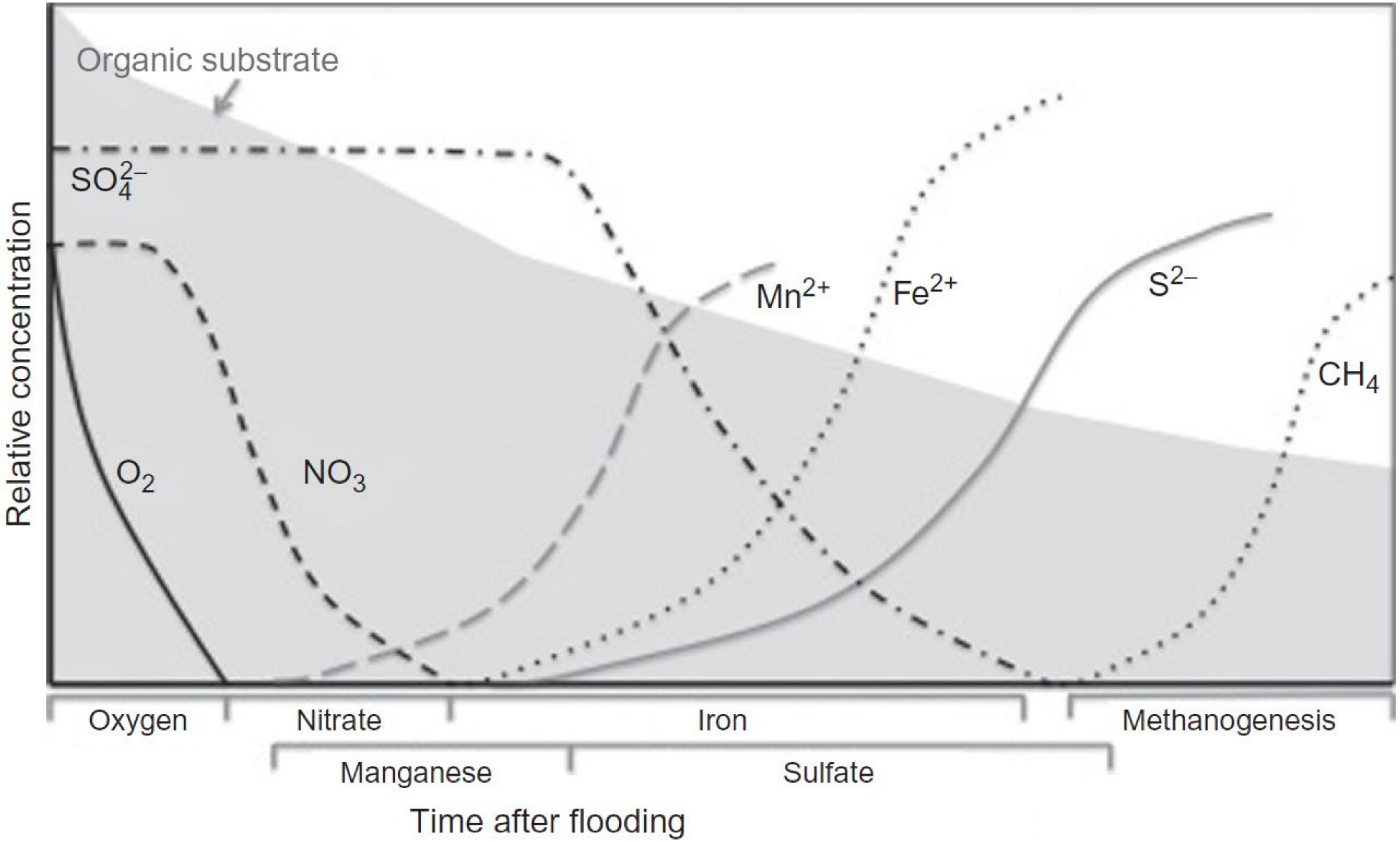
    $$\mathbf{CO_2 + 4\,H_2 \rightarrow CH_4 + 2\,H_2O}$$ → **Rumen of cattle!**

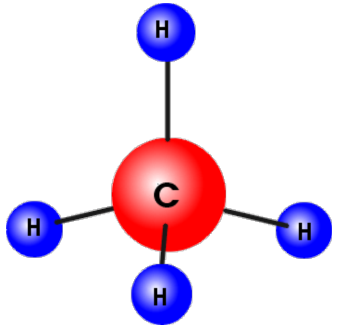
  - **Acetoclastic**: Reduction of acetic acid to CH_4

    $$\mathbf{CH_3COO^- + H_2O \rightarrow CH_4 + HCO_3^-}$$ → **2/3 of biogenic CH_4 (incl. soils)!**

- Conducted by autotrophic methanogenic archaea
- Strictly anaerobic process → supressed by O_2!
- Ocurrs in anoxic ecosystems (e.g. water-saturated soils, peat bogs, rice fields, manure slurry pits, manure heaps)

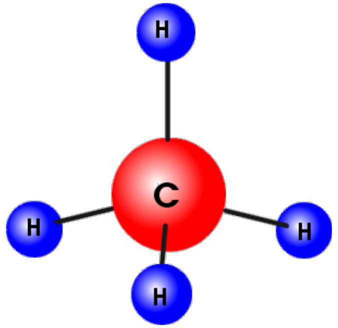
Methanogenesis (CH_4 production)

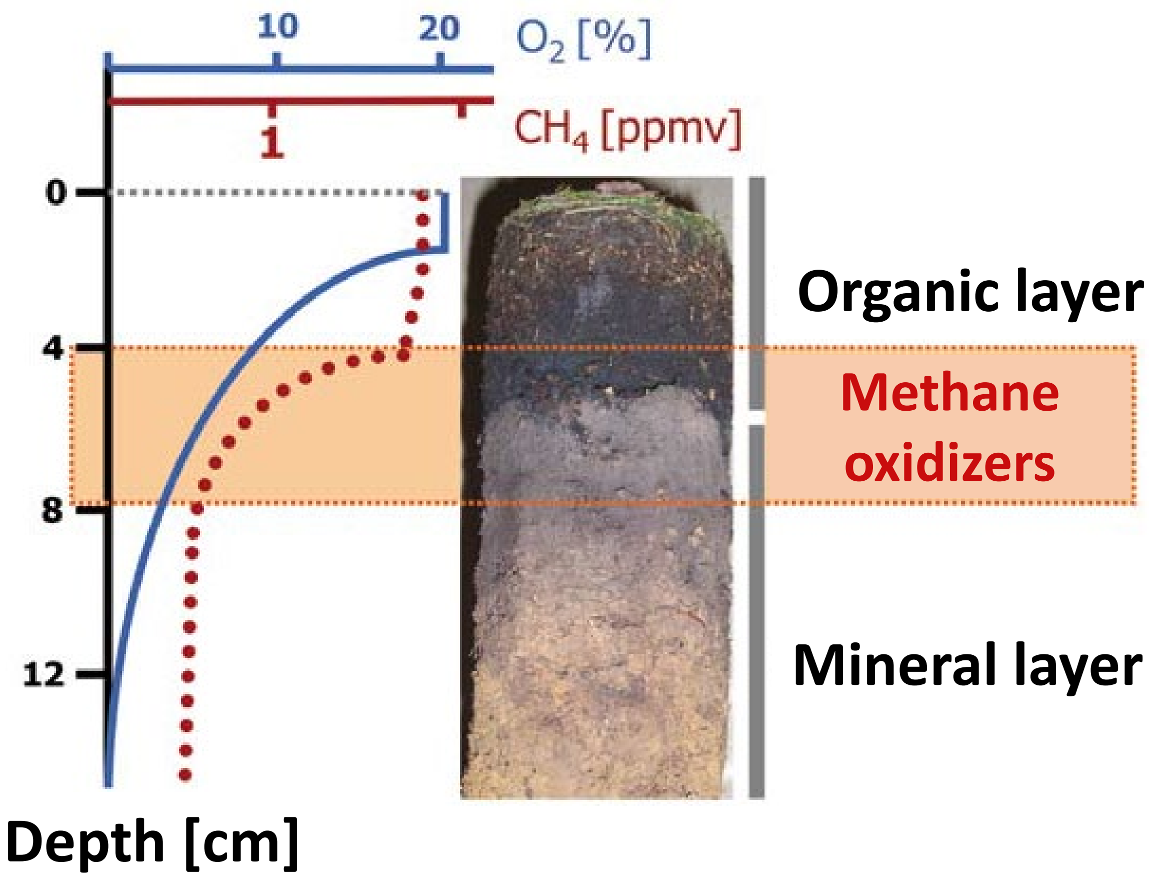




Schlesinger, 2013

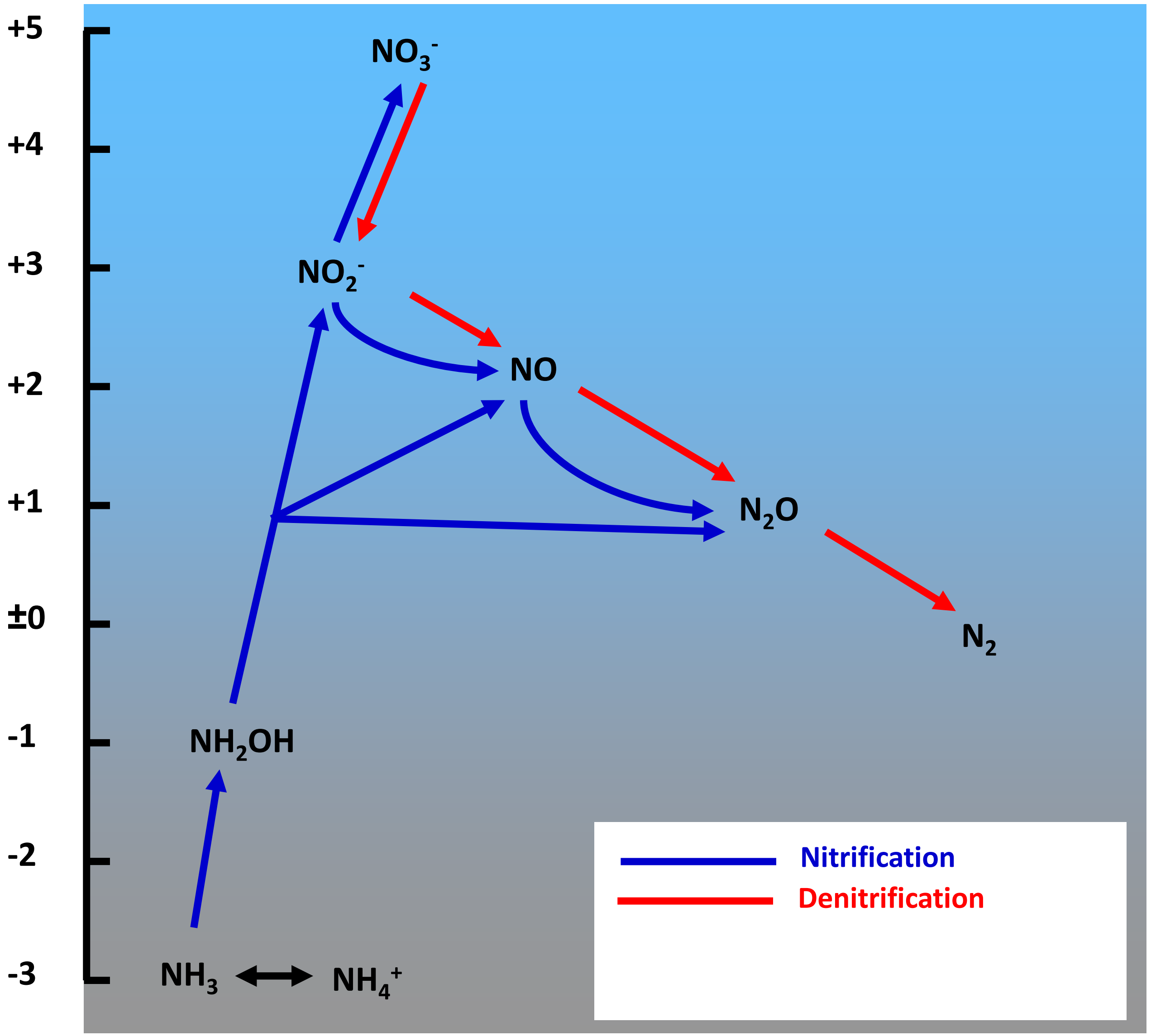
Methanotrophy (CH_4 uptake)





- Oxidation of CH_4 in upland soils via methanotrophic bacteria
- Controlled by O_2 supply (→ moisture) and soil diffusivity (→ texture, litter layer)

Soil nitrogen cycle & N_2O

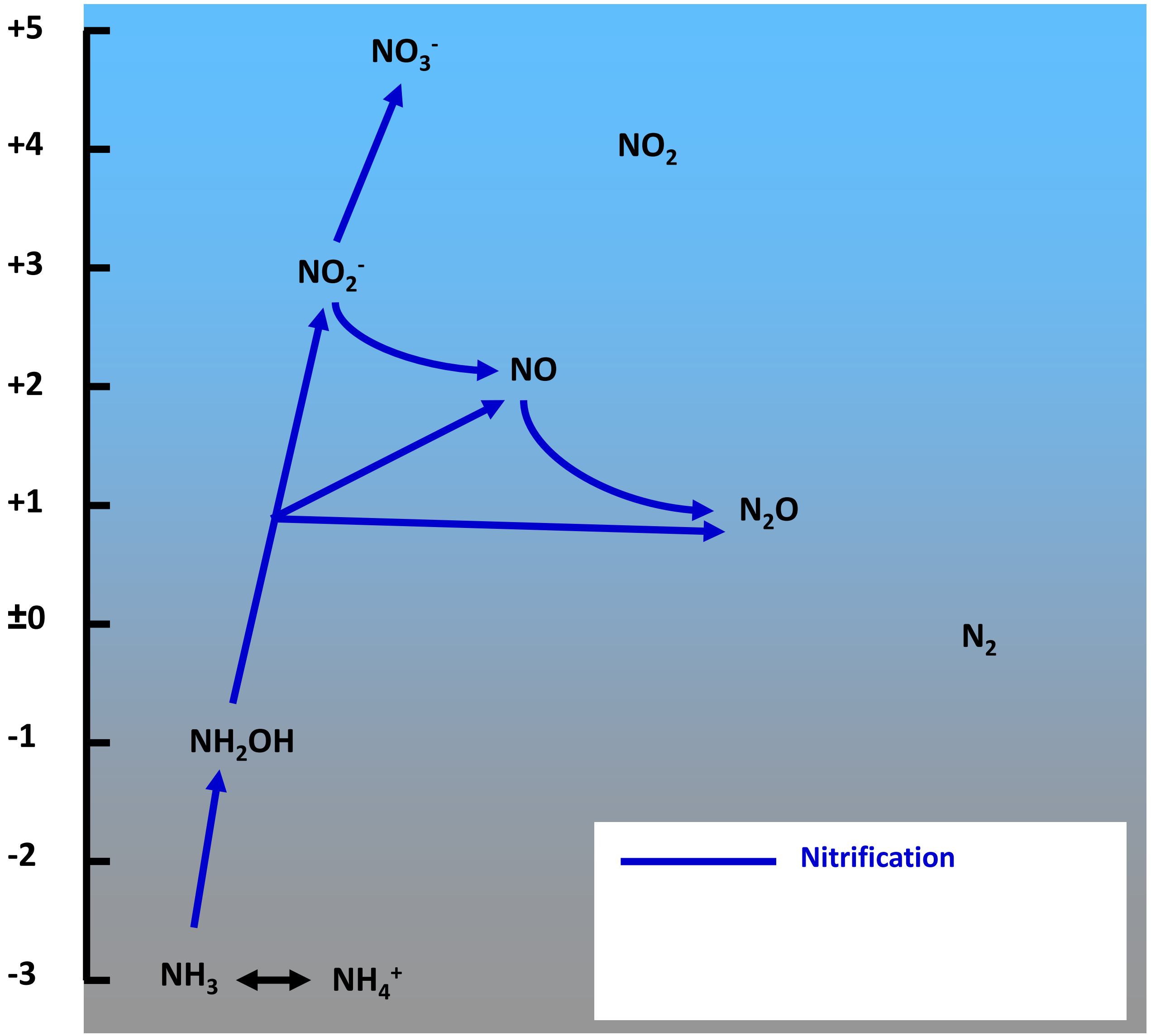


Nitrification & denitrification in soils and manure
→ 75 % of global N_2O emissions

Soil nitrogen cycle & N_2O

Nitrification

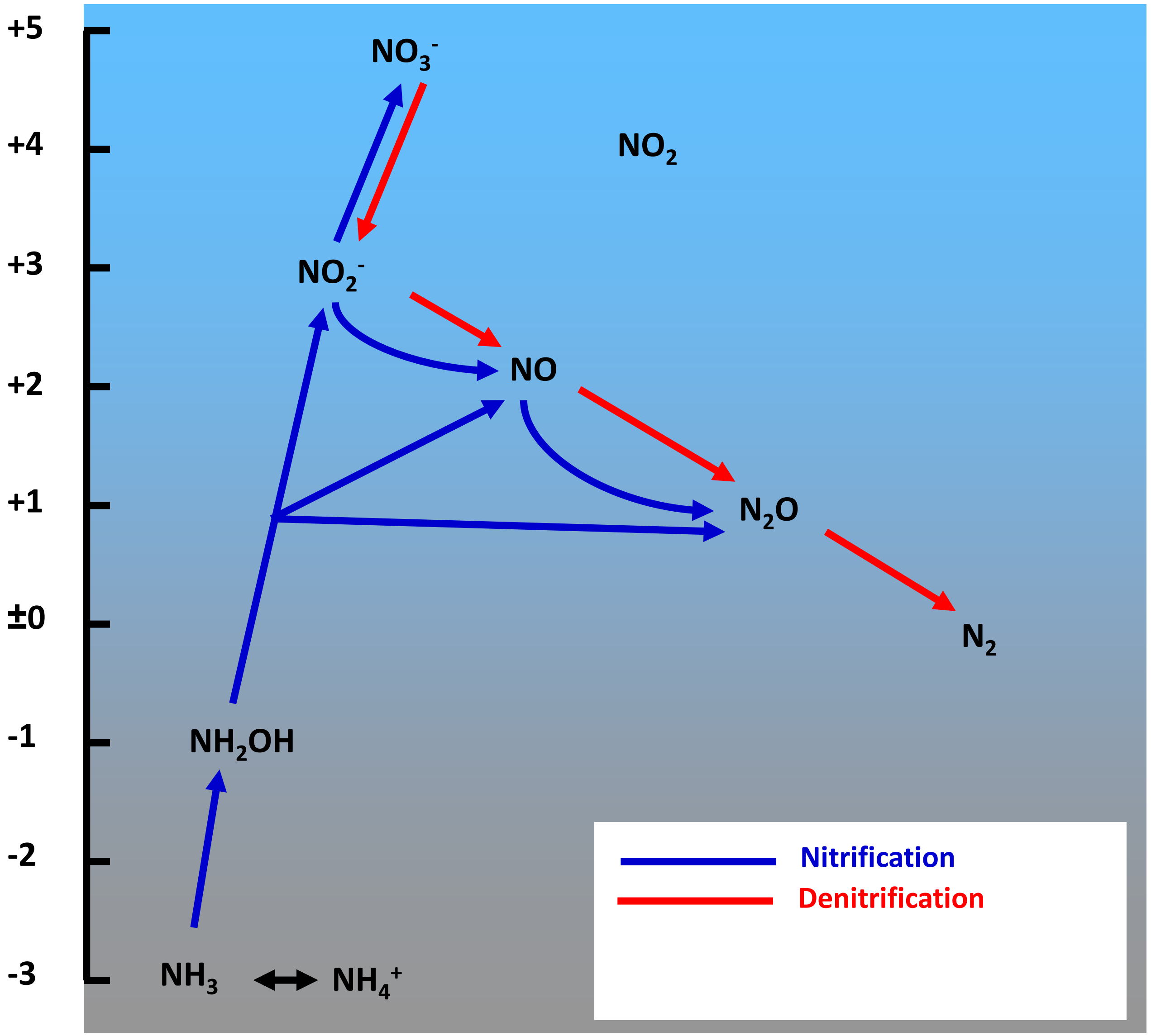
- Oxidation → O_2
- NH_4^+ supply
  → N mineralization, fertilizer addition, manure deposition
- Ammonia oxidixing archaea (AOA) & bacteria (AOB)



Soil nitrogen cycle & N_2O

Denitrification

- Reduction → (Facultative) anaerobic process
- NO_3^- supply → nitrification, N fertilization & manure
- Heterotrophic organisms → need C supply
- Most important N_2O producing process

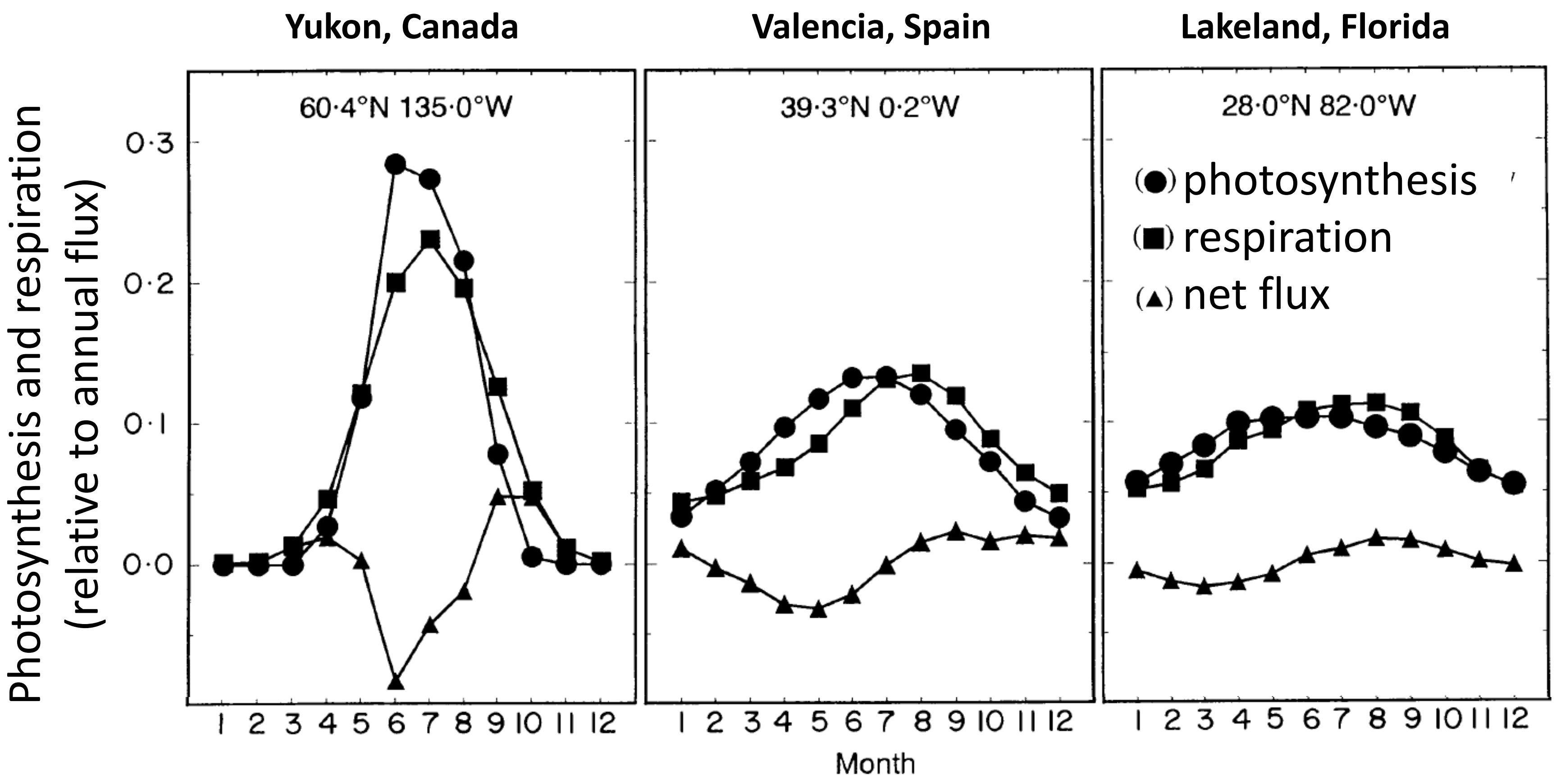


Controlling factors for soil & manure GHG emissions

Photosynthetic activity

Seasonal scale:

Soil respiration follows plant activity



GPP = Gross primary productivity (photosynthesis)

Lloyd & Taylor, Functional Ecology, 1994

When shall I measure? Annual budget or experimental comparison (e.g. growing season)?

Photosynthetic activity

Seasonal scale:

Soil respiration follows plant activity

GPP = Gross primary productivity (photosynthesis)

Driver #1: Photosynthetic activity & ecosystem productivity

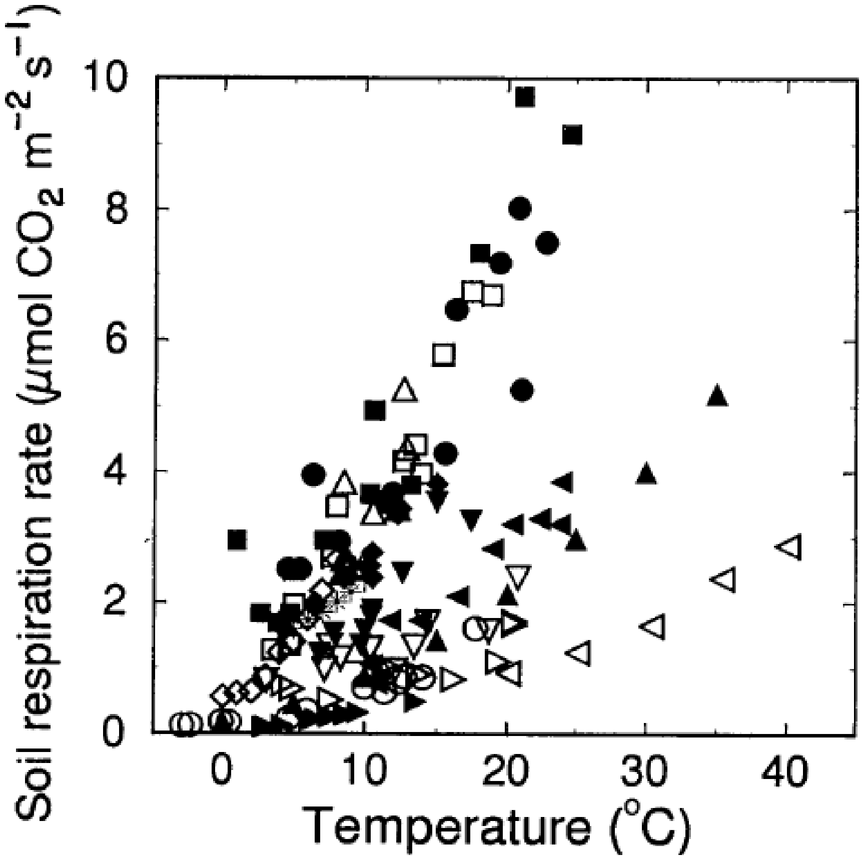
When shall I measure? Annual budget or experimental comparison (e.g. growing season)?

Lloyd & Taylor, Functional Ecology, 1994

Temperature

Seasonal scale:

Respiration rate varies with temperature



Ecosystems

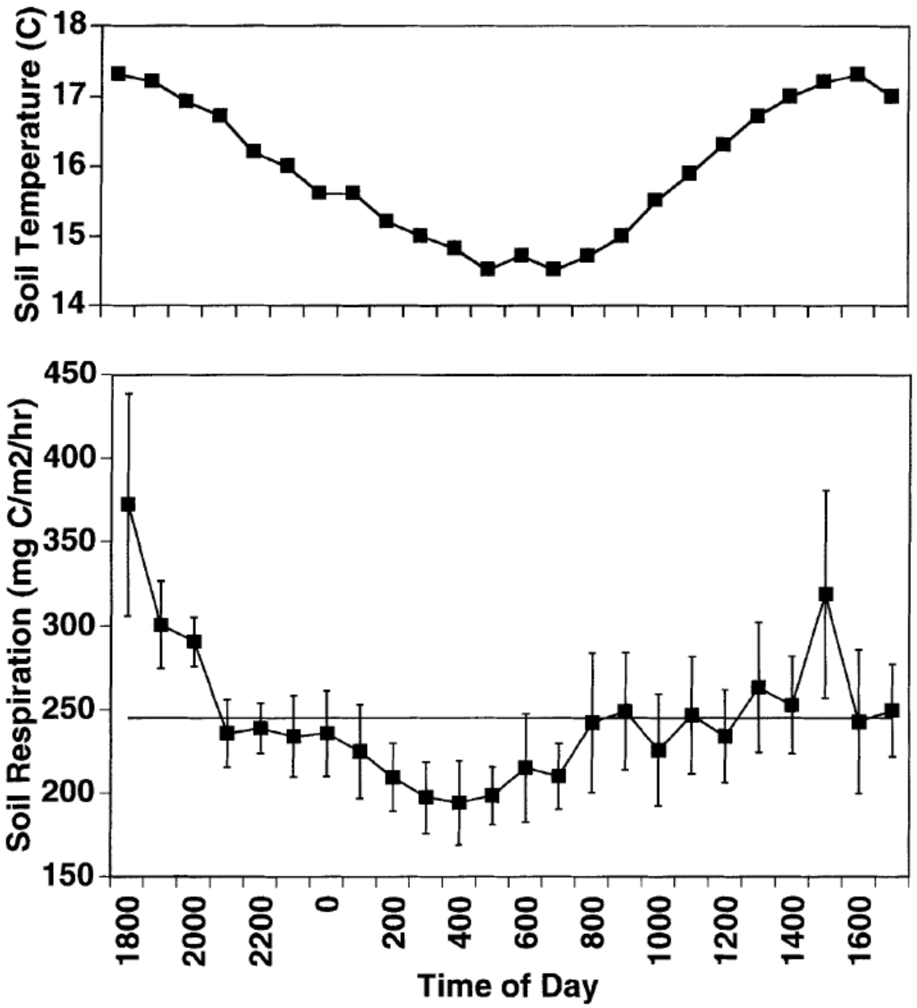
Symbol	System
●	*Pinus densiflora* (Japan)
○	Birch forest (Japan)
■	*Quercus* (Japan)
□	Beech forest (UK)
◆	*Calluna vulgaris* Heathland (UK)
◇	Tundra grass and sedges (Alaska, USA)
▲	Tall grass prairie (Missouri, USA)
△	Barley (UK)
◀	Temperate grassland (Germany)
◁	Savannah woodland (soil cores: Queensland, Australia)
▼	Subtropical rain forest (NSW, Australia)
▽	Peatland (Finland)
▶	Subarctic mire (Sweden)
▷	*Pinus palustris* (South Carolina, USA)
*	Grassland (Germany)

Lloyd & Taylor,
Functional Ecology, 1994

Temperature

Daily scale:

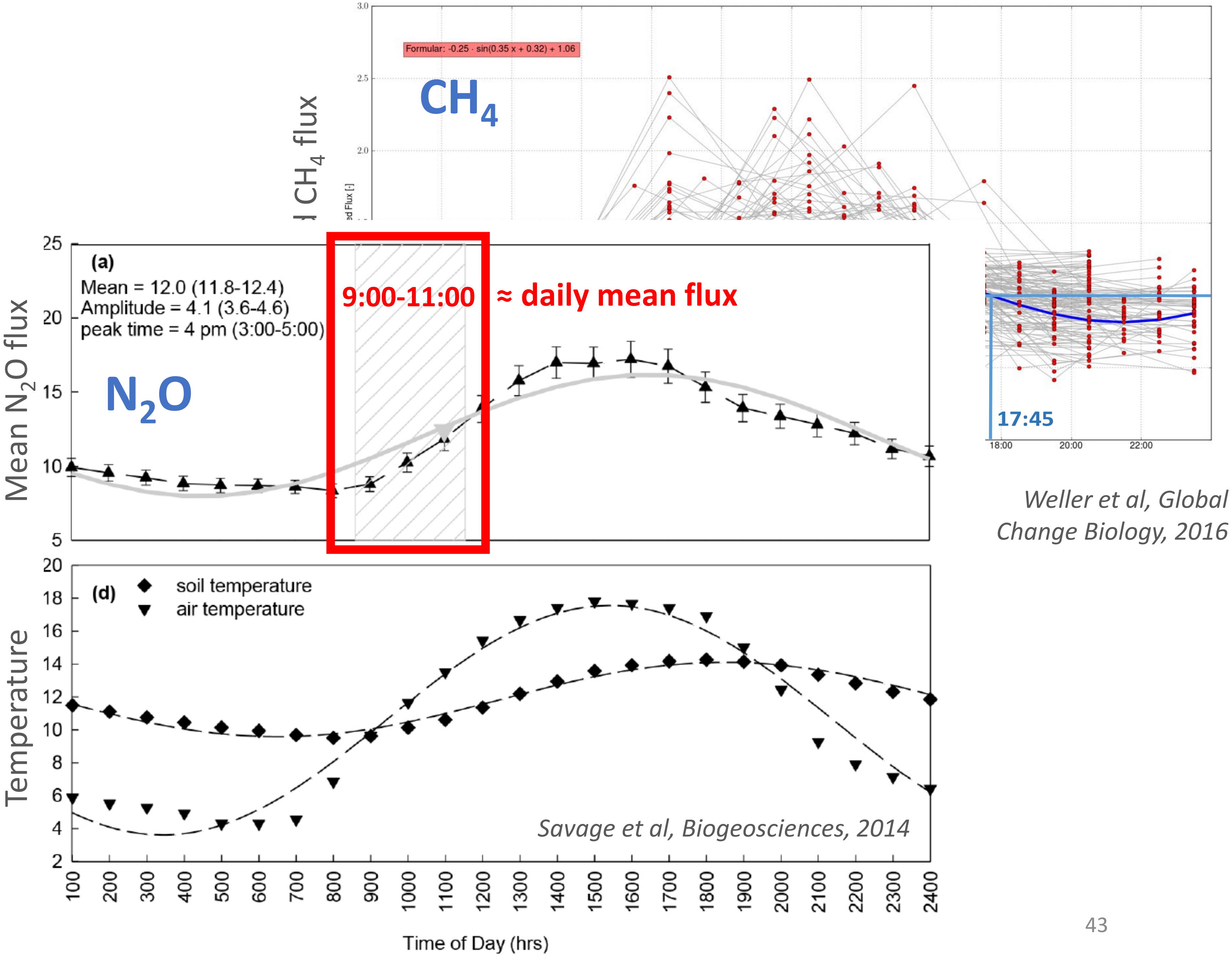
Diurnal pattern of soil respiration follows soil temperature



Davidson et al, Global Change Biology, 1998

Temperature

At what time should I measure?



Weller et al, Global Change Biology, 2016

Savage et al, Biogeosciences, 2014

Daily scale:
Diurnal pattern of CH_4 and N_2O efflux related to temperature

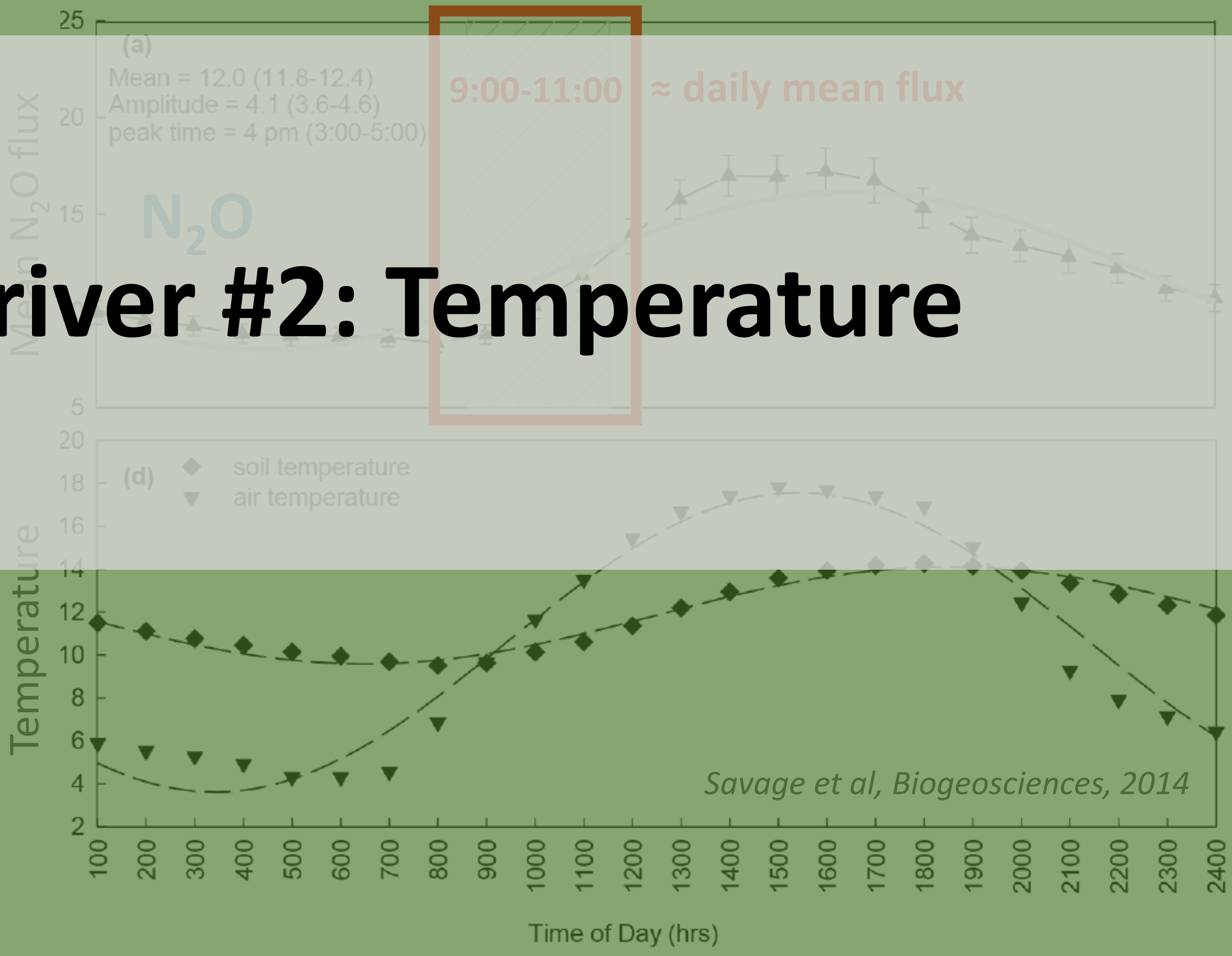
Temperature *At what time should I measure?*

Controlling factors:

- Photosynthetic activity
- Temperature
- Moisture
- Nitrogen availability
- Carbon availability

Driver #2: Temperature

Weller et al, Global Change Biology, 2016

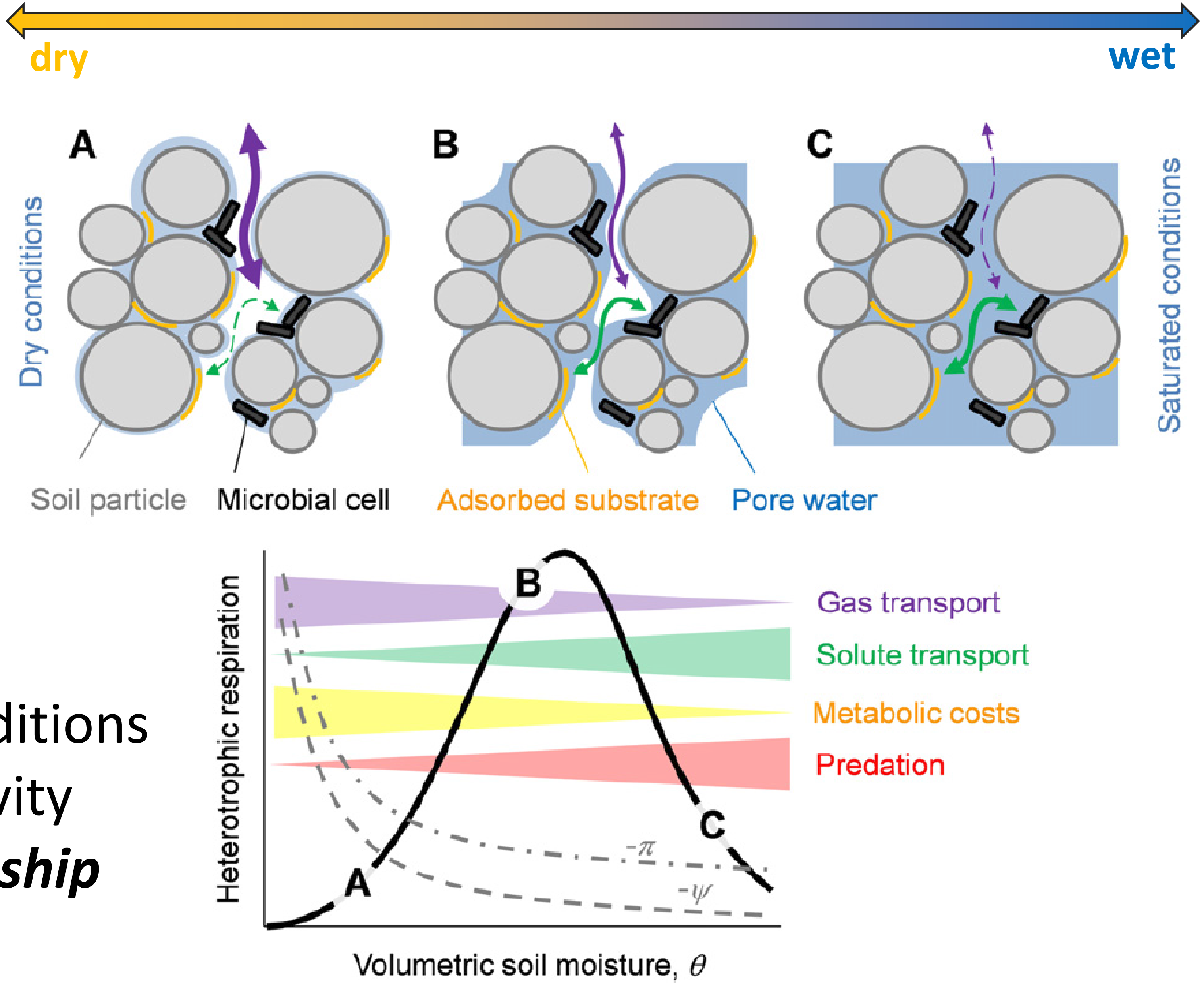


Daily scale:

Diurnal pattern of CH_4 and N_2O efflux related to temperature

Savage et al, Biogeosciences, 2014

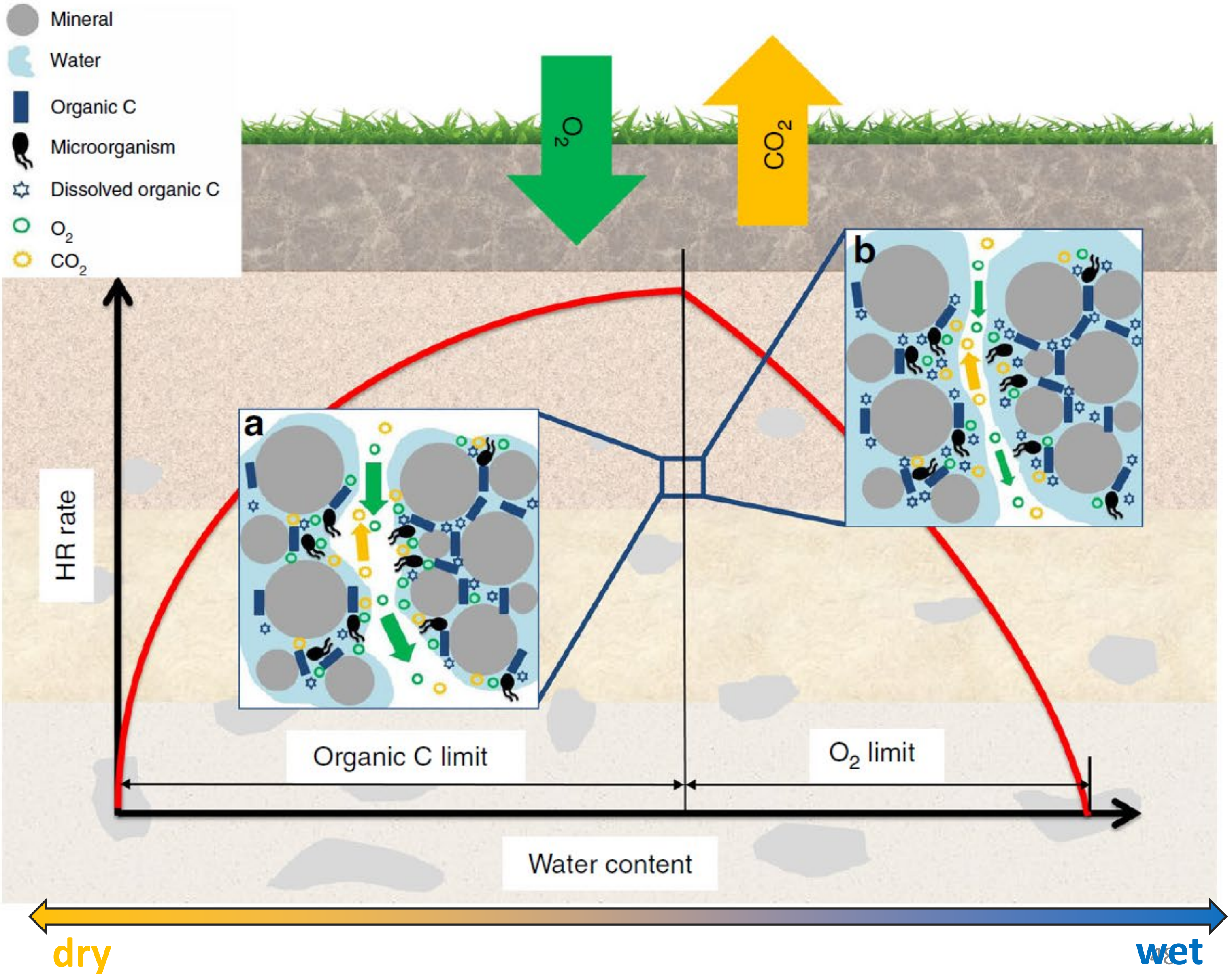
Moisture



Very wet or dry soil conditions inhibit microbial activity
→ ***non-linear relationship***

Moyano et al, Soil Biology & Biochemistry, 2013

Nitrogen and carbon availability



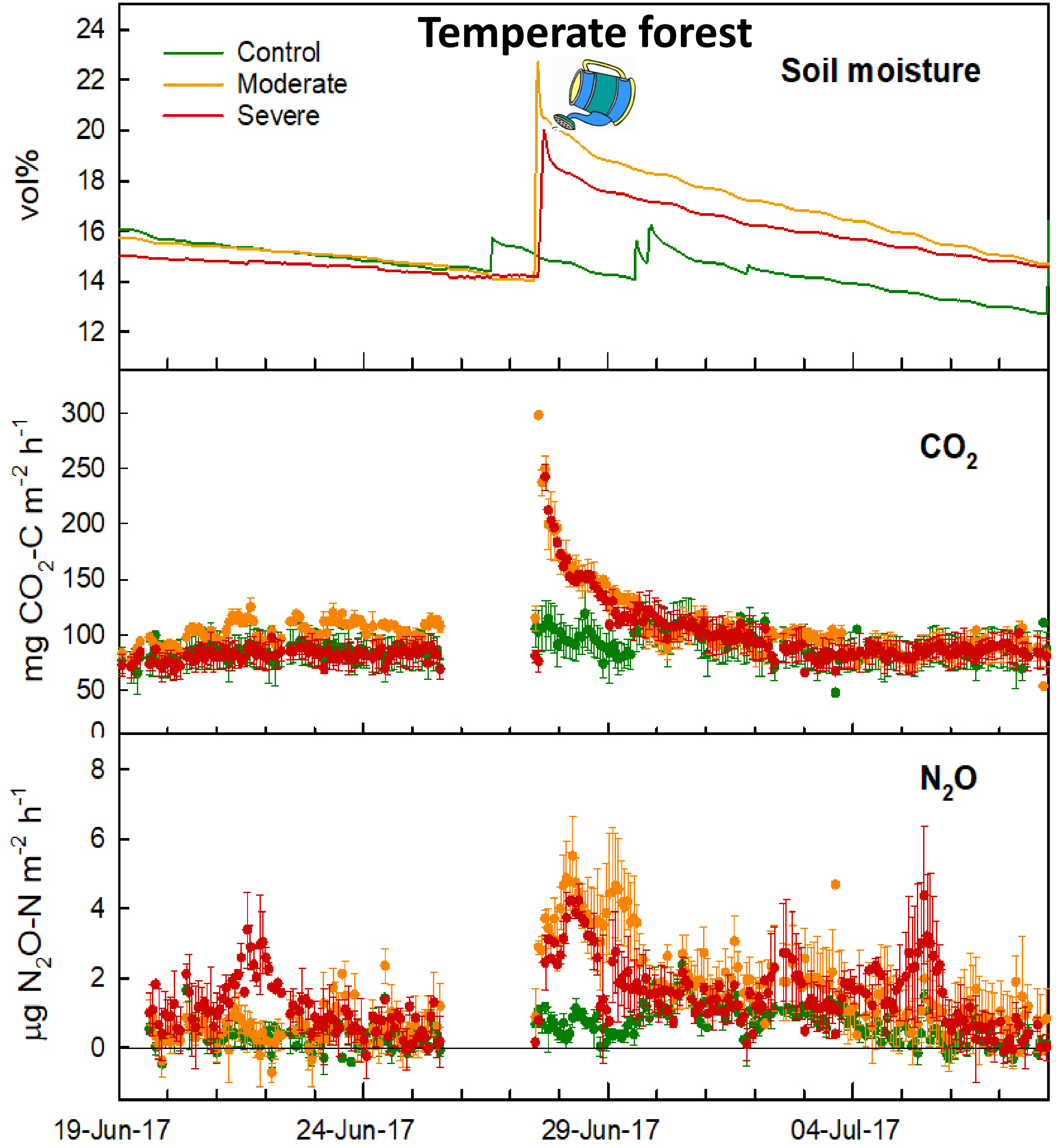
Low moisture: C + N limitation

High moisture: O_2 limitation

Yan et al, Nature communications, 2018

Episodic events ("pulses")

How frequently shall I measure?



Rewetting after drought:

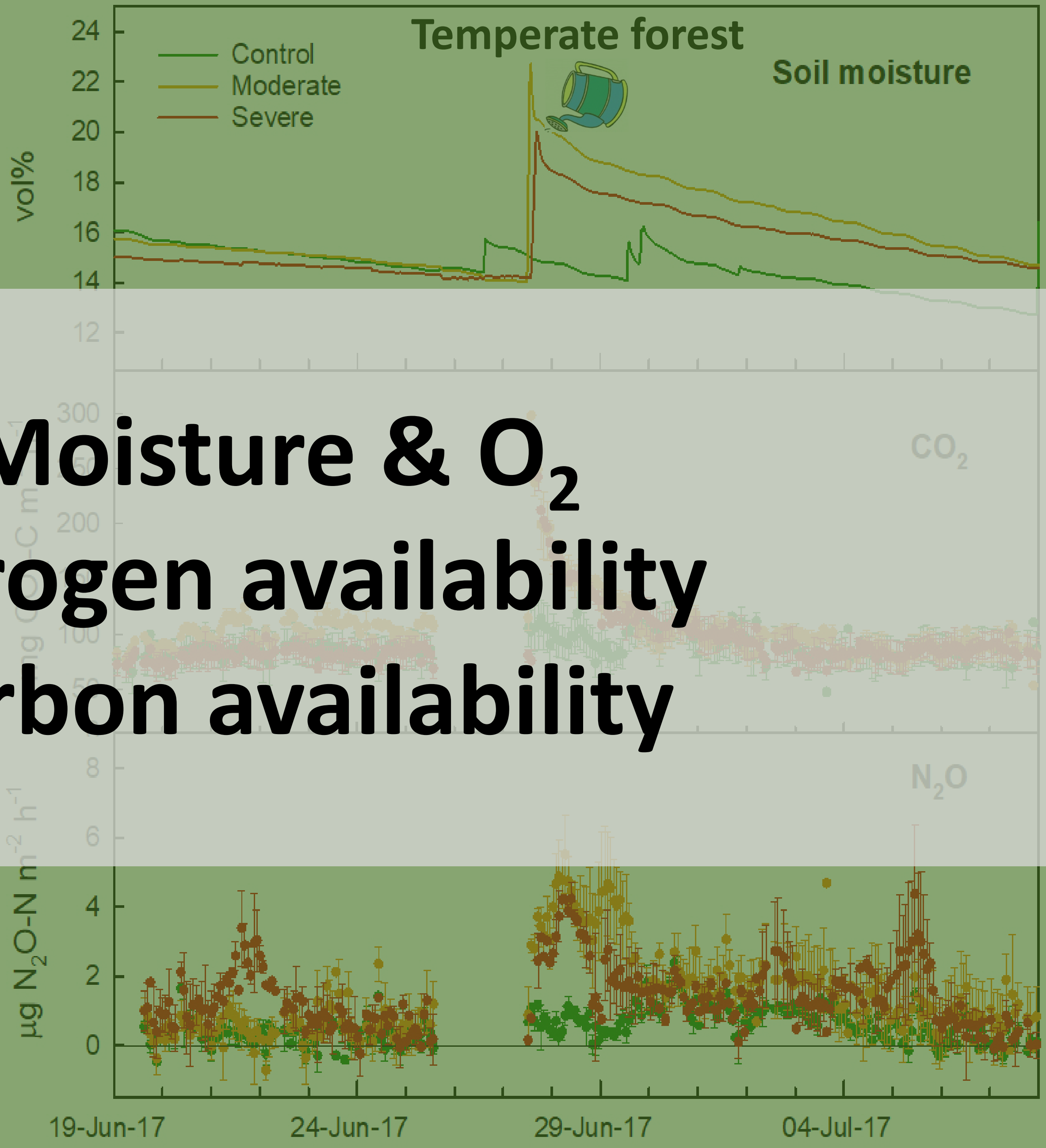
CO_2 pulse: 16% (monthly)

N_2O pulse: 40% (monthly)

Leitner et al, in preparation

Episodic events ("pulses")

How frequently shall I measure?



Driver #3: Moisture & O_2

Driver #4: Nitrogen availability

Driver #5: Carbon availability

Rewetting after drought:

CO_2 pulse: 16 % (monthly)

N_2O pulse: 20-57 % (monthly)

Leitner et al, in preparation

Outline

1) Background (why are soils important?)
2) Processes (biotic & abiotic) & controls
3) **Measurements & flux calculation**
4) Practice (field work, hands-on data)

Field chambers (static or dynamic)
+ Versatile + Easy construction + Automatization possible - Small surface - Temporal & spatial variations at different scales - Inherent chamber perturbation

Lab incubations/ parameterizations
+ Easy handling, allows for high no. of replicates. + Control of environmental conditions (H, T) - Representativeness questioned - Perturbation and sample conservation

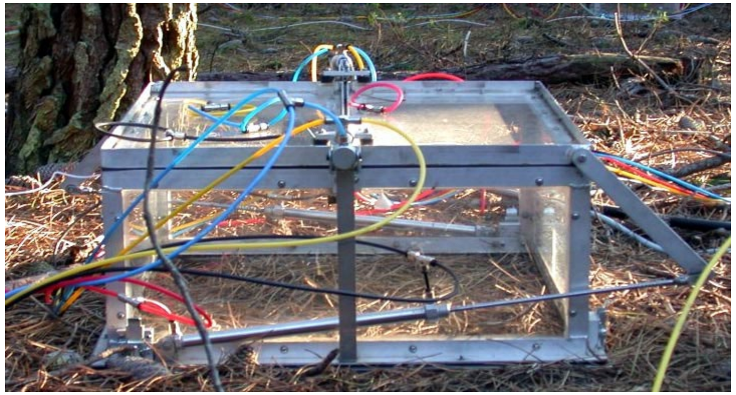
Chamber technique: Most common approach for measuring GHG emissions from soils and manure

➢ **Two types**:
- Closed/Static chambers
- Dynamic chambers

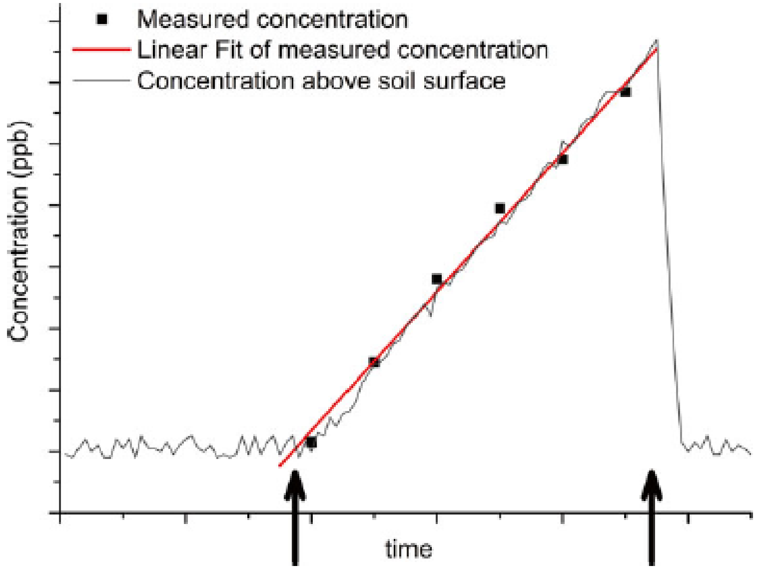
➢ **Two operation modes**
- Manual
- Automatic

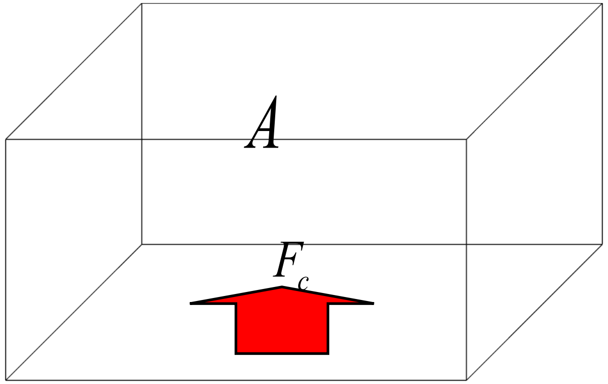
Closed chamber

- Gas-tight enclosure of a soil- or soil-plant system or plant part
- Follow the increase/ decrease in gas concentration with time (e.g. N_2O, CO_2, CH_4)
- Slope of increase/ decrease is used to calculate the flux
- **Advantages:** low tech, cheap, easy to use, no power supply needed, high sensitivity (if closed long enough
- **Disadvantages:** change environmental conditions, soil-atmosphere exchange is a balance of consumption-production processes → equilibrium might be changed



Butterbach Bahl et al, Springer, 2016

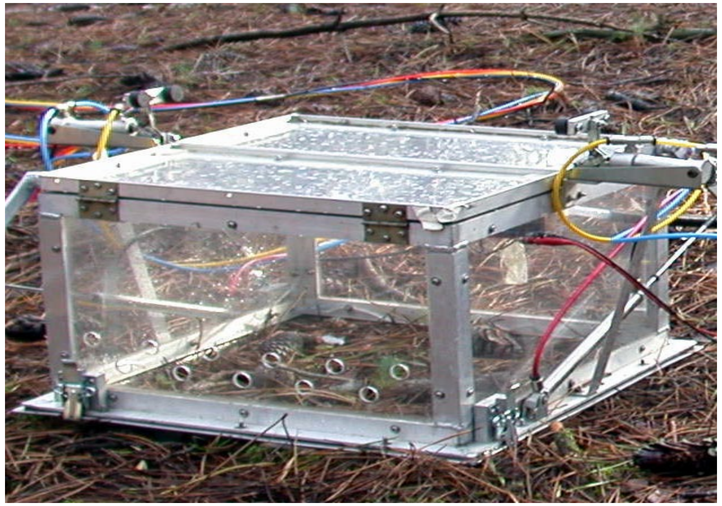


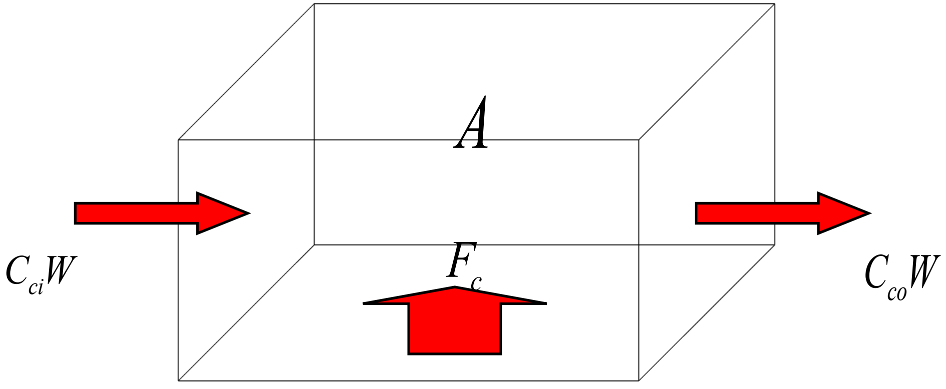


$$F_c = \frac{V}{A}\frac{\partial C_c}{\partial t}$$

Dynamic chamber

- Gas-flow through a chamber enclosing a soil- or soil-plant system or plant part
- Measurement of gas concentration at the inlet and at the outlet (e.g. CO_2, CH_4, NO or NO_2)
- Fluxes are calculated from concentration differences and air mass flow
- **Advantages:** less disturbance, easy to apply, medium to high sensitivity (depends on detector)
- **Disadvantages:** high gas flow rates → pumps and thus power needed, still affects environmental conditions



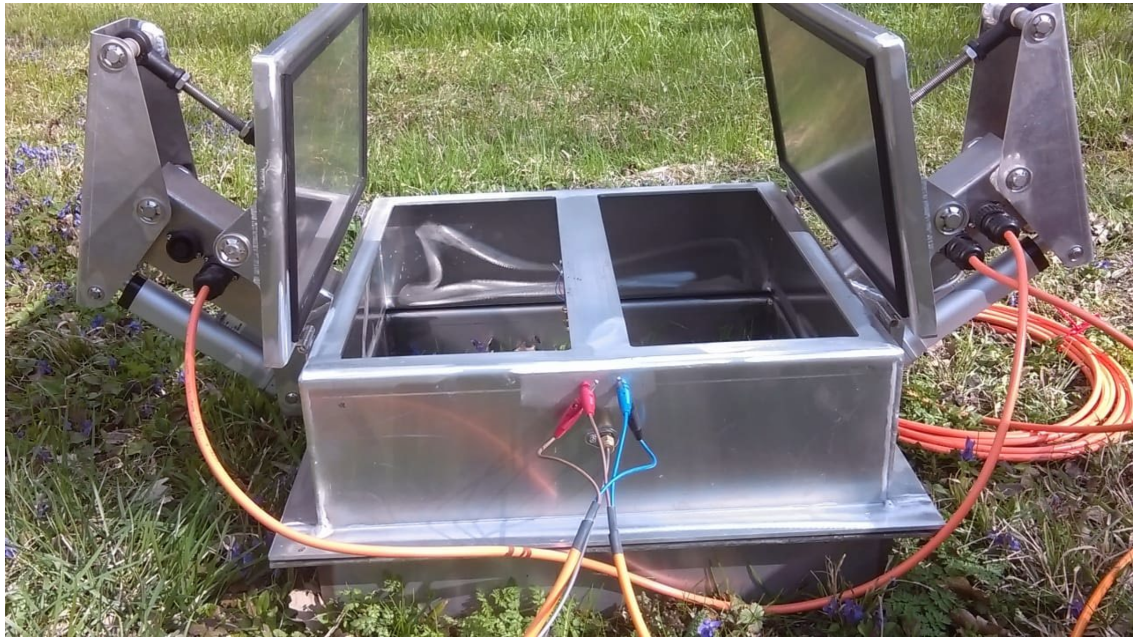


$$F_c = \frac{W}{A}\left(C_{co} - C_{ci}\right)$$

Butterbach Bahl et al, Springer, 2016

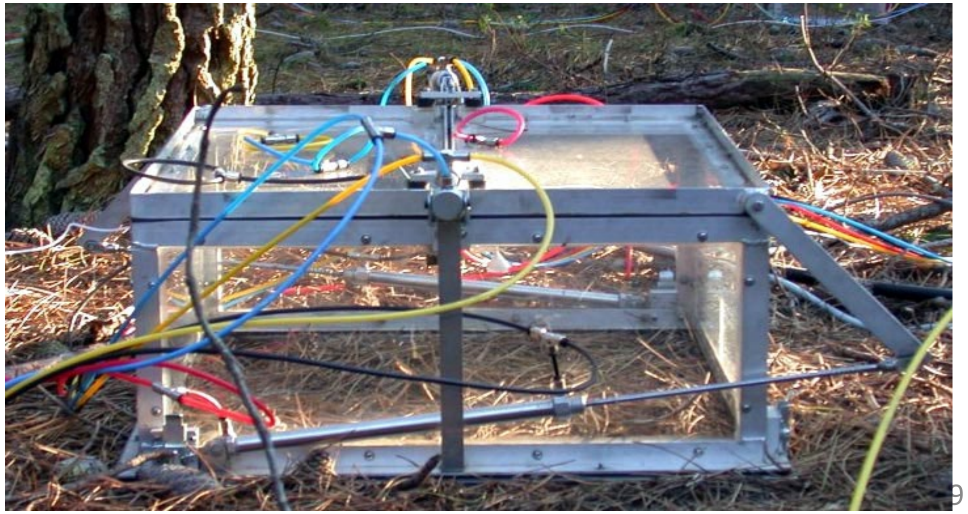
Dark chambers:

- No photosynthesis, only **respiratory fluxes** active



Transparent chambers:

- Both respiration and photosynthesis active: **Net ecosystem exchange**

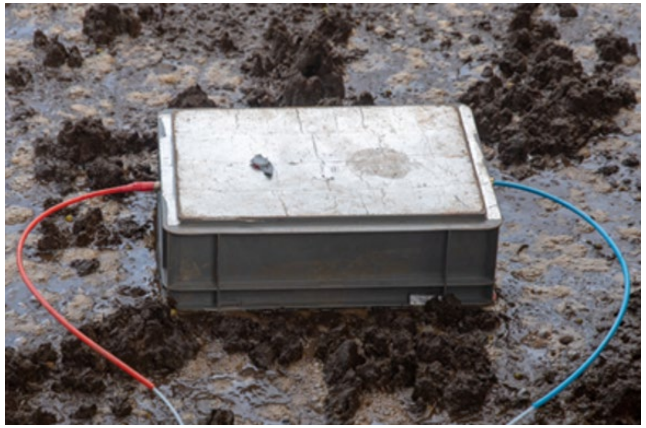


Manual chamber with litter exclosure. Rosalia, Austria

Manual chamber. Kilimanjaro, Tanzania

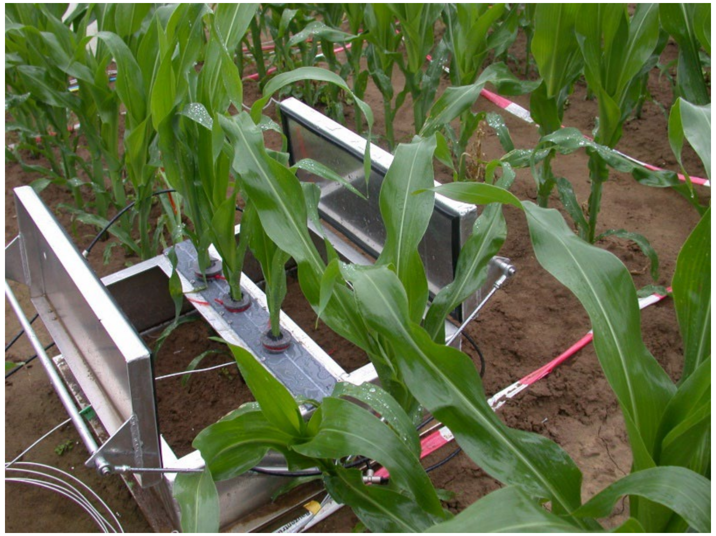
Manual chamber. Santa Barbara, California

Manual chambers, savannah, Kapiti, Kenya



Manual chambers in a boma (livestock enclosure), Kapiti, Kenya

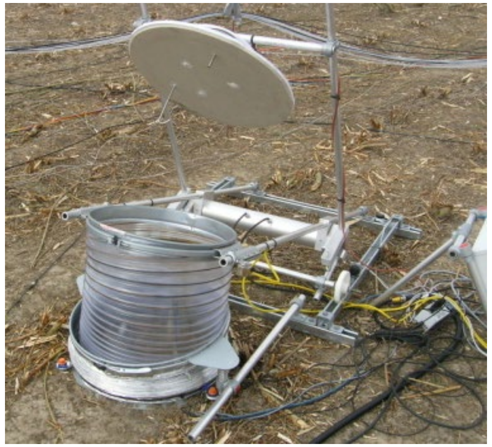
Lab incubation. Mazingira Centre, Nairobi, Kenya



Automated chamber enclosing plants.
Los Baños, Philippines

Automated chambers with extension enclosing plants.
Los Baños, Philippines

Robot system. Rottenbuch, Germany

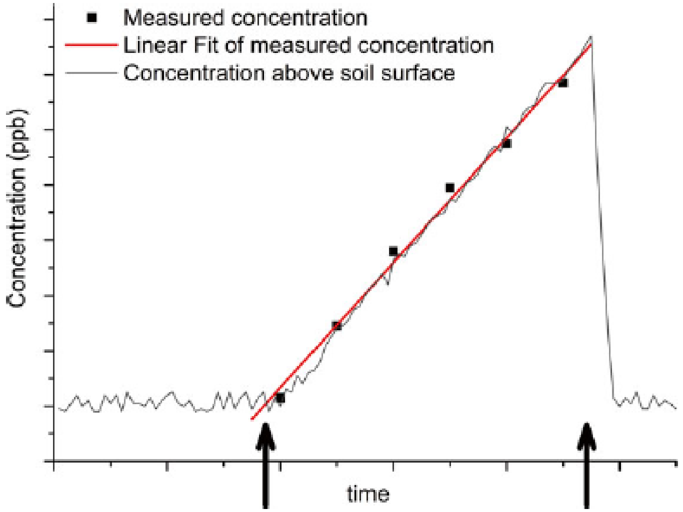


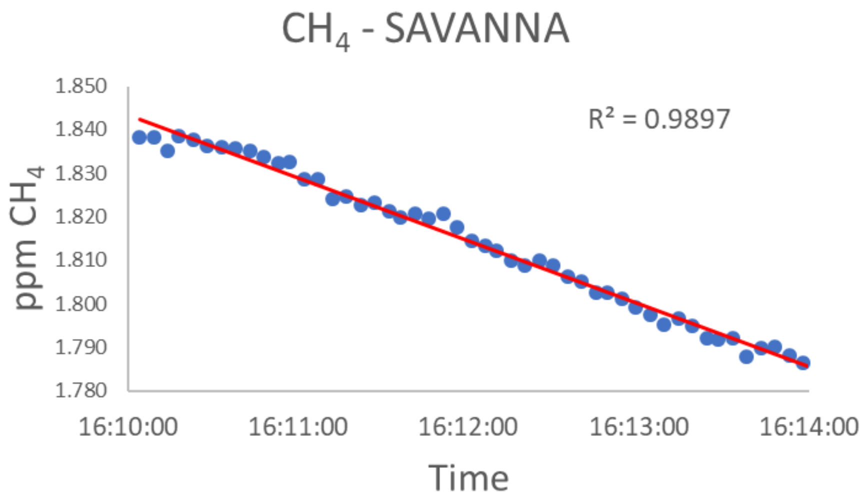
Automated chamber for NEE
and soil respiration. Roskilde, Denmark

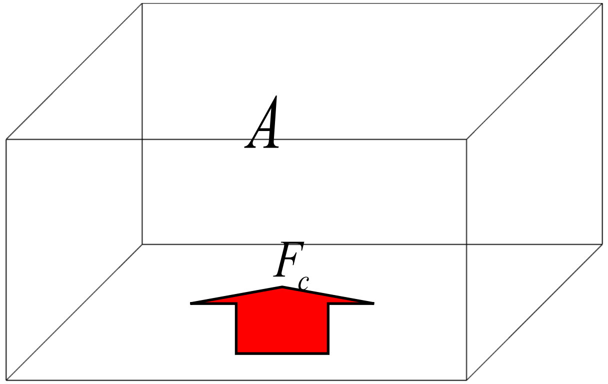
Automated chambers,
Mazingira Centre, ILRI, Nairobi,
Kenya

Application of dung and urine to
derive emission factors
representative for Kenyan cattle

Closed chamber







$$F_c = \frac{V}{A}\frac{\partial C_c}{\partial t}$$

Butterbach Bahl et al, Springer, 2016

Closed chamber = **non-steady state** measurement chamber

$$Gas\ flux\ (CO_2\ \&\ CH_4) = \frac{dConc}{dt} * \frac{P}{1013} * \frac{273}{T + 273} * \frac{12}{22.41} * \frac{V}{A} * 60$$

- Gas concentration change over time = SLOPE [ppm min^{-1}] → $\frac{dConc}{dt}$
- Field air pressure [mbar] → P
- Sea-level air pressure [mbar] → 1013
- Headspace temperature [°C] → T
- Molecular weight of C [g mol^{-1}] → 12
- Ideal gas volume [L mol^{-1}] → 22.41
- Chamber volume [m^3] → V
- Chamber area [m^2] → A
- Conversion to hour [min h^{-1}] → 60

Flux units:

CO_2: mg C m^{-2} h^{-1}

CH_4: mg C m^{-2} h^{-1}

Closed chamber = **non-steady state** measurement chamber

Gas concentration change over time = SLOPE [ppb min^{-1}]

Field air pressure [mbar]

Molecular weight of 2 N atoms [g mol^{-1}]

Chamber volume [m^3]

$$Gas\ flux\ (N_2O) = \frac{dConc}{dt} * \frac{P}{1013} * \frac{273}{T+273} * \frac{28}{22.41} * \frac{V}{A} * 60$$

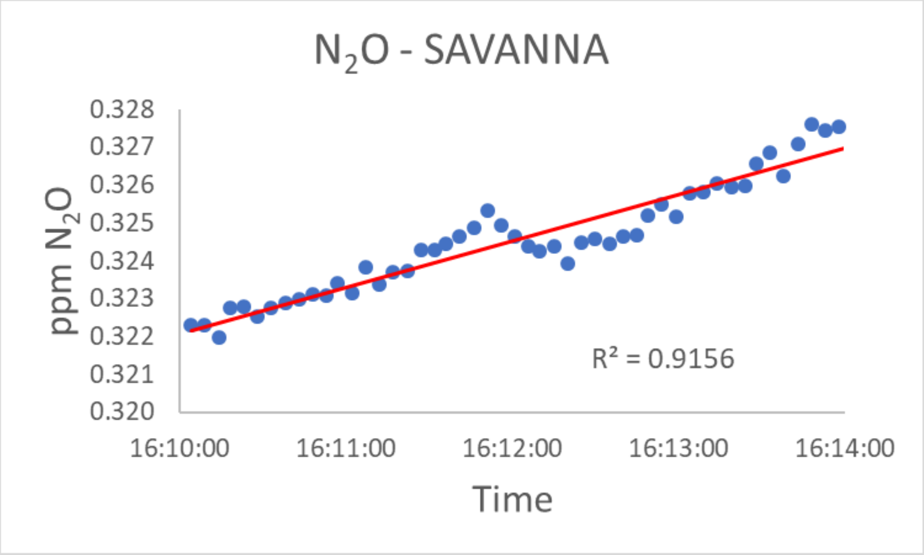
Conversion to hour [min h^{-1}]

Sea-level air pressure [mbar]

Headspace temperature [°C]

Ideal gas volume [L mol^{-1}]

Chamber area [m^2]



Flux units:

N_2O: µg N m^{-2} h^{-1}

For further reading:

Chapter 4: Quantifying GHG Emissions from Managed and Natural Soils
Butterbach-Bahl et al, 2016

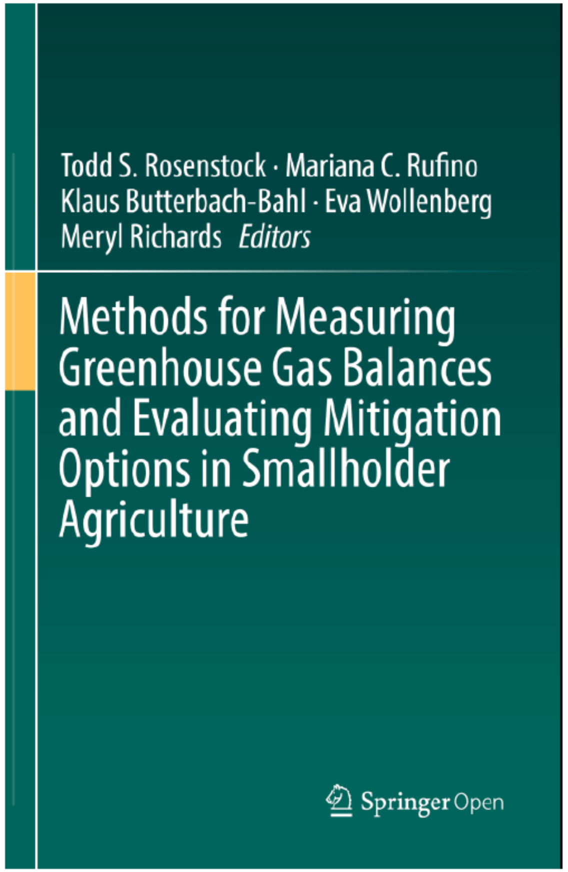


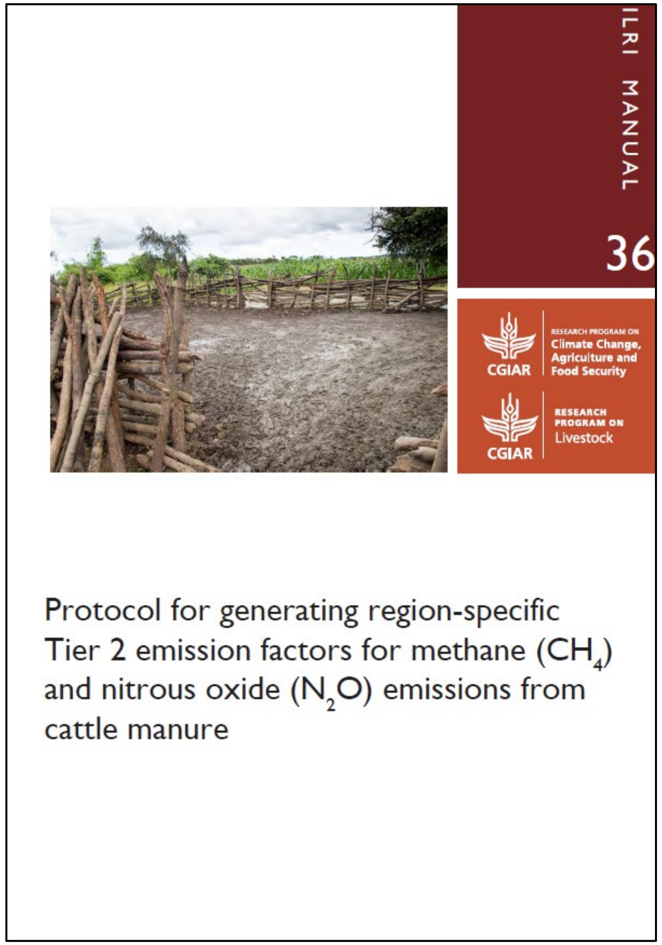
Table 4.2 Overview of recommended minimum requirements for closed chamber sampling in rice paddy and for measurements of field GHG fluxes from upland arable fields

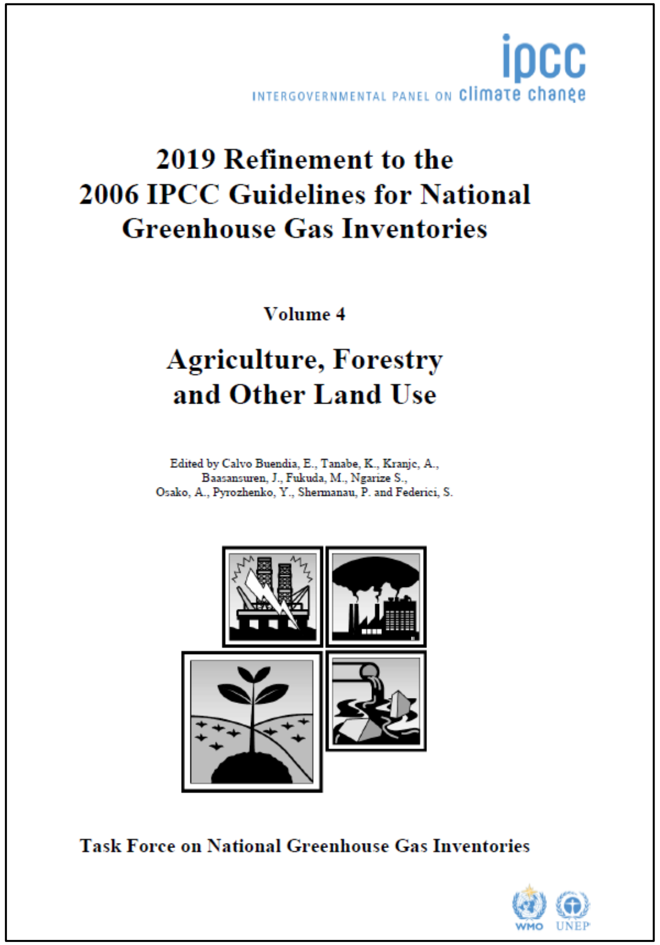
	Minimum requirement/recommendation	
Feature	Rice paddy	Arable field
Chamber dimension	4 rice hills included, $\geq 0.16\ m^2$, >1 m height *or* extendable, chamber base ~20 cm high	Height 10–40 cm (flexible height if possible), insertion depth 5–20 cm, minimum area $0.04\ m^2$. Include plants as long as possible, consider row/ inter-row effects
Chamber material	Reflective *or* white *and*/*or* insulated	Opaque, insulated (use transparent material only if NEE should be measured)
Chamber equipment	Thermometer, fan, sampling port, hole for irrigation water, vent	Thermometer, fan, vent
Frequency	Once per week *or* elaborated flexible schedule	Once per week, following the first 10 days after fertilization or re-wetting of dried soils if possible daily measurements
Length of measuring period	1 year	1 year
Spatial replicates	At least 3, possibly use gas pooling technique	At least 3, possibly use gas pooling technique
Time of day	At the time of approx. average daily soil temperature (often mid-morning). Record diurnal flux variation from time to time	Record diurnal flux variation
Closure time	As short as possible, as long as necessary. In hot environments 20–30 min, not more than 45 min	As short as possible, as long as necessary. In hot environments 20–30 min, not more than 45 min
Number of gas samples for flux calculation	≥ 4 per deployment	≥ 4 per deployment

Indirect estimation of manure GHG emissions – IPCC approach

- Manure CH_4 and N_2O emissions can be calculated following IPCC methodology
- Manure CO_2 is considered "carbon neutral" and not included in national GHG budgets
- Most important parameters needed to calculate manure GHG emissions:
  - **Nitrogen excretion rates** (Nex) → function of feed intake and feed N content
  - Manure **volatile solids excretion rates** (VS) → function of feed intake and digestibility
  - Manure **management systems** (e.g., solid storage, slurry, composting, …)
  - **Emission factors** for N_2O and CH_4 from manure management

Indirect estimation of manure GHG emissions – IPCC approach





Volume 4 (Agriculture)
Ch. 10: Livestock manure management
Ch. 11: Soils and manure on pasture

https://hdl.handle.net/10568/108788 https://www.ipcc-nggip.iges.or.jp/public/2019rf/vol4.html

Outline

1) Background (why are soils important?)
2) Processes (biotic & abiotic) & controls
3) Measurements & flux calculation (chambers, detection systems, …)
4) **Practice (lab demonstration)**

THANK YOU!

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