THE OHIO STATE UNIVERSITY

Soil as a Sink of Atmospheric CO_2 and CH_4

Rattan Lal
Carbon Management and Sequestration Center
The Ohio State University
Columbus, OH 43210 USA

INTERNATIONAL YEAR OF SOILS 2015

The 68th UN General Assembly (A/RES/68/232) declared 2015 the "International Year of Soils"

The Objectives of IYS are:

- To create full awareness of civil society and decision makers about the fundamental roles of soils for human's life
- To advance full recognition of the prominent contributions of soils to food security, climate change, adaptation and mitigation, essential ecosystem services, poverty alleviation and sustainable development.
- To promote effective policies and actions for the sustainable management and protection of soil resources.

THE LIVING SOIL

Soil is an organic-carbon mediated realm in which solid, liquid, gas and <u>biology</u> all interact from a scale of nanometer to landscape.

The weight of live organisms in arable land is 5 t/ha

CARBON POOLS IN DIFFERENT RESERVOIRS FOR THE SHORT-TERM CYCLE

Reservoir	Pool (10^{15} g)
Ocean	42,000
Fossil Fuel	5,000
Soils (2-m)	4,000
Atmosphere	800
Biota	620

SCIENTIFIC CHALLENGES IN-SHORT-TERM CARBON CYCLE

1. Understand the biogeochemical mechanisms determining the carbon exchanges between the land, oceans and atmosphere,

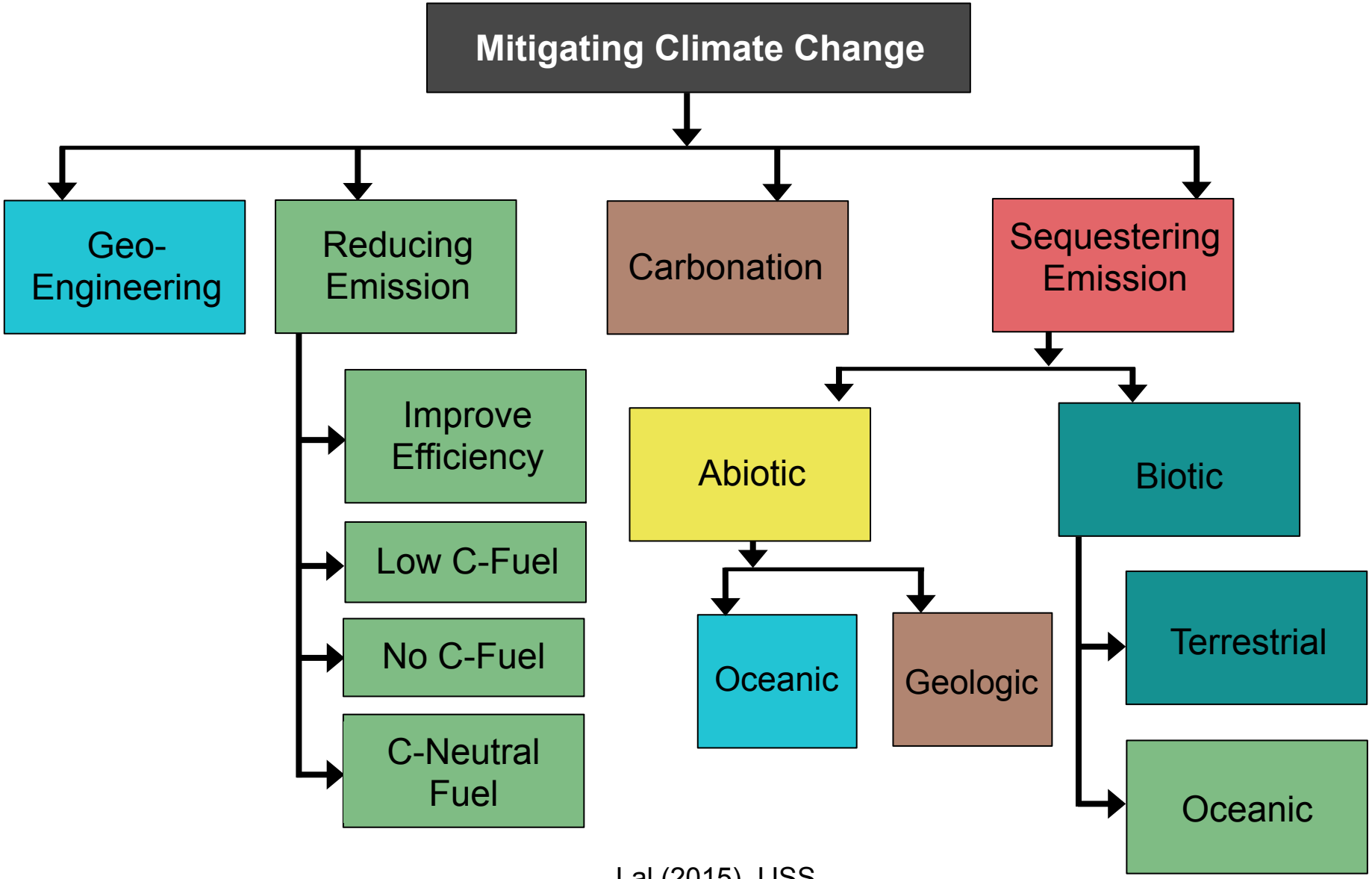
2. How these exchanges respond to climate change through climate-ecosystem feedbacks, which may accentuate or dampen both regional and global climate change, and

3. What are possible interventions to manage these feedbacks.

ROLE OF TERRESTRIAL ECOSYSTEMS IN THE SHORT-TERM CARBON CYCLE

1. By being a source or sink of atmospheric gases via
   - (i) Natural and anthropogenic disturbances
   - (ii) N enrichment by converting N_2 into reactive N
   - (iii) S deposition

2. Climate change and soil carbon
   - (i) Release of CO_2 by warming induced decomposition,
   - (ii) Increase in erosion



Lal (2015), IJSS

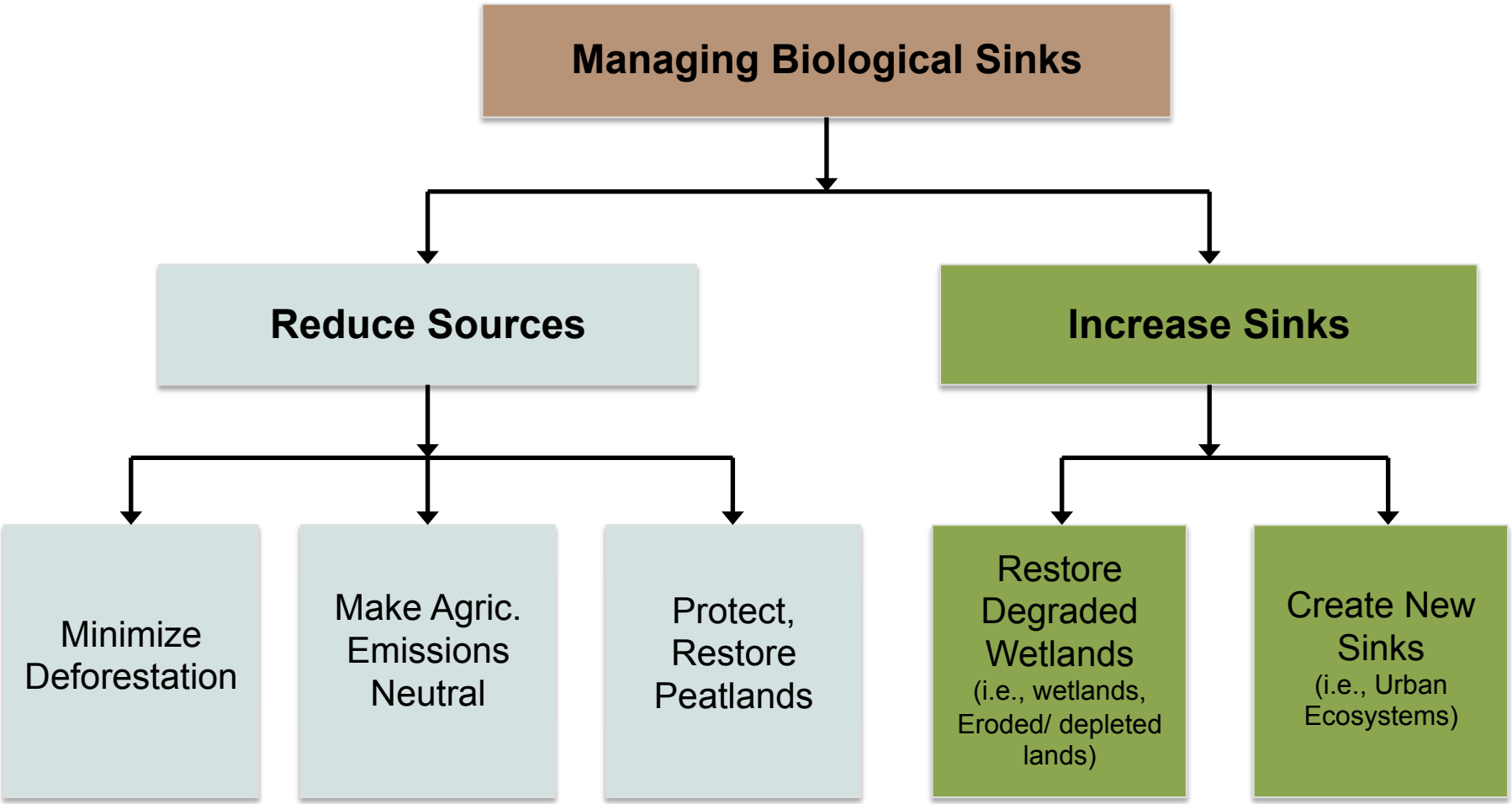
BIOSEQUESTRATION OF ATMOSPHERIC CO_2

Only 0.05% of the 3800 zettajoules (10^{21}J) of solar energy is absorbed annually as GPP

- **Gross Primary Productivity (GPP) = 123 Gt C/yr**
- **Net Primary Productivity (NPP) = 63 Gt C/yr**
- **Net Ecosystem Productivity (NEP) = 10 Gt C/yr**
- **Net Biome Productivity (NBP) = 3 Gt C/yr**

"If we control what plants do with carbon, the fate of CO_2 in the atmosphere is in our hands"

-Freman Dyson (2008), BioScience (10/10)



Lal (2015), IJSS

FORMATION OF SECONDARY CARBONATES

a) **Reduced conditions**: ($FeCO_3$) from Fe^{2+} through reduction of Fe^{3+}, but the process is impeded in the presence of H_2S leading to formation of FeS, and FeS_2 (Pyrite)

b) **Xeric/Aridic conditions**: Formation of pedogenic carbonates of Ca, Mg, Na when cation are supplied from outside the ecosystem

FACTORS AFFECTING SOC POOL

1. Input by NPP: Quantity and Quality

2. Losses by decomposition, erosion and leaching

SOIL WITH MORE C SINK CAPACITY

- Within each pedoclimatic region, some soils have more SOC sink capacity than others

Examples of such soils are:

Ali-Humic Umbrisols in Spain

Humic Latosols in Brazil

Chernozems in Russia

Tierra Negras in Spain

Andosols in Central America

PRIORITY SOILS AND ECOREGIONS FOR CARBON SEQUESTRATION

- Restoring degraded/desertified soils (e.g., eroded)
- Restoring wetlands
- Adopting BMPs on agricultural soils for sustainable intensification

MRT OF SOIL ORGANIC CARBON

- MRT varies from a few seconds to a few millennia.
- It is only the SOC with a long MRT of decades to millennia that can mitigate the climate.
- It is the environmental and biological controls, rather than molecular structural properties (recalcitrance), which impact the MRT.

DECOMPOSITION OF SOM

- Decomposition is mainly microbially meditated,
- Only 10-15% of the energy of SOC is utilized by soil animals,
- Abiotic chemical oxidation accounts for <5% of OM decomposition

Lützow et al. (2006)

SPATIAL INACCESSIBILITY AGAINST MICROORGANISMS AND ENZYMES

- **Abiotic mechanisms** such as formation of Fe- and Al- oxides or hydroxides

- **Biotic mechanism** of occlusions of SOC by aggregation by cementing agents (e.g., microbial cells, secretions, root exudates and faunal mucus), and enmeshment of larger fragments of POM with aggregate surface and mineral particles by fungal hyphae and by roots.

SOIL CARBON STABILIZATION BY CLAY MINERALS

- Amount reactivity and surface area of clay minerals
- Absorption of SOC on silt and clay-sized particles. Thus, there is:

  i. Protective capacity or an upper limit to the capacity of soil to protect SOC by clay adsorption,

  ii. The existing capacity of the soil to protect SOC and depends on the extent to which the protective capacity is already occupied

MECHANISMS OF STABILIZATION

Process	Mechanisms
1. **Selective Preservation:**	• Primary recalcitrance: indigenous molecular structure • Secondary recalcitrance: microbial products, humic polymers, charred materials
2. **Spatial Inaccessibility:**	• Occlusion of OM by aggregation • Hydrophobicity • Intercalation within phyllosilicates • Encapsulation in organic macromolecules
3. Interaction with Surface and Metal Ions	• Inter-molecular interactions • Ligand exchange • Polyvalent cation bridges • Metal ion complexation • Weak interaction

Modified from Lutzow et al. (2006)

MECHANISMS OF SOC PROTECTION

Protection Mechanism	Component
Chemical	Silt + Clay
Physical	Micro-aggregates
Biochemical	Non-hydrolyzable C
Unprotected	POM in sand fraction

Six et al. (2002)

SOC PROTECTIVE CAPACITY & SILT + CLAY CONTENT

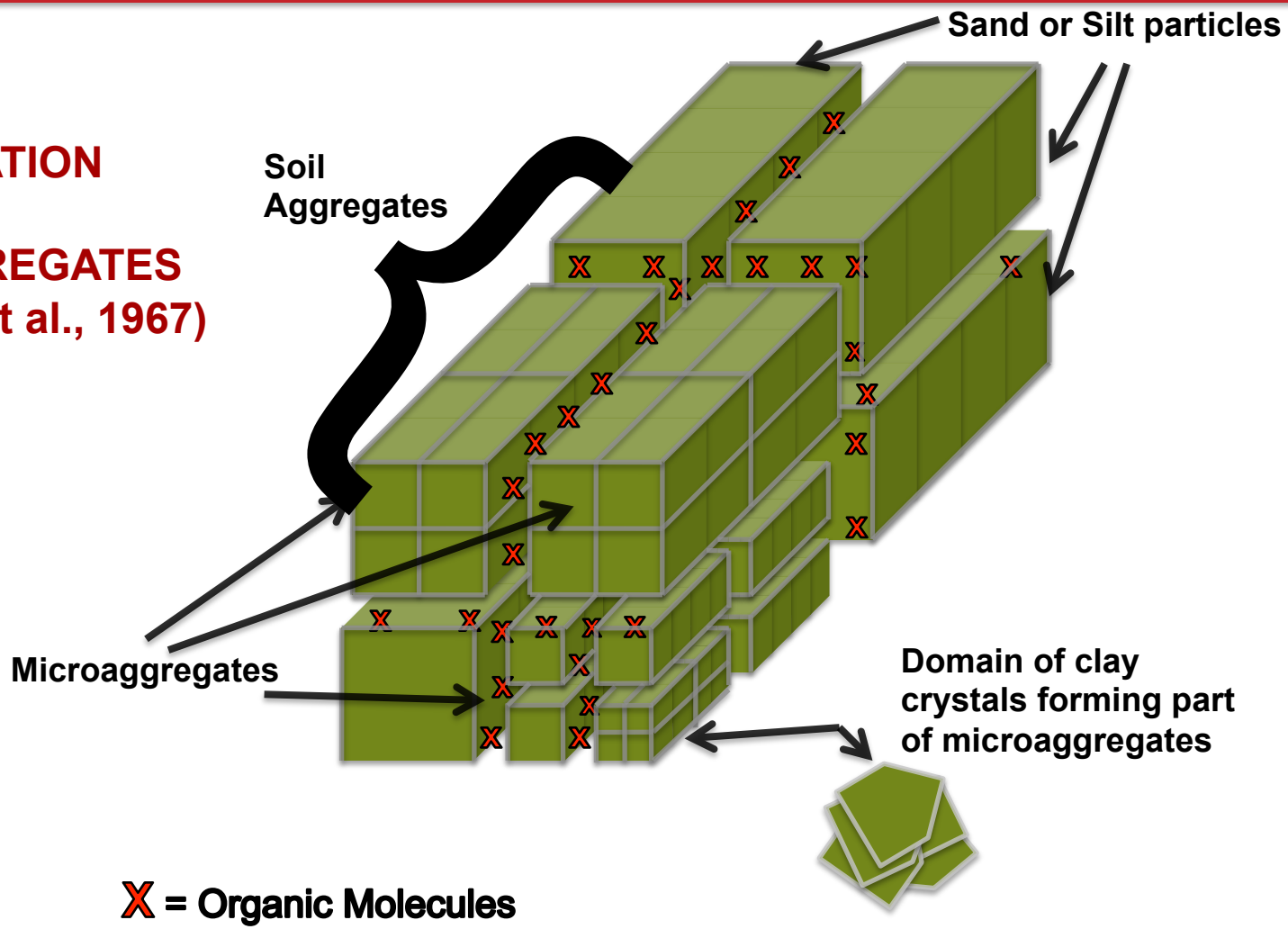
- Soil capacity to protect SOC depends on silt + clay content.

- Application of SIC in excess of the protective capacity would lead to higher rates of decomposition because it is accumulated in the light and intermediate macro-organic matter fractions (POM fractions)

SOC PROTECTIVE CAPACITY AND AGGREGATION

- In addition, chemical protection by adsorption on silt and clay, soil capacity to sequester C also depends on aggregation.

CARBON SEQUESTRATION IN STABLE MICROAGGREGATES (WILLIAMS et al., 1967)



A hypothetical model of a soil aggregate, illustrating the clustering of clay crystals to form domains, of domains to form microaggregates, and of microaggregates to form aggregates. Molecules of soil organic matter acts as bonding agents between domains and microaggregates, and sand and silt particles (after Williams et al., 1967)

THE OVERALL SOIL CARBON STORAGE CAPACITY

I. External Factors

- Biomass-C input and its composition (C:N)
- Nutrients (N, P, S)
- Climate (P, ET, E)

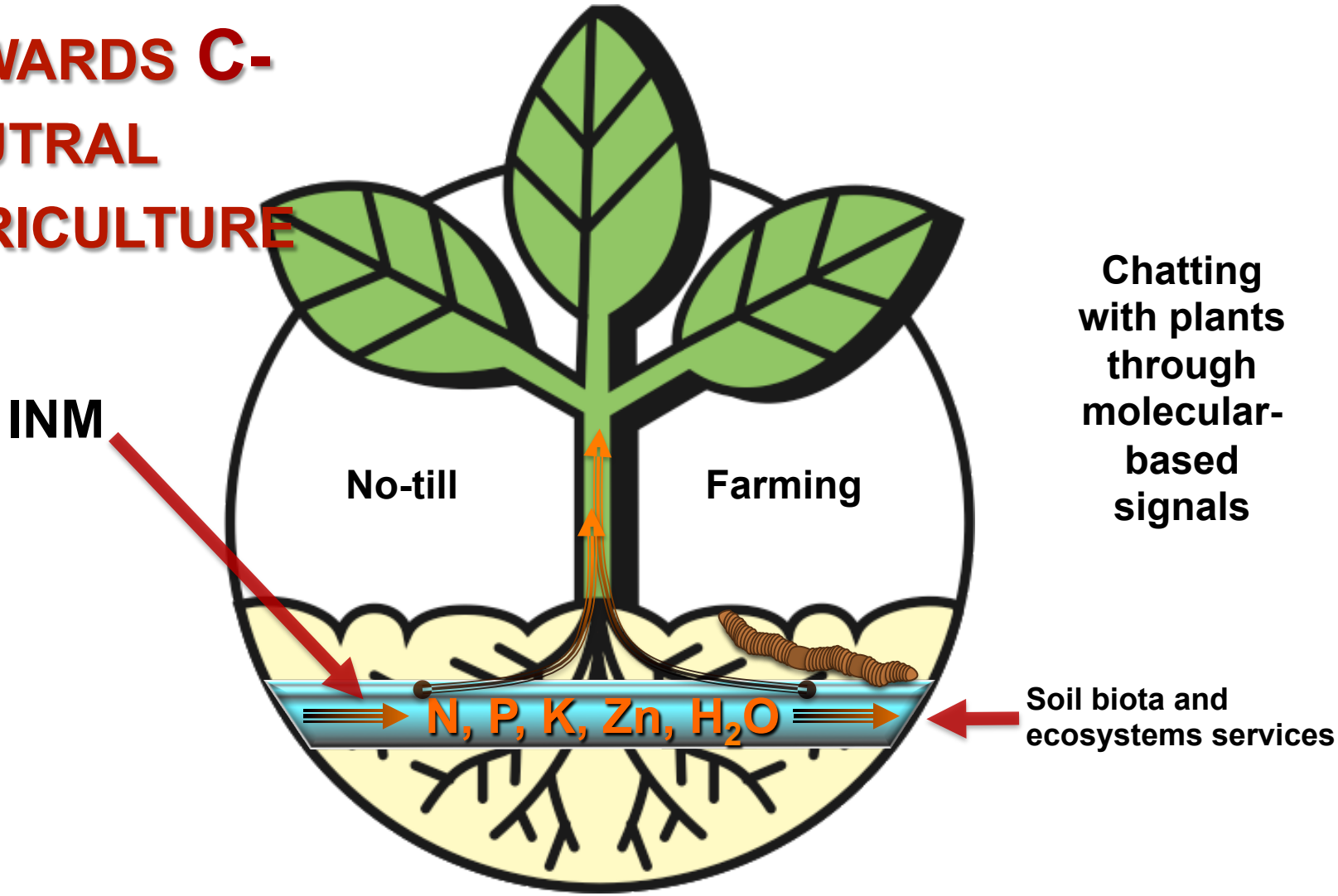
II. Soil Factors

- Silt + Clay content
- Clay mineralogy
- Aggregation and aggregate stability

SUSTAINABLE SOIL MANAGEMENT

- Replace what is removed,
- Respond wisely to what is changed, and
- Predict what will happen from anthropogenic and natural perturbations

TOWARDS C-NEUTRAL AGRICULTURE



Delivering nutrients and water directly to plant's roots

THE PEDOSPHERE AND QUEST FOR SURVIVAL

It involves:

- **understanding** of pedospheric processes and their interactions with nature (hydrosphere, atmosphere, biosphere and lithosphere);
- **recognizing** the limits of its potential and challenges to optimize its ecosystem services;
- **pursuing** relentlessly technologies and options to enhance efficiency and better use of natural resources:
- **improving** soil organic carbon content and pool for restoring degraded soils and landscapes; and
- **creating** climate-smart soils and agroecosystems.

HUMAN-PEDOSPHERIC RELATIONSHIP

- A paradigm of mutual respect based on ecological integrity and symbiotic co-existence.

- Anthropogenic exploitation and drastic perturbations of the pedospheric processes would not only challenge human wellbeing, but also jeopardize intra-social and extra-social biospheric relationships and separate the human from the landscape and nature that has nurtured it throughout its evolutionary history.

CAN SOIL C SEQUESTRATION MITIGATE CLIMATE CHANGE?

- No, C sink capacity of soils of agro-ecosystems is finite (~1 PgC/yr for 50-100 years).
- But, it has numerous co-benefits and is the more cost-effective option.
- Restoring soil quality, of which SOC pool is the important determinant, is essential to human wellbeing and nature conservancy.

CAPACITY OF SOIL CARBON SINK

- Total SOC pool to 2-m depth = 2400 Pg
- Increasing SOC pool by 1% = 24 Pg
- 1 Pg = 0.47 ppm

C sink capacity for every 1% increment ≈ 11 ppm

SOIL STEWARDSHIP

Soil stewardship and care must be embedded in every fruit and vegetable eaten, in each grain ground into the bread consumed, in every cup of water used, in every breath of air inhaled, and in every scenic landscape cherished.

SOIL: THE GLOBAL ICON

Soil is Life and Life is Soil

Lal (2014)