Organic Carbon accumulation and greenhouse gas emission reductions from Conservation Agriculture: a literature review

Sandra Corsi
The challenges for agriculture

Higher and diversified food consumption

Sustainability for future generations

Growing world population

Water issues:
- Irregular water availability
- Extreme weather events
- Higher normal temperatures

Land issues:
- Genetic resources
Crop production growth

Overlap of high population growth and land degradation

DEVELOPING WORLD

Most of the crop production growth worldwide is expected to originate from the developing Countries.

- Boosting crops yields (ca 77%)
- Increasing multiple cropping with shorter fallow periods (ca 13%)
- Expansion of the agricultural land area (ca 10%)
Sustainable Crop Production Intensification aims to increase crop production per unit area, taking into consideration all relevant factors affecting the productivity and sustainability in the following three dimensions:

• Farmers (socio-economic status, traditions, knowledge)

• Technology (agronomic, transfers and linkages) and

• Policy (national, land tenure, market and extension)
Agriculture and forestry
major components of the climate change

Even as the agricultural sector struggles with the effects of global warming, agriculture and forestry are major components of the climate change and are responsible for approximately \( \frac{1}{3} \) of the global GHGs emissions.

For this reason the solutions to the challenges agriculture will have to face (i.e. developing a sustainable food production system and enhancing factor productivity, ensuring global food security) are completely interlinked, and agronomic management can allow to achieve the future production intensification sustainably.
Practices that increase OM in the soil

• **Improve soil fertility**
  (enhanced soil nutrients recycling, plant biomass production)

• **Improve soil management**
  (agronomy, nutrient management, avoid mechanical soil disturbance, residue management, avoid burning crop residues, agroforestry)

• **Improve grazing land management**
  (intensive rotational grazing for integrated livestock and crop production, grazing intensity, increased productivity, nutrient management, fire management, species introduction)

• **Restore degraded lands**
  (erosion control, organic amendments, nutrient amendments).
Factors influencing Carbon sequestration

- climatic conditions, temperature, soil moisture, soil pH
- soil type and texture
- previous land use
- rotation pattern (and hence input rates and C/N ratio) of the Organic Matter returned to the soil
- soil disturbance
Correctly assessing C sequestration potentials

- Rates should be referred to specific C pools, as each C category has different turnover rates.

- Undisturbed soils under natural vegetation should be used as a benchmark and compared to soils disturbed by human activities.

- Data analysis should be carried out at the level of agro-ecological zones or more detailed.
Factors influencing Carbon sequestration

- climatic conditions, temperature, soil moisture, soil pH
- soil type and texture
- previous land use
- rotation pattern (and hence input rates and C/N ratio) of the Organic Matter returned to the soil
- soil disturbance
C stabilization through protection within aggregates

 BINDING AGENTS prevent nutrients and soil components to get lost

- TEMPORARY BINDING AGENTS
  - roots (main + hair)
  - fungi hyphae
  - polysaccharides exuded from roots

- TRANSIENT BINDING AGENTS
  - polysaccharides exuded from fungi
  - partially decomposed residues

- RECALCITRANT BINDING AGENTS
  - humic compounds (that can be separated with strong reagents)

These are the main binding agents. These are the first to be lost once macroaggregates are disrupted.

The residence time of soil aggregates and associated SOM increases as size decreases.

Oxidation and Release of CO₂

Figure 1. Dr. Charles Rice presentation adapted from Jastrow and Miller, 1997.
C sequestration

LITERATURE SURVEY

Factors influencing Carbon sequestration

- **poor management of crop residues:**
  - removal of crop residues

- **mixing of crop residues**
  Residues mixed into the soil decay more rapidly (Magdoff and Weil, 2004)

Mixing readily decomposable carbon into native soils induces a priming effect; the composition of crop residues not mixed does not affect the decay of the native SOM (Chadwick *et al.*, 1998; Flessa and Beese, 2000; Kuzyakov *et al.*, 2000; Chantigny *et al.*, 2001; Bol *et al.*, 2003; Fontaine *et al.*, 2004; Sisti *et al.*, 2004; Fontaine, 2007)

**In a soil not tilled for many years SOM active fractions increases**
(Franzluebbers *et al.*, 1995; Stockfisch *et al.*, 1999; Tebrügge and During, 1999; Horáček *et al.*, 2001)

**Soil life increases in cropping systems with cover crops or organic residues**
fallow-based crop rotations
These should not be associated with the concept of CA

monocropping in no-till systems
Monoculture is in itself a reason for exclusion from CA systems

Changing monocrop to multicrop rotation results in positive influence on SOC concentration
(Havlin et al., 1990; Entry et al., 1996; Mitchell et al., 1996; Robinson et al., 1996; Robinson et al., 1996; Buyanovsky and Wagner, 1998; Gregorich et al., 2001; Lopez-Fando and Pardo, 2001)

rotations that do not guarantee a positive N balance
Rotations that do not allow C sequestration

- **barley - wheat - soybean**
  (Angers et al., 1997)
  
  Barley is a versatile species often cultivated where growing conditions are less favourable.

- **maize - wheat - soybean**
  (Yang and Kay, 2001; VandenBygaart et al., 2002)
  
  These experiments are based on too few soil profiles sampled and the previous land use is not mentioned.

- **soybean as the only legume in the rotation**
  (Machado and Silva, 2001; Freixo et al., 2002)
  
  When a green-manure crop with high annual aboveground biomass production is included, carbon stocks are significantly greater under CA than under TA (Diekow et al., 2005)

C accumulates in the soil when the N balance of the rotation is positive
(Sidiras and Pavan, 1985; Bayer and Mielniczuk, 1997; Boddey, 1997; Alves et al., 2002, 2003, 2006; Sisti et al., 2004; Bayer and Bertol, 1999; de Maria et al., 1999; Amado et al., 1999, 2001; Bayer et al., 2000 a,b)
Factors influencing Carbon sequestration

- climatic conditions, temperature, soil moisture, soil pH
- soil type and texture
- previous land use
- rotation pattern (and hence input rates and C/N ratio) of the Organic Matter returned to the soil
- soil disturbance
LITERATURE SURVEY

No C accumulation in the soil associated with:

- soil disturbance

SOC accumulation is a reversible process: with even a single tillage event, sequestered soil carbon and years of soil restoration may be lost (Grandy et al., 2006)

Formation of stable microaggregates within macroaggregates is inhibited under tillage-based agricultural systems (Six et al., 1998)

In tilled soils, the mixing of the litter favours bacteria, hence quick degradation processes (Beare et al., 1992; Guggenberger et al., 1999)

The mouldboard plough disturbs the highest soil volume, produces the maximum CO₂ flux and uses the most energy. NT the least.

Tillage erosion is the major cause of the severe soil carbon loss on upper slope positions of upland landscapes (Lobb et al., 1995; Lobb and Lindstrom, 1999; Reicosky et al., 2005)
Soil tillage is a very energy consuming process that releases large amounts of CO$_2$ from fossil fuels and from the oxidative breakdown of SOM.

Tillage-based agricultural systems require energy and often lead to SOM reduction and lower biological soil structuring rates.

Vicious circle

- Need to build soil structure
- Tillage
- Lower biological soil structuring rates
- SOM mineralization
- SOM reduction
sampling in deep soil layers

In the medium term, C concentration in deep layers is higher in tilled soils (Baker et al., 2007)

However, when the C-enriched top layer is turned upside-down:

→ recalcitrant C from deeper layers becomes exposed to rapid mineralization at the surface
→ SOC accumulated ceases and regresses as soon as the external carbon input is interrupted

In the long run, in CA system the depth of the Organic horizon increases

→ translocation of soluble carbon compounds from surface residues (Eusterhues et al., 2005; Wright et al., 2007)
→ roots, due to their chemical recalcitrance, contribute twice the C than surface residues (Hussain et al., 1999; Wilts et al., 2004; Johnson et al., 2006)
Conservation Agriculture (CA) is based on three principles (FAO, 2009):

1. Minimum mechanical soil disturbance (the minimum soil disturbance necessary to sow the seed)
2. Permanent organic soil cover (retention of adequate levels of crop residues on the soil surface)
3. Diversified crop rotations including cover crops (to help moderate possible weed, disease and pest problems)
Benefits of CA over tillage-based agriculture

- reduced CO$_2$ emissions
- higher biological activity
- improved capture and use of rainfall
- less peak runoff
- lower production costs
- energy savings

(Smith et al., 1998; Tebrügge, 2000; FAO, 2001, 2008, 2009a)

**But:**

introduction of CA takes time before advantages become apparent
Constraints to CA implementation

- Cultural background (tradition, prejudice)
- Lack of knowledge on how to implement CA (know-how)
- Lack of experience with the new cropping system
- Different weed control
- Different management of residues
- Lack of adequate seeding equipment
- Inadequate policies
Agrochemicals

- Biological herbicides and fertilizers

<table>
<thead>
<tr>
<th>PRODUIT</th>
<th>DESCRIPTION</th>
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</thead>
<tbody>
<tr>
<td>SupaSilica Agrichem</td>
<td>produit à base de extraits d'algues pour augmenter teneur finale en N du grain</td>
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<tr>
<td>Opteine Goëmar</td>
<td>produit stimulant à base de extraits d'algues</td>
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<tr>
<td>Forthial Goëmar</td>
<td>stimulateurs physiologique à base de humus liquide</td>
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<tr>
<td>HL Elvisem (IT)</td>
<td>stimulants bio à base de amino-acides</td>
</tr>
<tr>
<td>SS3 Elvisem (IT)</td>
<td>1.5 l HL Elvisem + 0.5 SS3 Elvisem = 1.5 l Bombardier Kinitec</td>
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<tr>
<td>Bombardier Kinitec (ES)</td>
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<tr>
<td>Sonata Agraquest</td>
<td>Bacillus subtilis</td>
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<tr>
<td>Serenade Agraquest</td>
<td>Bacillus pumilus</td>
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</tbody>
</table>

- Comparison of post-emergence, non-selective systemic herbicides

<table>
<thead>
<tr>
<th>Herbicide</th>
<th>Mode of Action</th>
<th>Time to Symptoms</th>
<th>Rate for Spot Appl.</th>
<th>Toxicological properties*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reward</td>
<td>contact</td>
<td>2 to 24 hr</td>
<td>ᴛ/₂ to ᴛ/₂% + surfactant</td>
<td>WARNING: eye &amp; skin irritant; LD₅₀ = 230 mg/kg</td>
</tr>
<tr>
<td>Scythe</td>
<td>contact</td>
<td>½ to 2 hr</td>
<td>5 to 10%</td>
<td>WARNING: severe eye irritant; LD₅₀ &gt;5000 mg/kg</td>
</tr>
<tr>
<td>Finale</td>
<td>systemic</td>
<td>~2 days</td>
<td>½ to 3%</td>
<td>WARNING: may cause eye or mild skin irritation; LD₅₀ = 3570 mg/kg</td>
</tr>
<tr>
<td>Roundup-Pro</td>
<td>systemic</td>
<td>~7 days</td>
<td>1 to 3%</td>
<td>CAUTION: may cause mild skin or eye irritation; LD₅₀ &gt;5000 mg/kg</td>
</tr>
</tbody>
</table>

→ Soil biota favour the fast recycling of nutrients and help to immobilize most residual N in the soil so that carbon-expensive N-fertilizers could be reduced over time.
### Residues by climate

Quantities of residues achievable in different climates under common rotation systems, regardless of the agricultural practice:

<table>
<thead>
<tr>
<th>CROP ROTATION</th>
<th>CLIMATE</th>
<th>LOCATION</th>
<th>ORGANIC MATTER PRODUCED</th>
<th>AUTHOR</th>
</tr>
</thead>
<tbody>
<tr>
<td>pigeon pea cowpea</td>
<td>semi-arid tropics</td>
<td>India</td>
<td>3 t ha$^{-1}$ of dry leaf</td>
<td>Abdurahman et al. (1998)</td>
</tr>
<tr>
<td>velvetbean$^1$-based systems</td>
<td>Tropics</td>
<td>America central</td>
<td>35 - 50 t ha$^{-1}$ y$^{-1}$ of biomass</td>
<td>FAO (2001)</td>
</tr>
<tr>
<td>soybean</td>
<td>semi-arid temperate</td>
<td>Canada</td>
<td>twice the amount of soybean residue</td>
<td>Reicosky (1997)</td>
</tr>
</tbody>
</table>

$^1$ Velvetbean = Mucuna pruriens
### SOC by crop rotation

SOC quantities achievable in different climates under most common rotation systems (adapted from Jarecki and Lal, 2003)

<table>
<thead>
<tr>
<th>CROP ROTATION with and without cover crop or green manure</th>
<th>CLIMATE</th>
<th>LOCATION</th>
<th>SOIL type</th>
<th>SOC INCREASE relative to the same rotation without cover crop or green manure [t C ha⁻¹ yr⁻¹]</th>
<th>AUTHOR</th>
</tr>
</thead>
<tbody>
<tr>
<td>millet - wheat - green manure - sesbania²</td>
<td>Tropics</td>
<td>India</td>
<td>Sand loam</td>
<td>0.20</td>
<td>Chander et al. (1997)</td>
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<tr>
<td>millet - wheat - fallow</td>
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<tr>
<td>wheat - barley - green manure</td>
<td>humid and subhumid temperate</td>
<td>Sweden</td>
<td>Sandy clay loam</td>
<td>0.35</td>
<td>Paustian et al. (1992)</td>
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<tr>
<td>wheat - barley</td>
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<tr>
<td>cotton³ - rye⁰</td>
<td>humid and subhumid subtropics</td>
<td>USA, Alabama</td>
<td>Sand loam</td>
<td>5.413</td>
<td>Nyakatawa et al. (2001)</td>
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<tr>
<td>cotton - fallow</td>
<td></td>
<td></td>
<td></td>
<td>0.90</td>
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<tr>
<td>hairy vetch into tomato - maize</td>
<td>humid and subhumid subtropics</td>
<td>USA, Georgia</td>
<td>Sand loam</td>
<td>0.63</td>
<td>Sainju et al. (2002)</td>
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<tr>
<td>tomato - eggplant - rye</td>
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<td>0.51</td>
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<tr>
<td>tomato - eggplant</td>
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<td>0.90</td>
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<tr>
<td>tomato - eggplant - clover³</td>
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<td>0.50</td>
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<tr>
<td>tomato - eggplant</td>
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</table>

1. **Sesbania** = *Sesbania sesban*
2. **Cotton** = *Gossypium spp.*
3. **Rye** = *Secale cereale L.*
4. **Eggplant** = *Solanum melongena*
5. **Clover** = *Trifolium spp.*

### CROP ROTATIONS with and without cover crop or green manure

<table>
<thead>
<tr>
<th>CROP ROTATION with and without cover crop or green manure</th>
<th>CLIMATE</th>
<th>LOCATION</th>
<th>SOIL type</th>
<th>SOC INCREASE relative to the same rotation without cover crop or green manure [t C ha⁻¹ yr⁻¹]</th>
<th>AUTHOR</th>
</tr>
</thead>
<tbody>
<tr>
<td>alfalfa⁶</td>
<td>humid and subhumid temperate</td>
<td>USA, Ohio</td>
<td>Silty day loam</td>
<td>0.48</td>
<td>Lal et al. (1998a)</td>
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<tr>
<td>maize monocrop</td>
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<td>-0.04</td>
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<tr>
<td>Kentucky bluegrass⁷</td>
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<td>2.12</td>
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<td>maize monocrop</td>
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<td>2.08</td>
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<td>fescue³</td>
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<td>maize monocrop</td>
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<td>bromegrass³</td>
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<td>maize monocrop</td>
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<tr>
<td>maize - rye</td>
<td>humid and subhumid temperate</td>
<td>USA, Washington state</td>
<td>Silty loam</td>
<td>0.53</td>
<td>Kuo et al. (1997)</td>
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<tr>
<td>maize - Austrian winter pea¹⁰</td>
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<td>0.16</td>
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<tr>
<td>maize</td>
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<td>0.32</td>
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<tr>
<td>maize - ryegrass</td>
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<td>0.40</td>
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<td>maize</td>
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<td>-0.11</td>
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<td>maize - vetch</td>
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<td>maize - rapeseed¹¹</td>
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<td>maize</td>
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6. **Alfalfa** = *Medicago sativa*
7. **Kentucky bluegrass** = *Poa pratensis*
8. **Fescue** = *Festuca arundinacea*
9. **Bromegrass** = *Bromus inermis*
10. **Austrian winter pea** = *Lathyrus hirsutus L.*
11. **Rapeseed** = *Brassica napus*
**SOC by tillage system**

Experimental results on the long-term impact on SOC content / carbon (C) inputs of different tillage systems under the same crop rotation schemes.

<table>
<thead>
<tr>
<th>PRIOR HISTORY</th>
<th>CROP ROTATION</th>
<th>CLIMATE</th>
<th>LOCATION</th>
<th>SOIL texture</th>
<th>SOIL type</th>
<th>AGRIC. SYSTEM</th>
<th>EXPERIMENT DETAILS</th>
<th>RESULTS</th>
<th>AUTHOR</th>
</tr>
</thead>
<tbody>
<tr>
<td>continuous wheat</td>
<td>wheat - soybean vs.</td>
<td>Canada, west</td>
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<td></td>
<td>Higher C sequestration achieved with this rotation. N-fertilizer application beneficial.</td>
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<td>continuous soybean</td>
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<tr>
<td>continuous wheat vs.</td>
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<td>wheat grass(^1) vs.</td>
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<td>fallow - wheat</td>
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<td>flax(^2) vs.</td>
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<td>wheat</td>
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<tr>
<td>hay - fallow - wheat</td>
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<tr>
<td>lentil(^3) or red clover(^4) - wheat - wheat vs.</td>
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<tr>
<td>fallow - wheat - wheat vs.</td>
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</tbody>
</table>

\(^1\) Wheat grass = Agropyron cristatum or Agropyron trichophorum  
\(^2\) Flax = Linum usitatissimum  
\(^3\) Lentil = Lens culinaris  
\(^4\) Red clover = Trifolium pratense
<table>
<thead>
<tr>
<th>PRIOR HISTORY</th>
<th>CROP ROTATION</th>
<th>CLIMATE</th>
<th>LOCATION</th>
<th>SOIL texture</th>
<th>SOIL type</th>
<th>AGRIC. SYSTEM</th>
<th>EXPERIMENT DETAILS</th>
<th>RESULTS</th>
<th>AUTHOR</th>
</tr>
</thead>
<tbody>
<tr>
<td>fallow - fall rye</td>
<td>fall rye vs.</td>
<td>SOC stored at a rate of $0.1 \pm 0.14$ t of carbon ha$^{-1}$y$^{-1}$</td>
<td></td>
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<td></td>
<td></td>
<td>2.3 less t of carbon ha$^{-1}$ stored</td>
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<tr>
<td>fallow - wheat</td>
<td>wheat</td>
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<td>SOC stored at a rate of $0.12 \pm 0.09$ t of carbon ha$^{-1}$y$^{-1}$</td>
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<tr>
<td>straw removal</td>
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<td></td>
<td>SOC stored at a rate of $1.3$ less t of carbon ha$^{-1}$ stored</td>
<td></td>
</tr>
<tr>
<td>alfalfa$^5$ or red clover - maize</td>
<td>maize vs.</td>
<td>SOC stored at a rate of $0.44 \pm 0.28$ t of carbon ha$^{-1}$y$^{-1}$</td>
<td></td>
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<td></td>
<td></td>
<td>14.4 $\pm$ 11.5 less t of carbon ha$^{-1}$ stored</td>
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<tr>
<td>continuous maize</td>
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</tr>
<tr>
<td>wheat - sunflower</td>
<td>Spain, south</td>
<td>Vertisol</td>
<td>NT vs. TA</td>
<td>Comparison of 4 different rotations for TA and NT over more than 11 years</td>
<td></td>
<td></td>
<td>Over 11 years, wheat - sunflower and wheat - wheat rotations accumulate greater above-ground C than other rotations for both tillage systems.</td>
<td></td>
<td>López-Bellido et al. (2010)</td>
</tr>
<tr>
<td>wheat - wheat</td>
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<td>wheat - faba bean</td>
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$^5$ Fall rye = Lolium perenne  
$^6$ Alfalfa = Medicago sativa  
$^7$ Faba bean = Vicia faba
• \( N_2O \) is approximately 310 times more potent than \( CO_2 \)

• Agriculture is the main source of \( N_2O \) emissions worldwide. \( N_2O \) is mainly produced by nitrification under microaerophilic soil conditions and through \textit{denitrification} under anaerobic soil conditions. The main factor controlling the speed of both processes is substrate availability: ammonia in the case of nitrification and oxidized nitrogen forms (nitrates and nitrites) in the case of denitrification processes.

Microaggregates in CA soils (that offer a more \( O_2 \)-limited environment than in TA soils) and substrate availability for microbial degradation may increase emission of \( N_2O \) by denitrification: higher \( N_2O \) flux of \( 0.00291 \pm 0.00078 \) t N-\( N_2O \) ha\(^{-1}\) y\(^{-1}\) times (corresponding to \( 1.418 \pm 0.382 \) t C-equivalents ha\(^{-1}\) y\(^{-1}\)) in CA than in TA nullifies the beneficial effect of higher \( CH_4 \)-uptake and Csequestration of CA in terms of GHG balance.

However, asphyctic soil conditions that favour \( N_2O \) emissions (typical of humid, heavy and compacted soils) are not desirable for crop production in general. If structural and drainage problems should always be addressed and corrected (i.e. drainage systems, plough pans broken, cover crops with robust and deep rooting systems chosen, rotations to favour nitrogen-fixing bacteria).
CH₄ has an approximately 20 times higher global warming potential than CO₂

CH₄ flux from soil to atmosphere is the net result of two bacterial processes: CH₄ production in strictly anoxic micro-environments (methanogenesis) and CH₄ consumption and oxidation in aerobic micro-environments by CH₄-oxidizing bacteria (methanotrophs).

The largest biological sinks for methane are microorganisms in aerobic soils.

Comparative data between CA and TA for CH₄ uptake are lacking. In temperate soils 0.00042 ± 0.0001 t C CH₄ ha⁻¹ y⁻¹ greater CH₄ uptake under CA

Growing irrigated aerobic rice can help to save water and reduce CH₄ emissions.
OM Mineralization

Mineralization is the process through which micro-organisms convert organic forms of carbon (C), nitrogen (N), phosphorus (P), sulphur (S) into mineral forms (autotrophs-accessible nutrients).

The opposite process of long-term storage of CO$_2$ within soil structures through biological, chemical and physical processes is called C sequestration.
Soil Organic Matter (SOM): vegetal and animal residues at various levels of decomposition and < than 2 mm

SOM pools can be distinguished based on SOM size:

LABILE POOL (ACTIVE POOL) 0.25 mm < AP < 2 mm
The least decomposed and youngest SOM, with rapid turnover, sensitive to land and soil management in the short-term.

PARTICULATE ORGANIC CARBON 0.053 mm < POM < 0.25 mm
From recently added plant and animal debris to partially decomposed organic material (in the range of microaggregates).

STABLE POOL (RECALCITRANT SOM) RSOM < 0.053 mm %
Most decomposed level of organic matter, resistant to further microbial decomposition through incorporation and protection into aggregates. RSOM holds moisture and cations for plant use, acting as a glue for microaggregates.

The residence time of soil aggregates and associated SOM increases as size decreases.
The “sandwich” soil organisms want to eat vs. the “sandwich” farmers prepare

**MICRO-ORGANISMS ASSIMILATION EFFICIENCY of the C content in the OM**

The C degradation efficiency of micro-organisms equals to **30% in aerobioc conditions** and **60% in anaerobioc conditions**: 30% - 60% of the C content in the OM is used as a source of energy and the remaining 70% - 40% is oxidized (breathed) to CO₂.

**MICRO-ORGANISMS C/N RATIO** describes the composition of the “sandwich” they will want to eat

N parts required by micro-organisms for each part of C eaten depends on the C/N ratio of the group and specie. In general:

- the average C/N ratio of fungi is **15:1** (6:1 through 25:1): fungi need 1 atom of N every 15 atoms of C they introduce
- bacteria average C/N ratio is **6:1** (3:1 through 10:1)

**OM C/N RATIO** describes the attitude to mineralization of the OM returned to the soil

- OM having C/N > **30** does not supply sufficient N and micro-organisms will draw any available soil N (NH₄⁺, NO₃⁻) in the proper proportion to make use of available C to continue decomposition and their bio-synthesis. This delays availability of N to plants (immobilization).
- OM having C/N < **10** is subject to fast mineralization.

Because bacteria have higher N requirements compared to fungi, OM rich in N favours fast mineralization processes operated by bacteria