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Monitoring soil quality

Prof. M. Cristina Moscatelli

Soil biochemist

Dept. for the Innovation in Biological, Agro-food and Forest Systems, DIBAF
University of Tuscia – Viterbo - Italy

The Environmental Science Education for Sustainable Human Health

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Structure of the presentation

1. Synthetic facts about soils
2. Concepts of soil quality and health
3. Need for monitoring soil quality
4. Soil indicators: main categories
5. Soil organic matter: a *key* indicator!
6. The bioindicators
7. How to proceed …
8. Final remarks
9. Main references

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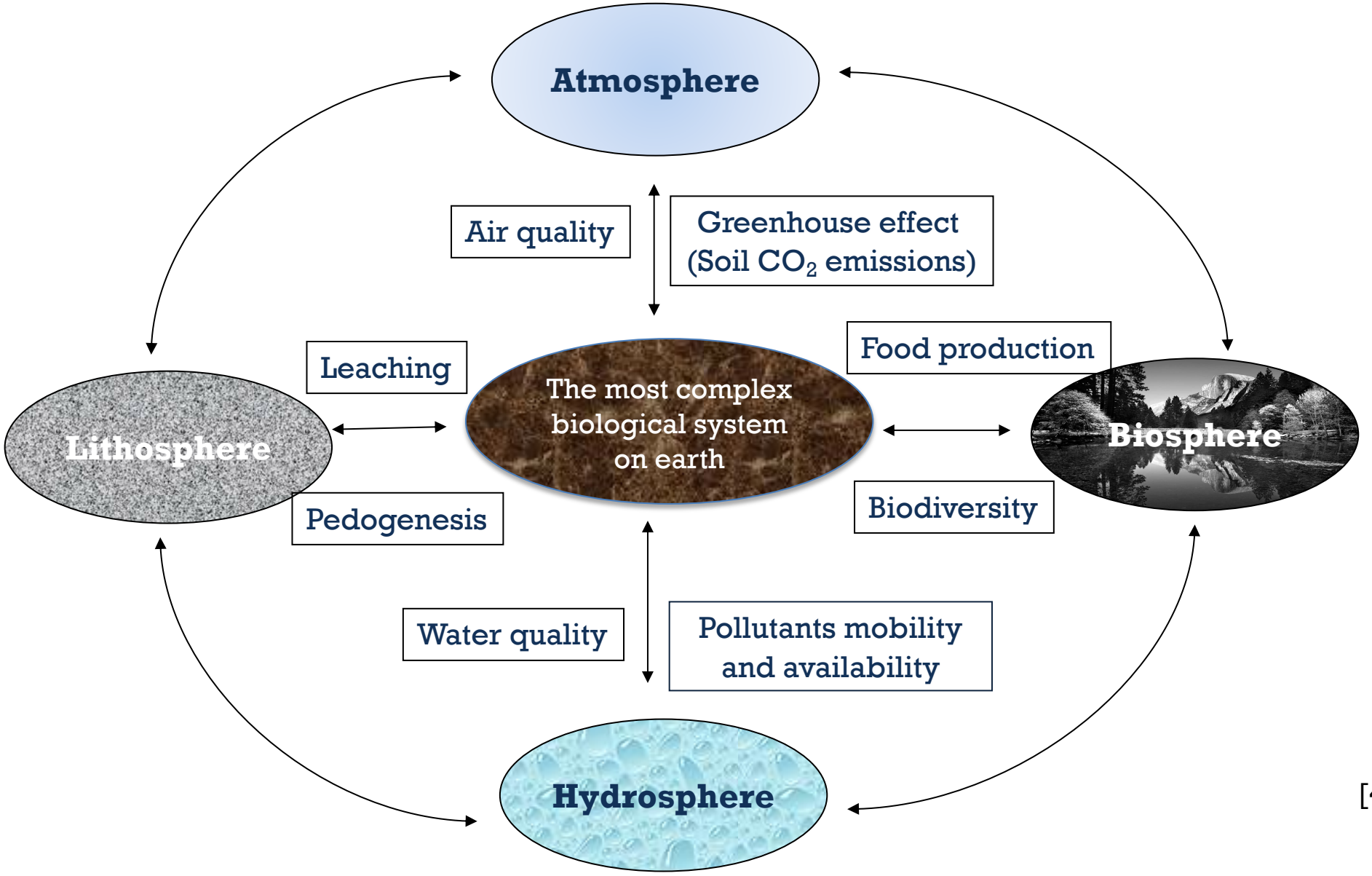
Soil: a central position in the ecosystem



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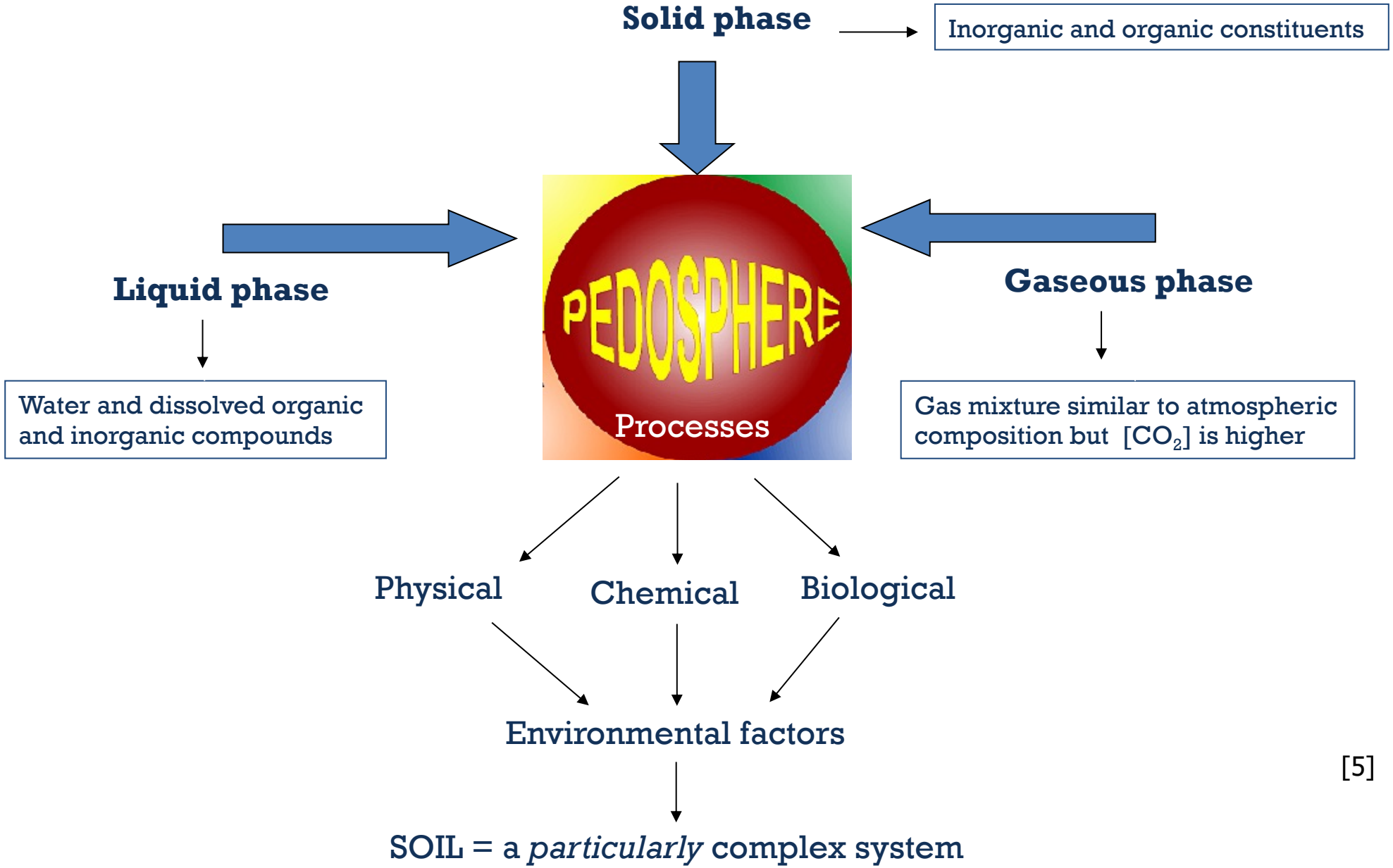
1. Synthetic facts about soils

Soil: a multicomponent, heterogeneous, complex system



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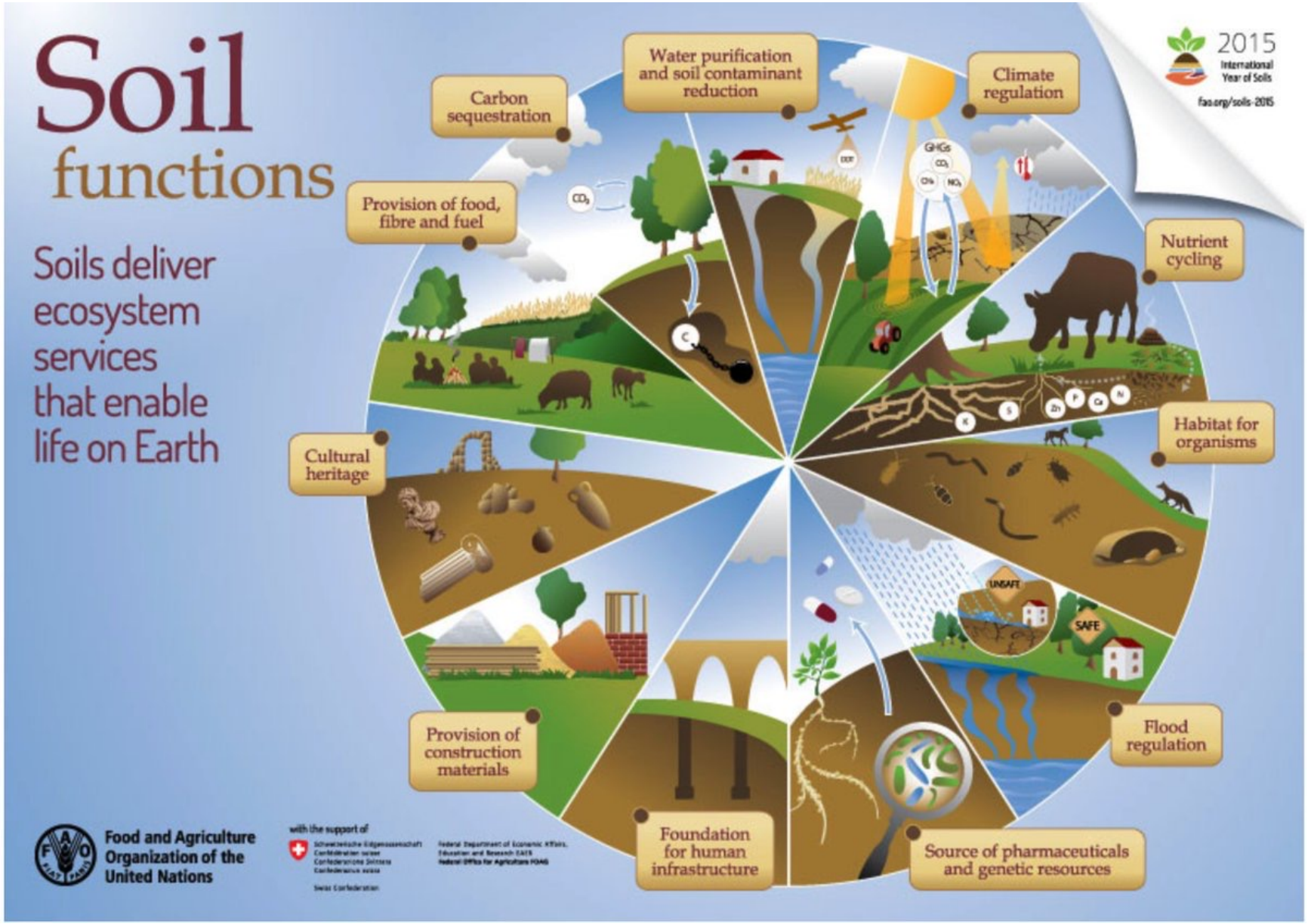
Soil functions



[6]

Source: FAO

1. Synthetic facts about soils

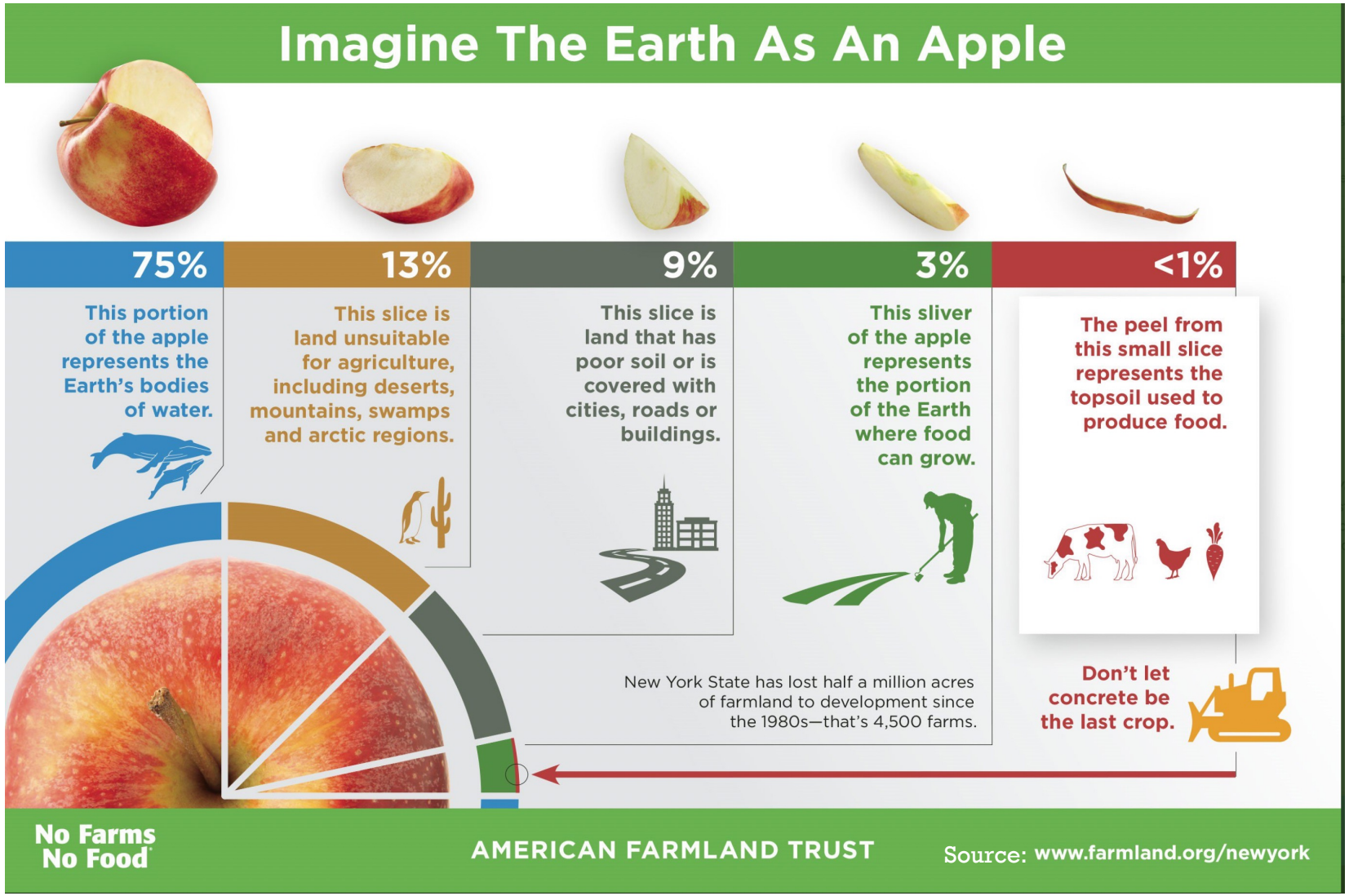
Ecosystem services

Ecosystem services defined as "the benefits which humans derive from ecosystems"
(Costanza et al, 1997)

[7]

Source: Millennium Ecosystem Assessment. 2005. Ecosystems and Human Well-Being: Synthesis. Washington, DC, Island Press.

How much fertile soil is available on earth?



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1. Synthetic facts about soils

Soil is non-renewable on a human time scale

Soil *gains*

5 soil forming factors

1 cm = 100-1000 years

Pedogenesis is a slow process

Soil *losses*

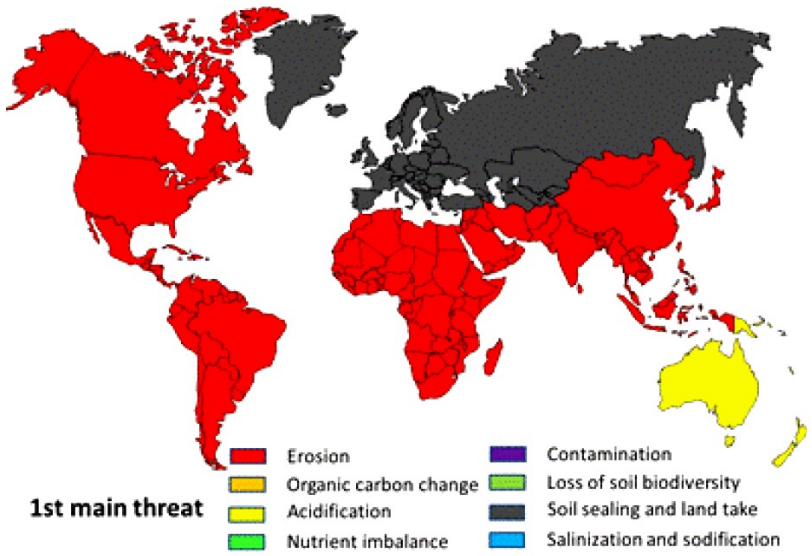
10 - 40 times faster than formation rate

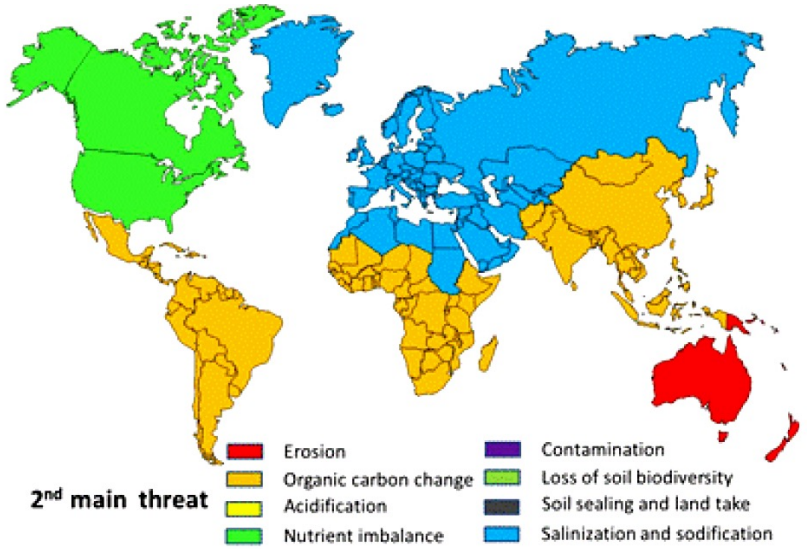
[9]

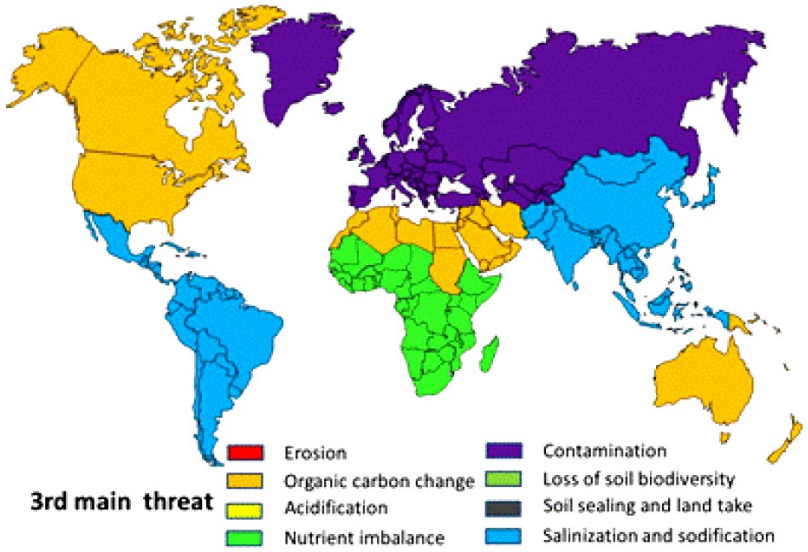
Erosion is a fast process

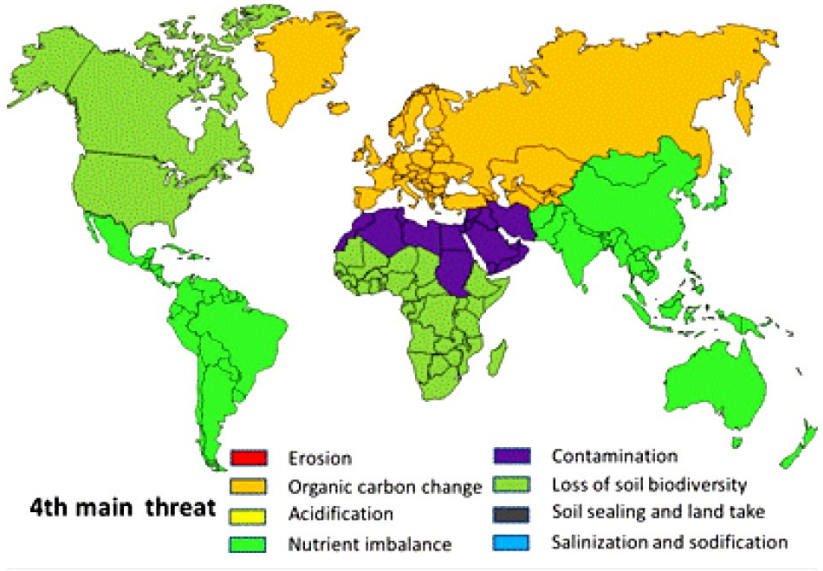
Soils are vulnerable and threatened

Global assessment of the four main threats to world soils









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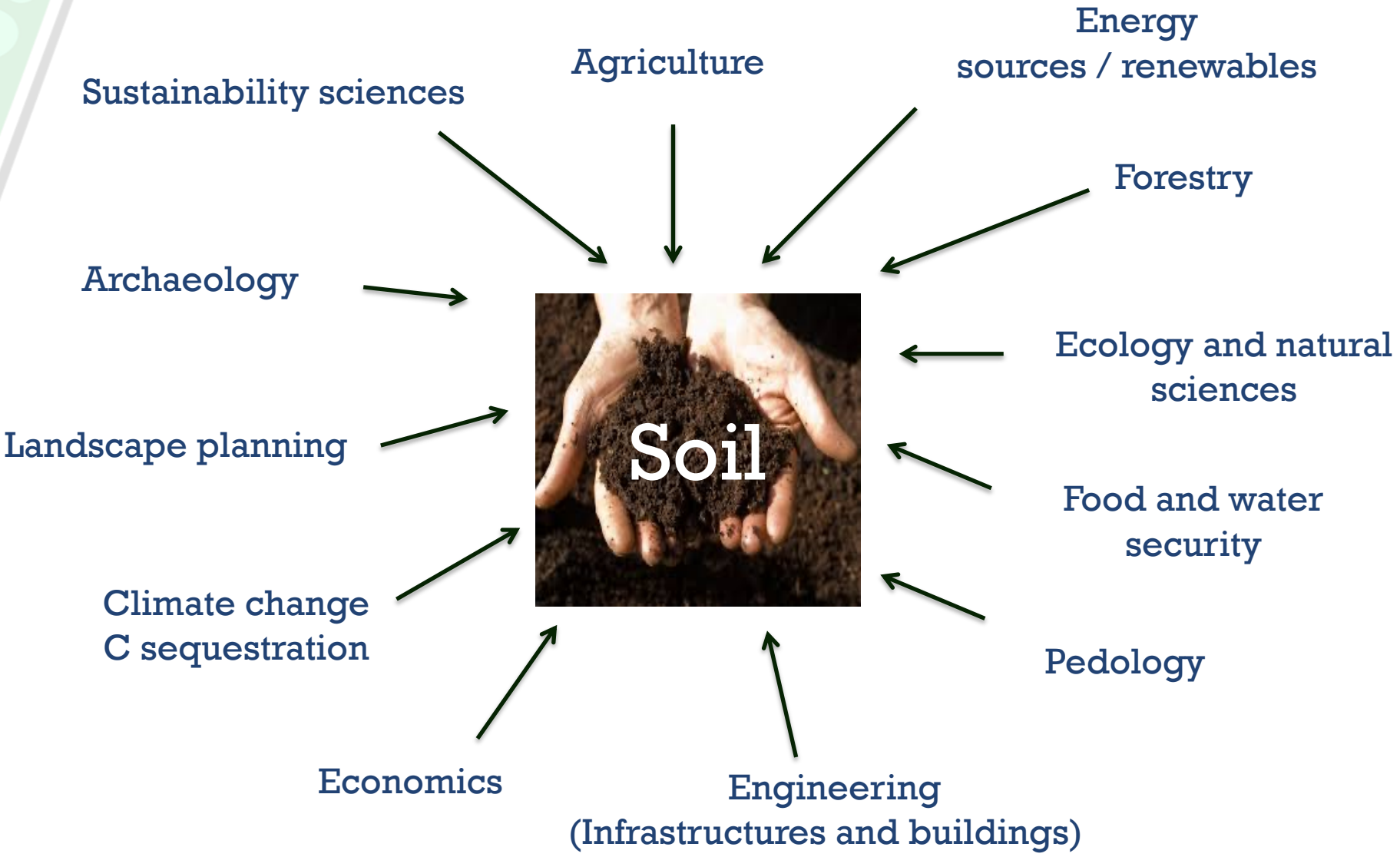
Source: Montanarella et al., Soil Discuss., 2015; FAO, 2015

Variety of perspectives and disciplines dealing with soil → different definitions



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Soil quality and soil health: definitions

"Soil **quality** is the capacity of a specific kind of soil to function within natural or managed ecosystem boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality and support human health and habitation"

(Official definition: Soil Science Society of America Ad Hoc Committee on Soil Quality (S-581), Karlen et al., 1997)

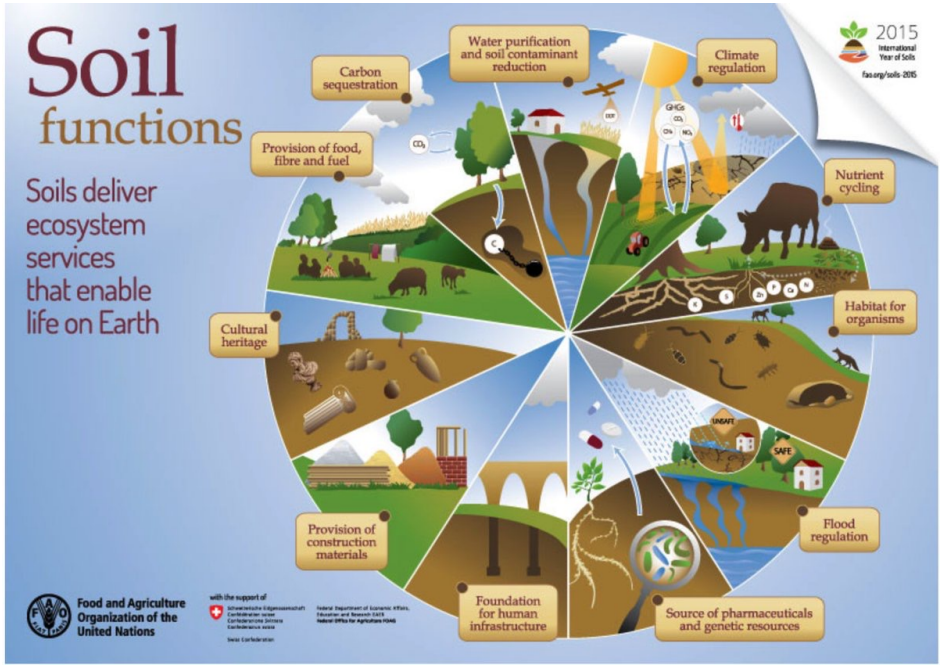
"Soil **health** is the continued capacity of soil to function as a vital living system within ecosystem and land-use boundaries, to sustain biological productivity, promote the quality of air and water environments, and maintain plant, animal and human health"

(Doran et al., 1996)

Frequently used as synonims in the scientific literature

Soil quality

The quality of a soil, as distinct from health, is largely defined by the ability of soil to perform various functions



Anthropocentric definition: mainly linked to the functions (when an intended use of the soil is specified) and to the considered ecosystem [14]

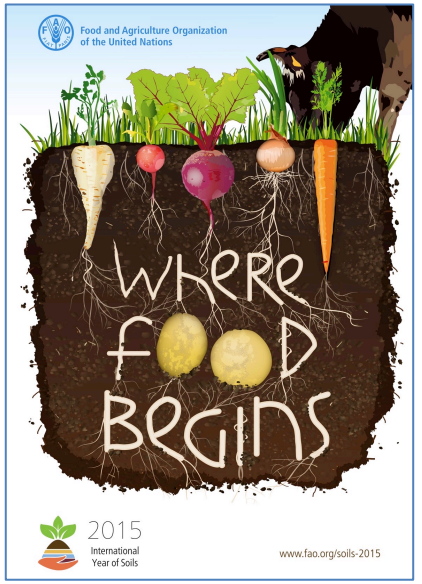
Perception of the term “quality”

Air quality →

Water quality →

It can directly impact human and animal health and natural ecosystems

Soil quality ?



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The nexus between soil health and human health is still not clearly perceived

(Pepper, The Soil Health-Human Health Nexus, 2013)

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To evaluate soil quality we need specific, sensitive and reliable tools.

We can use physical, chemical and biological

INDICATORS

[17]

3. Need for monitoring soil quality

Requisites for soil indicators

Source: Pulleman et al., Current Opinion Env Sustain, 2012

1. Meaningful – Indicators must relate to important ecological functions
2. Standardized – Parameters should be standardized to ensure comparability of data
3. Measurable and cost efficient – Parameters should be assessable not only by experts, in order to ensure that the indicators will be used in practice and can be routinely collected
4. Policy relevance – Indicators should be sensitive to changes at policy-relevant spatio-temporal scales, and allow for comparisons with a baseline situation to capture progress towards policy targets
5. Spatio-temporal coverage – Indicators should be validated in a wide range of conditions and should be amenable to aggregation or disaggregation at different spatial scales, from ecosystem to national and international levels
6. Understandability – Indicators should be simple and easily understood
7. Accuracy – The value of the indicators should be precise and robust reflecting the changes they monitor

8. Be sensitive to variations in management and climate (sensitive enough to reflect the influence of management and climate on long term changes in soil quality but not be so sensitive as to be influenced by short term weather patterns);
9. Be components of existing soil data bases where/when possible.

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3. Need for monitoring soil quality

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The Minimum Data Set

Indicator	Rationale for its use
Physical	
• Texture	Retention /transport of water and chemicals
• Depth of soil and rooting	Estimates of productivity potential and erosion
• Infiltration, bulk density	Potential for leaching, productivity and erosion
• Water holding capacity	Water retention, transport etc.
Chemical	
• SOM, SOC etc.	C storage, potential fertility, stability
• pH	Biological and chemical activity thresholds
• Electrical conductivity	Defines plant and microbial activity thresholds
• Extractable N, P, K	Plant available nutrients / potential for N loss
Biological	
• Microbial C and N	Microbial catalytic potential and repository for C and N. Early warning of management effects
• Potentially mineralizable N	Soil productivity and N supply potential
• Soil respiration	Microbial activity
• Microbial numbers and characterization	Isolation of specific groups/strains of physiological interest

Soil fertility - productivity

Soil biological fertility – soil health

Source: Doran e Parkin, 1994 - ASSS Defining and assessing soil quality

Main categories of soil indicators

We can choose

Static descriptors

- Soil organic matter (or SOC)
- Total N
- C/N ratio

Changes in the long period

Dynamic descriptors

- Microbial biomass
- Mineralization activity of organic C (respiration)
- Microbial quotients
- Inorganic N

Changes in the short period

We can choose

Pools

Soil organic matter, microbial biomass, different forms of C, total N or inorganic N

Processes

CO_2 fluxes, N mineralization, enzymatic activities

Soil indicators

ORGANIC MATTER

Definition

All soil organic components, living and not living (humus), excluding macroflora, macro- and mesofauna
Organic C accounts for 58% of SOM

Functions

Reserve of nutrients
Storage of organic carbon
Soil structure improvement
Water retention
Bioavailability of xenobiotics

Why?

The physical, chemical and biological properties of OM influence **all** soil functions

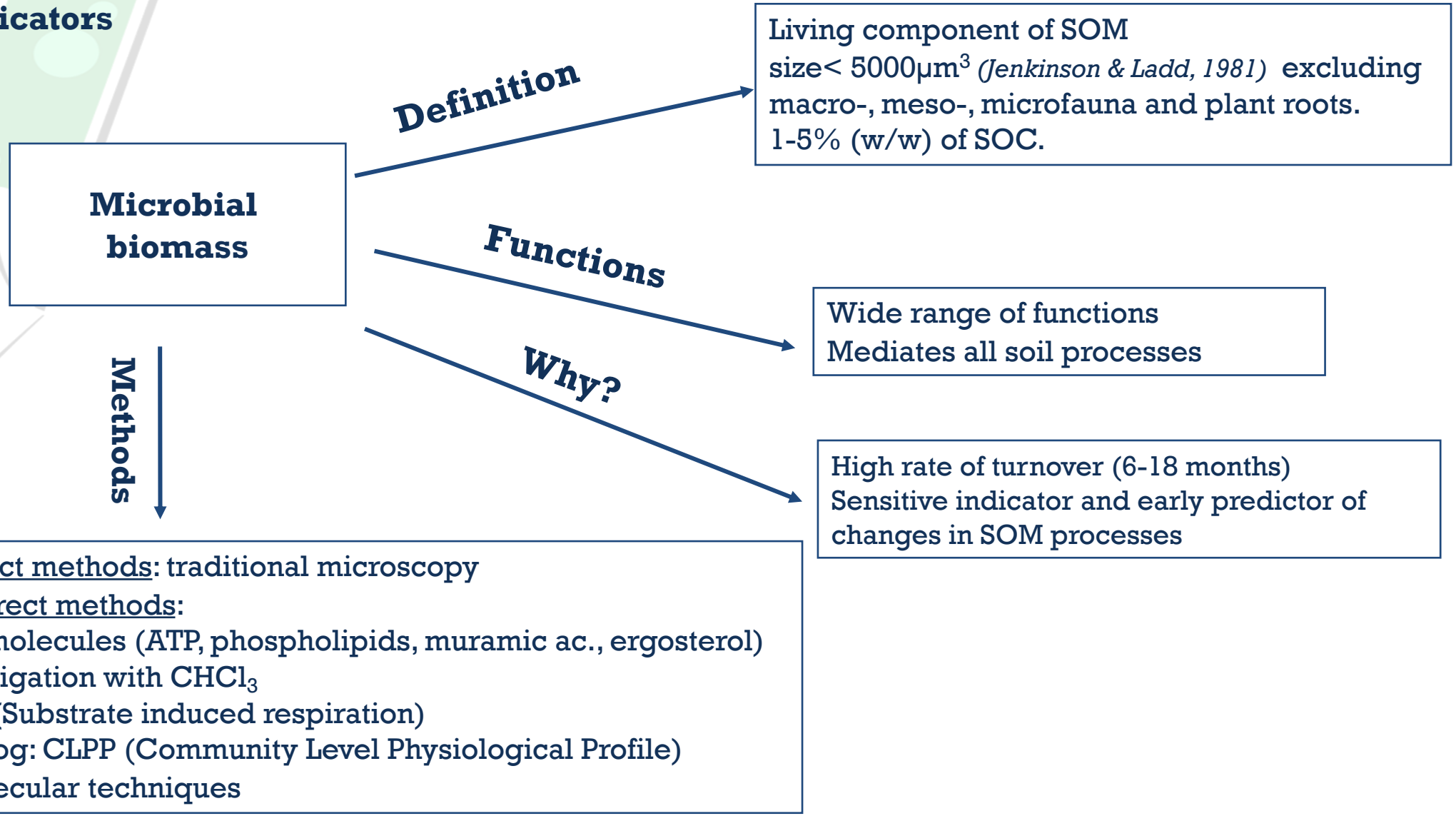
Methods

In situ/laboratory analytical approaches:
NIR/MIR: near/mid infrared spectroscopy

Chemolytic
Spectroscopic
Fractionation
Determination of Total Organic Carbon (TOC) dimension vs. quality

Acronyms to keep in mind!
***SOM**: soil organic matter*
***SOC**: soil organic C*
***DOM/DOC**: dissolved organic matter/C*
***TOC**: total organic C*

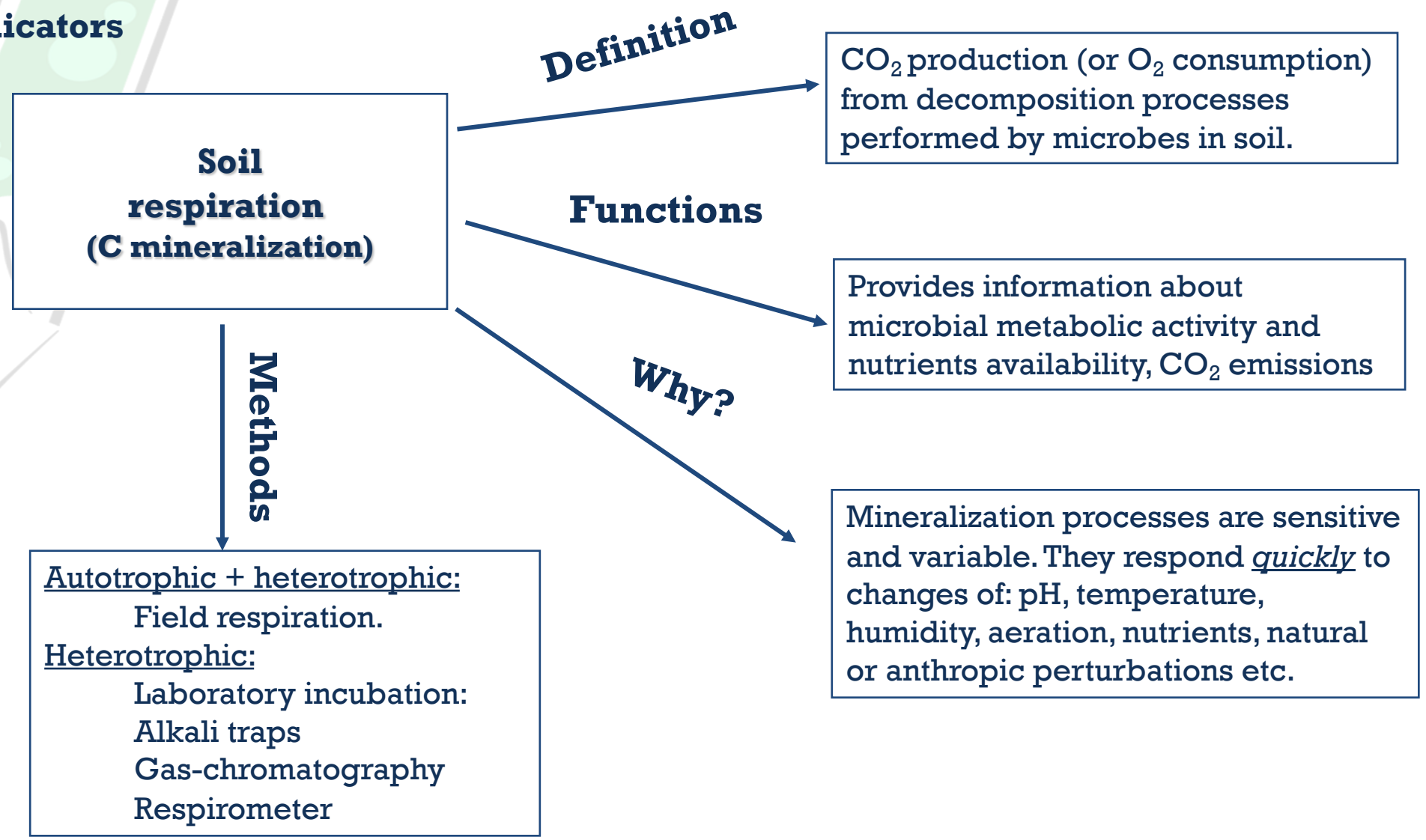
Soil *bio*indicators



[23]

4. Soil indicators: main categories

Soil *bio*indicators



[24]

4. Soil indicators: main categories

Soil *bio*indicators

Soil enzymes

Definition → Proteins of microbial origin: intracellular and extracellular (biontic or abiontic). Mediators and catalysts of important soil processes

Functions → SOM decomposition and transformation, release of nutrients, N_2 fixation, nitrification, denitrification, detoxification, humification

Why? → Assessment of enzymes offers potential as an integrative index of soil biological status or the ability of soil to carry out enzyme-catalysed processes

Methods

1. Colorimetric assays (UV-VIS spectrophotometer)
2. Fluorimetry (fluorometer)

→ Through the assessment of different enzyme activities it is possible to evaluate microbial functional diversity: a valuable bioindicator of soil quality and health

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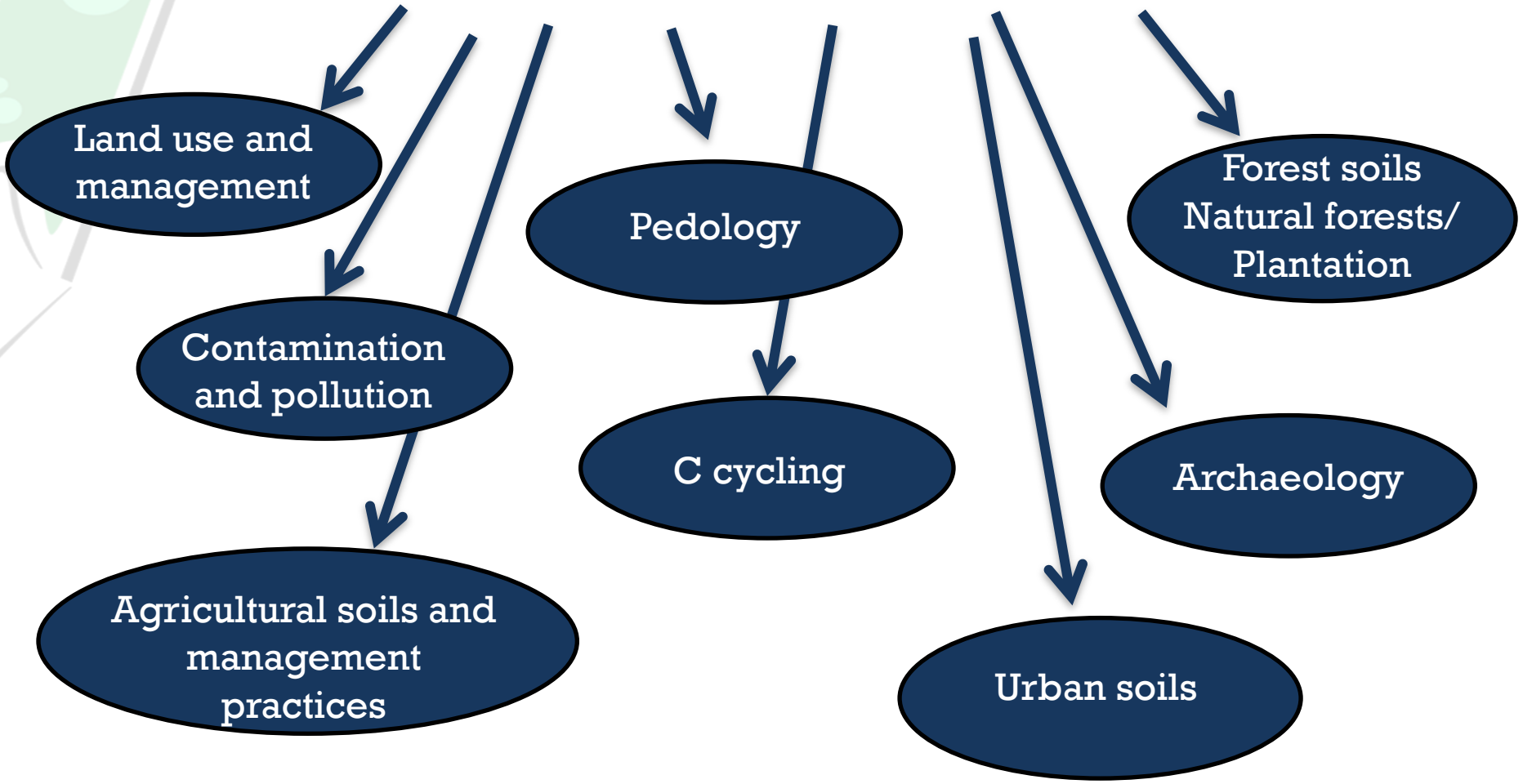
4. Soil indicators: main categories

Soil Quality Indexes (SQIs)

- There is not a unique Soil Quality Index
- Many different indexes have been suggested for a comprehensive evaluation of soil quality
- The Minimum Data Set of indicators chosen may vary in relation to:
  - Geographic location
  - Soil type
  - Land use
  - Type of pressure (e.g. salinization, erosion, pollution etc.)

[26]

Potential applications of soil indicators



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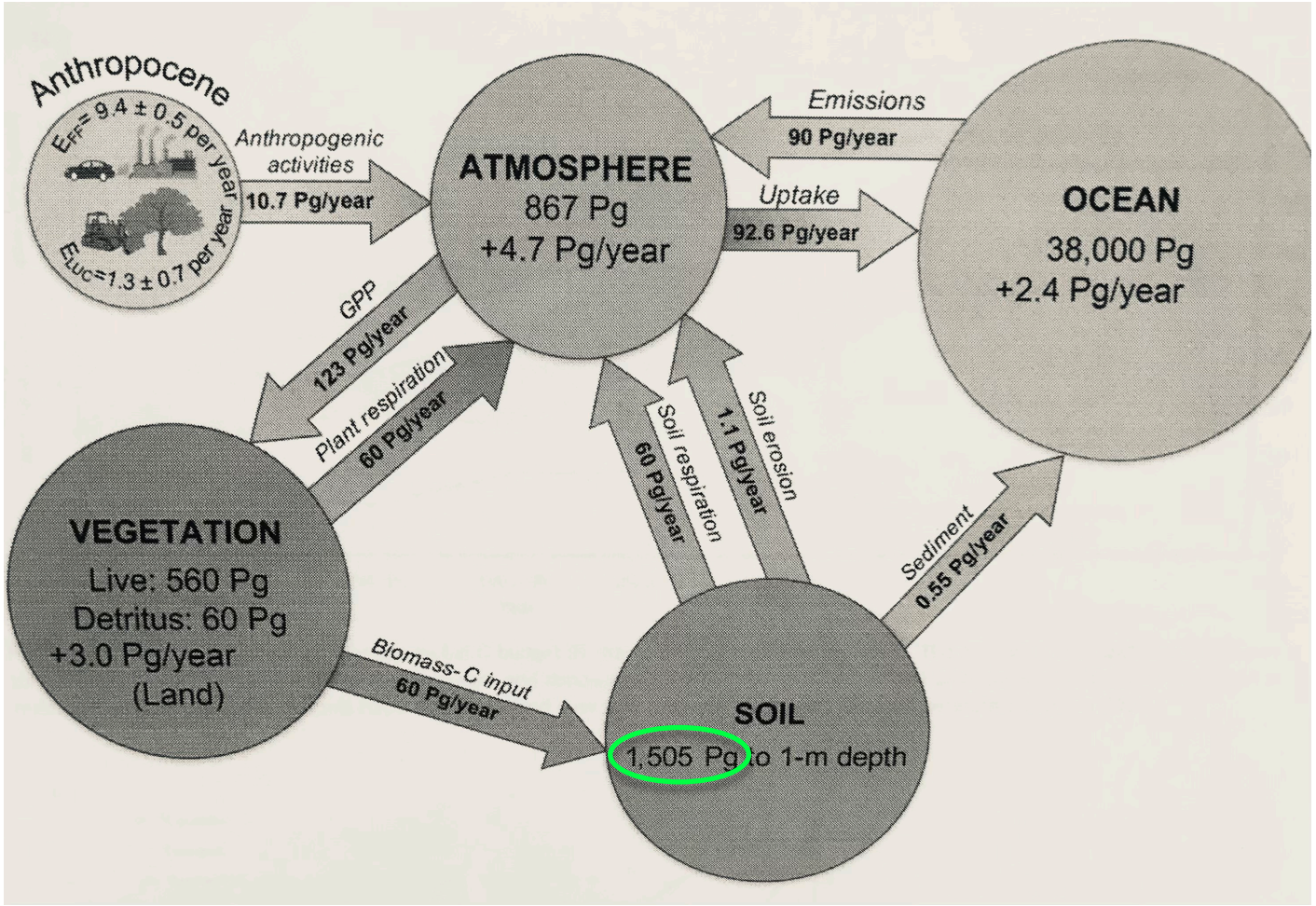
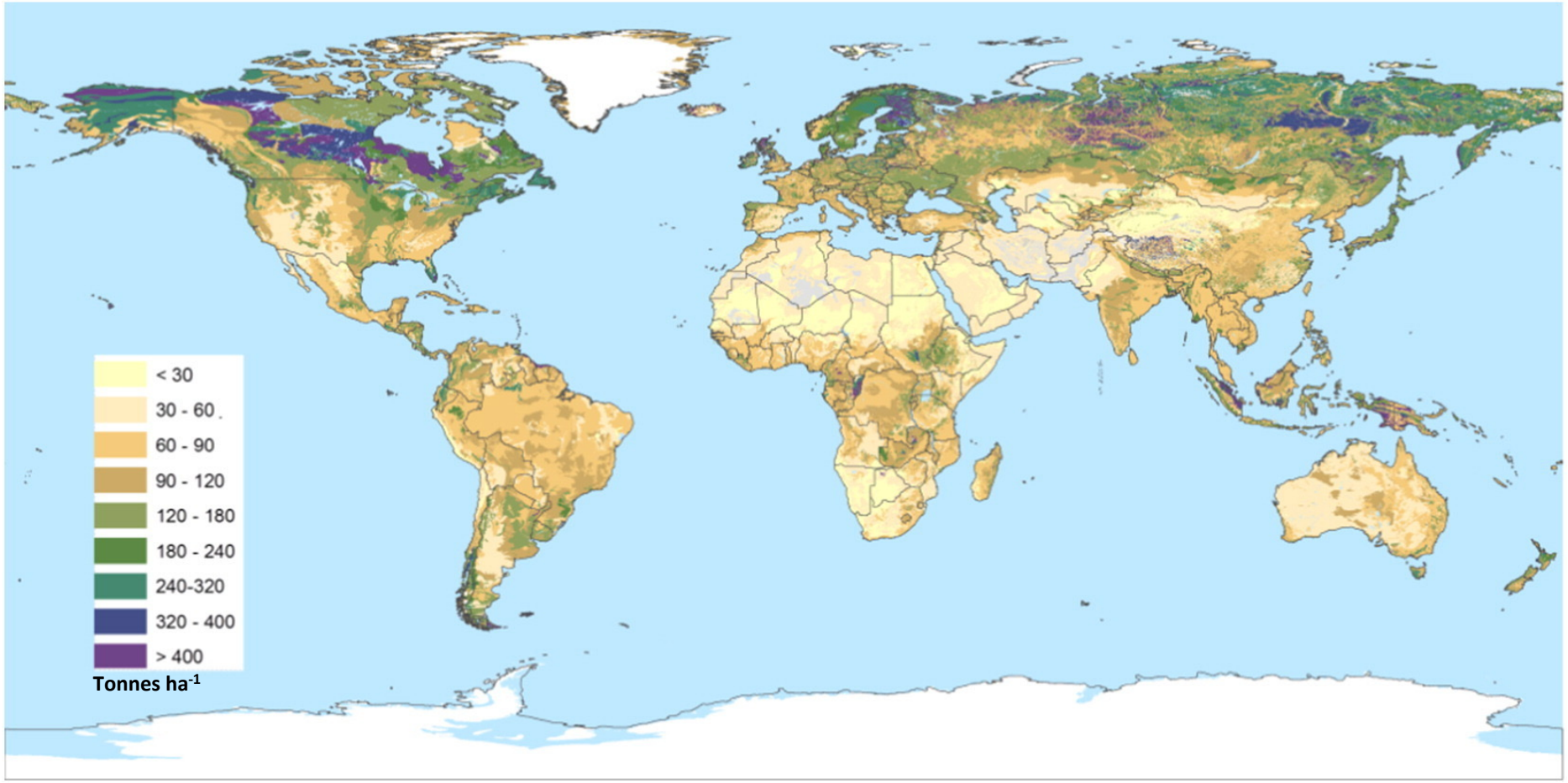
The global C cycle



Source: Lal, 2018

- ✓ 10,7 Pg of C are emitted globally each year from anthropogenic sources
- ✓ Soils are the largest terrestrial pool of C with 1,505 Pg stored in the 1st m
- ✓ Soils C stock are the result of the balance between input and output

SOC distribution in the world



FAO 2017. Soil Organic Carbon: the hidden potential

4. Soil organic matter: a *key* indicator

Properties of soil organic matter and soil functions

SOM property	*Soil functions*
Dark colour mainly due to the presence of humic substances	It favours soil heating after winter favouring seed germination
Water retention (up to 20 times of humic matter weight)	It prevents soil drying, reduces structure impoverishment and increases water retention capacity
Poor solubility in water (particularly for humic acids)	It prevents C losses through leaching and percolation
Capacity to bind to mineral particles	It favours aggregates formation, structure maintenance, permeability and gas exchanges

Physical properties

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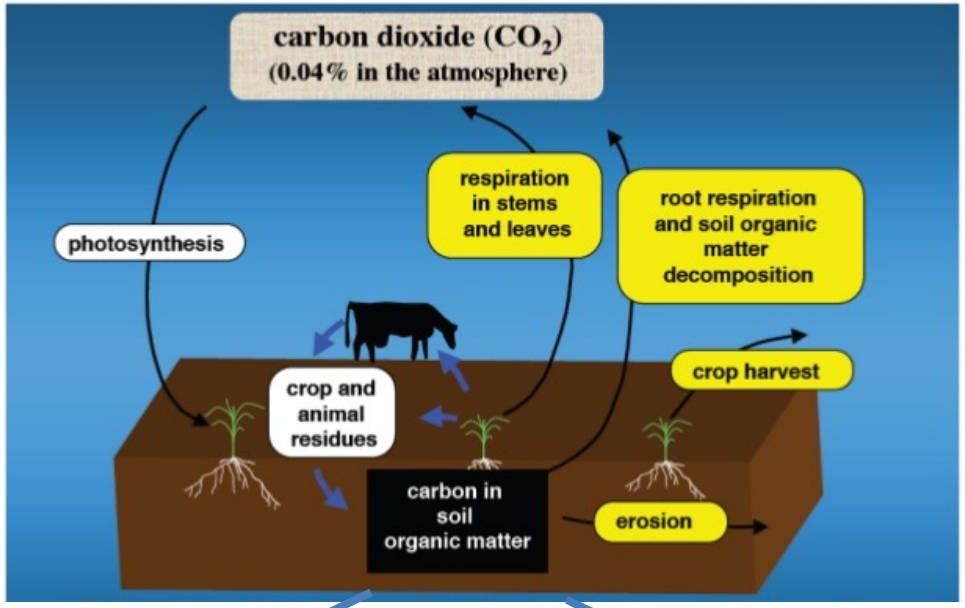
Properties of soil organic matter and soil functions

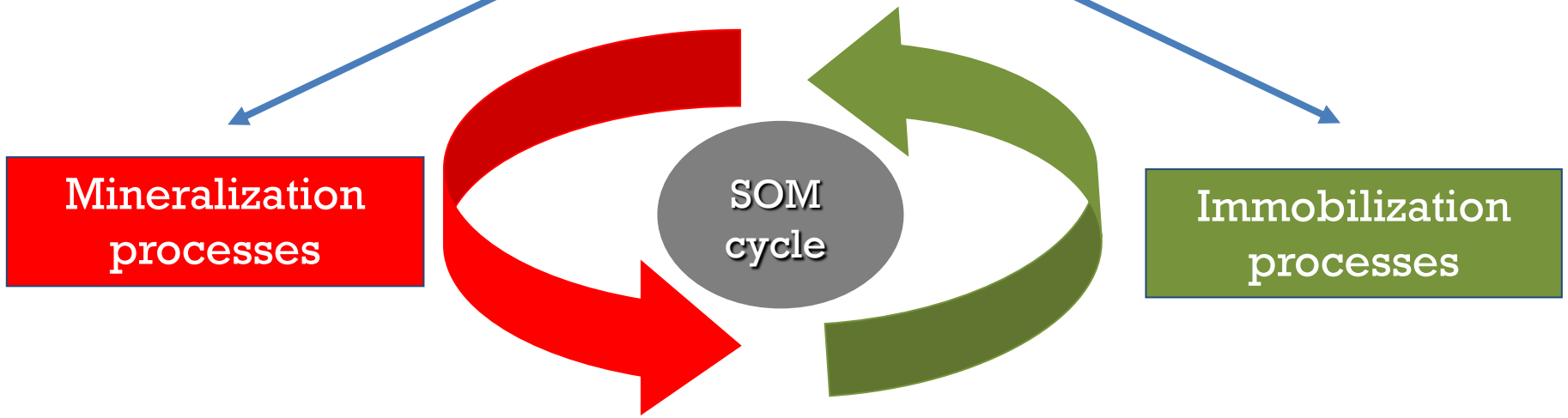
SOM property	*Soil functions*
Buffer capacity with respect to soil pH	It protects the delicate chemical and biochemical equilibrium existing in soil
High cation exchange capacity (CEC)	It largely contributes to soil CEC (up to 70%) favouring nutrients retention
Reserve of mineral nutrients	It releases NH_4^+, NO_3^-, SO_4^{2-}, phosphate etc.
Capacity to form stabilized complexes (*chelates*) with microelements	It influences the solubility and availability of microelements such as Cu^{2+}, Fe^{2+}, Zn^{2+}, Mn^{2+}
Capacity to interact with pesticides and extraneous compounds (*xenobiotics*)	It influences their bioavailability and persistence into the soil
Capacity to stabilize soil enzymes through the immobilization process	It favours enzymes protection from denaturation/hydrolysis allowing soil biological activity for longer periods

Chemical and biological properties

[32]

Soil organic matter cycle

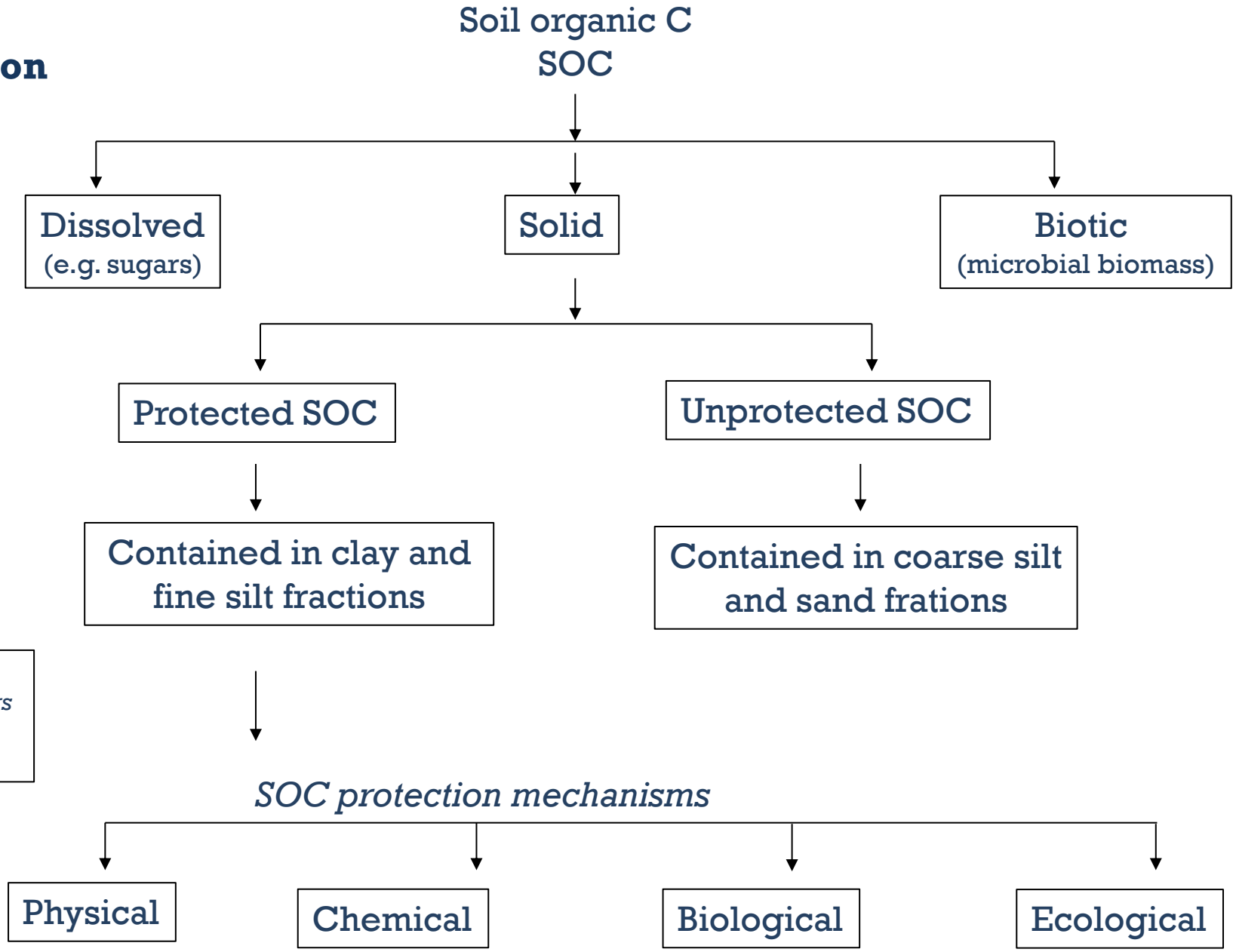




[33]

4. Soil organic matter: a *key* indicator

SOC fractions and stabilization



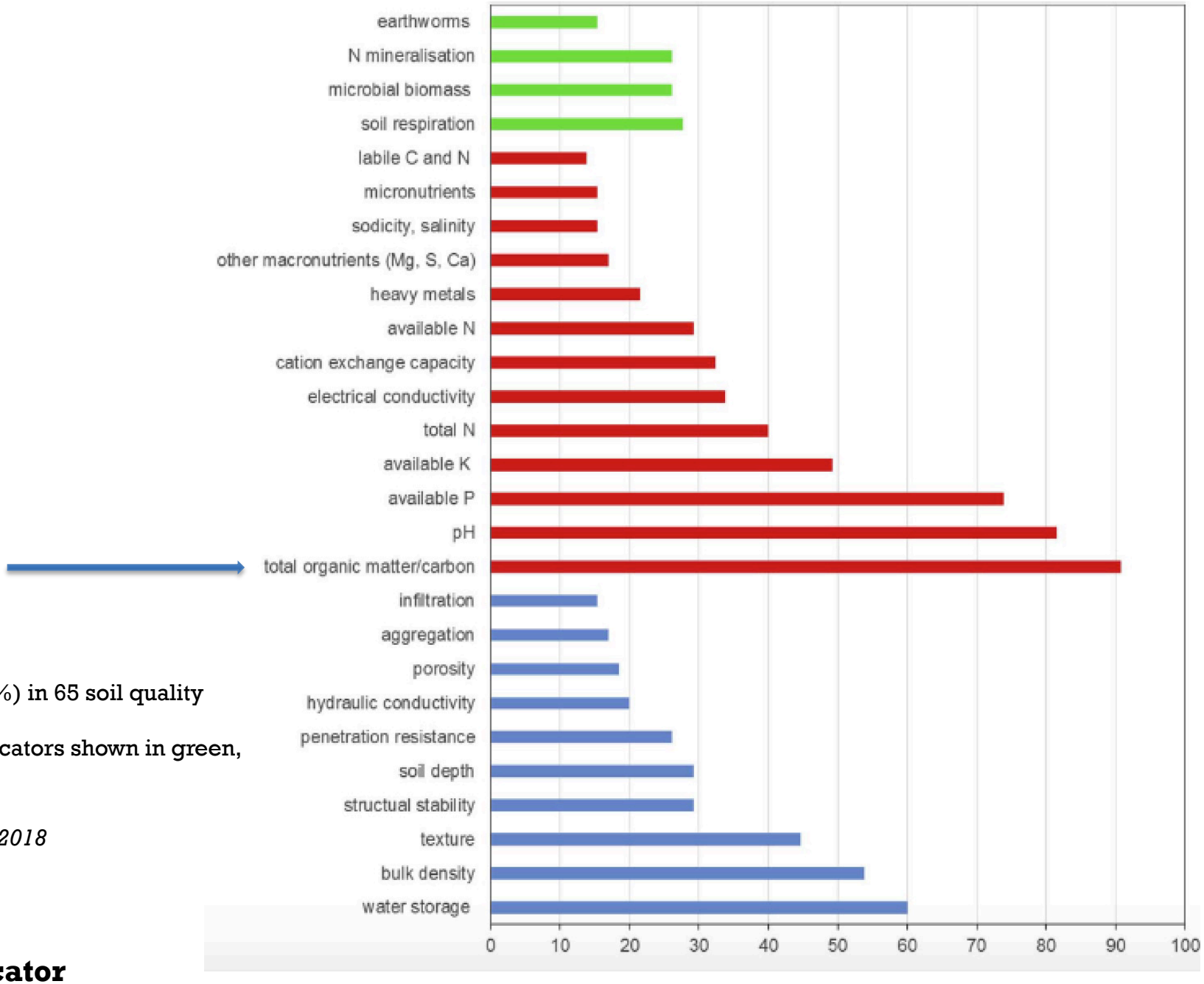
Fast pool *(labile or active) →1 or 2 yrs*
Intermediate pool *(partially stabilized) → 10-100 yrs*
Slow pool *(highly stabilized) → 100-1000 yrs*

[34]

redrawn from Lal, 2018; Schmidt et al, 2011)

Factors affecting decomposition of SOC

- Intrinsic chemical properties of SOC (e.g. C/N ratio), chemical complexity
- Soil properties (physical, chemical and biological)
- Latitude, climatic conditions (temperature, humidity), different biomes (boreal, temperate, tropical, wetlands, desert etc)
- Land use, management and land use change
- Mechanisms of physical and chemical protection



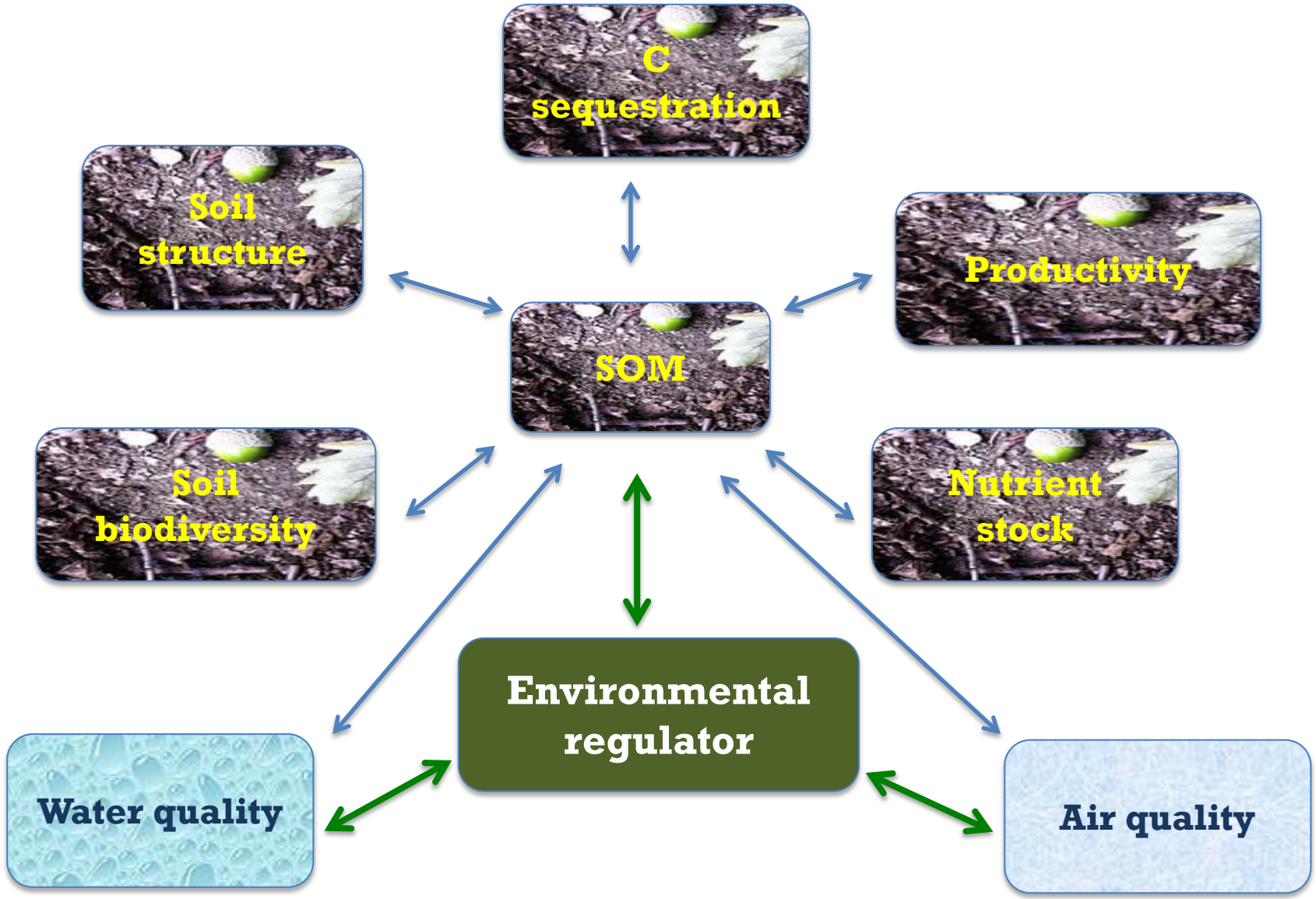
Frequency of different indicators (min. 10%) in 65 soil quality assessment approaches.
Soil biological, chemical and physical indicators shown in green, red and blue, respectively.

Source: Bünemann et al., Soil Biol Biochem, 2018

[36]

4. Soil organic matter: a *key* indicator

Soil organic matter as a complete and reliable indicator of soil quality



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4. Soil organic matter: a *key* indicator

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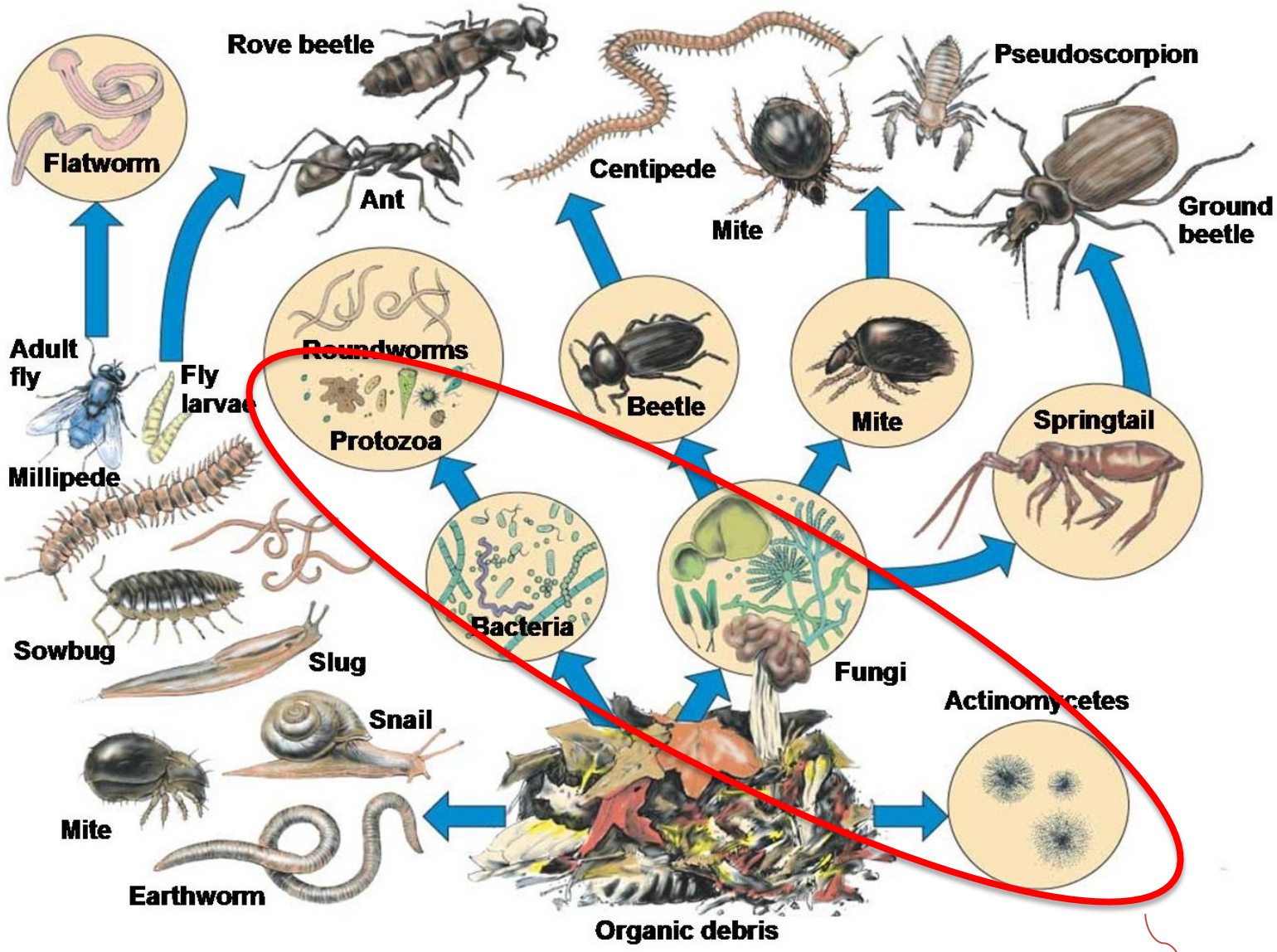
The *bio*indicators → life



[39]

Microbial biomass

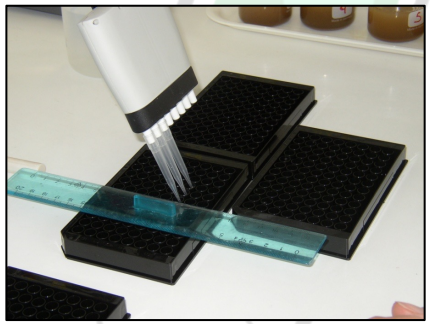
Processes performed by soil microrganisms

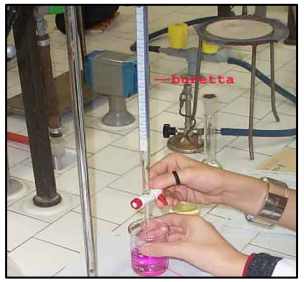
80-90% of the processes occurring into the soil is mediated by microrganisms

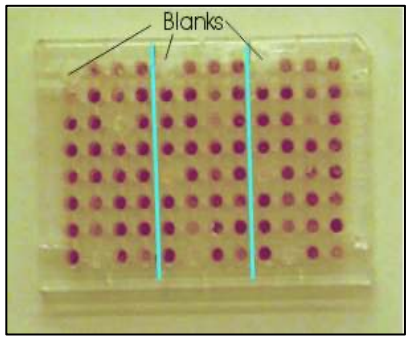
1. Humification
2. Hydrolysis or degradaton of organic polimers (lignin, starch)
3. Degradation of recalcitrant compounds included xenobiotics (pesticides, aromatic compounds, PAH polyciclic aromatic hydrocarbons etc.)
4. Catabolic reactions of organic compounds (glicolysis, oxidation of fatty acids etc.)
5. Synthesis of organic compounds (carbohydrates, fatty acids etc.)
6. N cycle reactions: mineralization (proteolysis, deamination), immobilization (synthesis of aminoacids and proteins), N-fixation, nitrification, denitrification
7. Mineralization and synthesis of P containing compounds (phospholipids, ATP etc.)
8. Reactions linked to S cycle (oxidation of sulphides, of elemental S, reduction of sulphates, synthesis of cysteine and methionine etc.)
9. Redox reactions of microelements (Fe, Mn,Mo etc.)
10. Chelation or precipitation of microelements and heavy metals
11. Static and dynamic source of nutrients (turnover 6/18 months)
12. *last but not least* …. bioremediation – detoxification

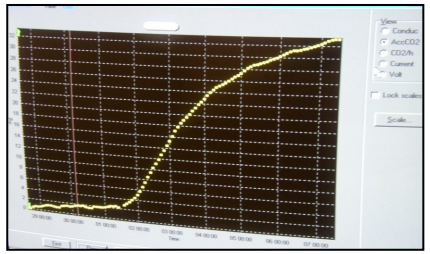
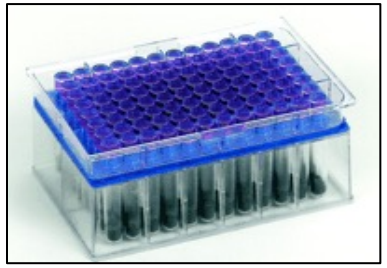
[40]

Biondicators: methodological approaches





Activity rates

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Processes carried out by soil organisms per unit of time

- Respiration
  (CO_2 production rate)
- N mineralization rate
- Enzymatic activities

Biomass
(microbial biomass)

↓

- Direct methods
- Indirect methods
  - Fumigation extraction
  - PLFA*
  - DNA extraction

Community structure

↓

- Functional subgroups
  (i.e. fungi and bacteria)
  - Microscopy
  - Selective inhibition
  - Biomarkers
- Diversity
  - Genetic (DNA, RNA)
  - Functional (CLPP**)

** PhosphoLipid Fatty Acids*
*** Community level physiological profile*

Source: Bloem et al., Microbiological methods for assessing soil quality, 2006

Biodiversity ⟶ Biological diversity

"Globally there are 1,5 millions species of fungi and 1 million species of nematodes which contrast with 6.000 species of reptiles and 9.000 species of birds!"

(Source: Wardle and Giller, 1996.
"The quest for a contemporary ecological dimension to soil biology"
Soil. Biol. Biochem)

A quarter of global biodiversity is in the soil!

Source: Soil Biodiversity - ESDAC - European Commission esdac.jrc.ec.europa.eu

6. The bioindicators

Species richness of soil key-groups

Group	Organisms	Known	% Known
Plants	Vascular plants	270000	84%
Macro-fauna	Earthworms	3500	50%
Meso-fauna	Mites	45231	4%
	Springtails	7617	15%
Micro-fauna	Protozoa	1500	7.5%
	Nematodes	25000	1.3%
Microorganisms	Bacteria	10000	1%
	Fungi	72000	1%
Marine species	All marine organisms	230000	30%[5]

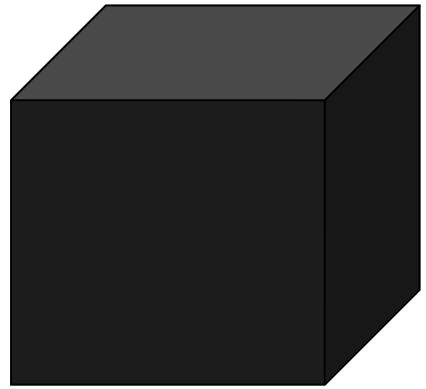
(Source: Coleman, 2001)

Soil is a "black box"

(Source: Paul, Soil microbiology, 1989)

Soil is *still* an unknown biological system

(Source: Nannipieri, Appl. Sci., 2020)



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2. Concepts of soil quality/health
3. Need for monitoring soil quality
4. Soil indicators: main categories
5. Soil organic matter: a *key* indicator!
6. The bioindicators
7. **How to proceed …**
8. Final remarks
9. Main references

1

Identify pressures

Climate change,
Urbanization,
Deforestation,
Pollution,
Salinization,
Waste disposal
Anthropic impact
…

2

Identify end-points

Ecosystem health
Plant health
Animal health
Human health
Soil microbial community
Nutrient stock/leaching
Atmospheric balance
Soil fertility/productivity
…

3

Identify soil ecosystem parameter

C-cycling
N-cycling
Biodiversity
Microbial biomass
Microbial activity
Nutrient cycling
Soil structure
…

4

Select the proper set of indicators

Chemical/physical properties
Microbial biomass size
C mineralization
Enzymatic activities
N mineralisation rate
Microbial diversity
(community composition)
Functional diversity
…

[45]

7. How to proceed…

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- Monitoring soil quality is necessary to assess environmental changes, stress conditions, effect of management practices, land use change, anthropic impact.
- It is important to choose the right set of indicators as the most suitable in relation to type of pressure, geographical area, soil type, management practices …
- Bioindicators are susceptible to a spatial and temporal variability. Long term studies are recommended.
- It is advisable to use several indicators and to integrate the information provided in a multidisciplinary approach
- It is recommended to combine indicators in indexes (ratios, mathematical functions etc.) for comparison among soils

Shortcomings still to be solved:

☹ Lack of standardized analytical methods (for certain properties)

☹ Lack of reference values (bioindicators) or broad databases for high quality soils that could be used to make comparisons.

☹ Scarce involvement of stakeholders, end-users, policy makers

8. Final remarks

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thanks for your kind attention!

Maria Cristina Moscatelli – mcm@unitus.it

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