C-FARM: A Simple Model to Evaluate the Soil Carbon Balance in Cropping Systems

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Carbon Cycling Modeling Relevance

• Soil Carbon is a key component of soil productivity and environmental integrity
• C, N, and P cycling are closely linked
• Carbon content of soils affects their erodability
• Carbon storage in soils can play a role in regulating atmospheric \([\text{CO}_2]\)
• Biomass harvest for bioenergy can affect soil carbon balance

There is a strong demand for methods to compute and certify the soil carbon balance under different agricultural managements due to both environmental concerns and to support the carbon and environmental credits markets.
Objective

Develop a tool to compute soil C balance

- The following are desirable features of a soil carbon model:
  - Simple structure
  - Consider the entire soil profile
  - No or minimum calibration needs
  - Transferable across locations
  - Consider environmental and management effects on soil carbon turnover
  - Accommodate different management scenarios
More than a century of research

- Hénin and Dupuis (1945): carbon balance
- Jansson (1958): tracer experiments
- Swift (1979): the cascade of decomposition
- Jenkinson and Rayner (1977): multiple carbon pools, Roth-C model
- Paul & coworkers (1979 - present)
- Phoenix model (McGill et al. 1981)
- Century, NCSoil, Verberne et al. (1980 - 1990)
**Challenge**  Quantitative treatment of complex processes

- Soil organic matter is composed of fractions with varying (continuum) turnover rates
- At best, SOM is treated as composed of discrete fractions with distinct properties

- Alternative approaches to treat this complexity:
  - Multiple carbon pools with fixed properties
  - Only one carbon pool, with variable properties
  - Multiple carbon pools with variable properties
Change in Carbon Storage = Inputs - Outputs

Hénin and Dupuis (1945) \[
\frac{dC_s}{dt} = hC_i - kC_s
\]

- \(C_s\) is the soil organic Carbon (Mg ha\(^{-1}\))
- \(t\) is time (year)
- \(h\) is the humification constant
- \(C_i\) is the carbon input
- \(k\) is the apparent soil turnover rate
Analytical solution for variable humification rate

Change in Carbon Storage = Inputs - Outputs

\[
dC_s/dt = h_x(1 - C_s/C_x)C_i - kC_s
\]

\[
C_s(t) = h_x C_i/c + (C_o - h_x C_i/c)\exp(-ct)
\]

\[
c = h_x C_i/C_x + k
\]

\(h_x\) is the maximum humification

\(C_x\) is the maximum soil carbon carrying capacity (Mg ha\(^{-1}\))
Analytical solution for variable turnover rate

Change in Carbon Storage = Inputs - Outputs

\[ \frac{dC_s}{dt} = hC_i - k_n(1 + \frac{C_s}{C_k})C_s \]

\[ C_s(t) = C_k \left[ a_2 A \exp(-k_n(a_2 - a_1)t - a_1) / [1 - A \exp(-k_n(a_2 - a_1)t)] \right] \]

\[ a_1 = - \frac{[1 + (1 + 4b)^{1/2}]}{2} \]

\[ a_2 = \frac{[(1 + 4b)^{1/2} - 1]}{2} \]

\[ b = \frac{hC_i}{(k_nC_k)} \]

A is an integration constant

\[ C_k \text{ is a reference soil carbon content (Mg ha}^{-1}) \]
The core carbon balance equation for each layer

\[ \frac{dC_s}{dt} = hC_i - kC_s \]

\[ h = h_c[1 - (C_s/C_x)^n] \]

\[ k = f_e f_t k_x (C_s/C_x)^m C_s \]

- \( h_c \) depends on soil texture resembling Roth-C
- \( C_x \) depends on soil texture (Hassink and Withmore, 1997)
- \( f_e \) soil temperature and water content factor (energy balance)
- \( f_t \) is a function of tillage tool and number of operations (NRCS)
Inputs
- daily weather
- soil texture and organic carbon by layer
- cropping systems sequence (seeding and maturity dates)
- grain yield (max, min, average) for each crop
- tillage sequence (tools, date, depth of operation)
- Irrigation scheme

Outputs
- soil organic carbon evolution by layer / year
- estimated carbon input
- estimated humified carbon
- estimated “respired” carbon
- water balance
Testing: Pendleton OR summer fallow wheat

Site: gently to strongly sloping landscape
Climate: semi-arid, winter precipitation, dry summer
Soils: mixed mesic Typic Haploxeroll (Walla Walla silt loam)
Original vegetation: shrub / sagebrush – grassland

Cropping System: winter wheat / summer fallow
Seeding: October / Harvest: July
Tillage: moldboard plow in April/May, three operations to control weeds during summer, fertilizer applied 15-cm deep in October, rodweeded before seeding, and seeded 25-cm row with spacing
Testing: Pendleton OR summer fallow wheat

**Treatment:** 90 kg N ha\(^{-1}\), no residue burn

<table>
<thead>
<tr>
<th></th>
<th>Obs</th>
<th>Sim</th>
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</thead>
<tbody>
<tr>
<td>Average yield, Mg ha(^{-1})</td>
<td>3.73</td>
<td>3.97</td>
</tr>
<tr>
<td>Average aboveground carbon input, Mg ha(^{-1})</td>
<td>1.24</td>
<td>1.27</td>
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</tbody>
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**Treatment:** no N input, no residue burn

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<tbody>
<tr>
<td>Average yield, Mg ha(^{-1})</td>
<td>2.62</td>
<td>3.09</td>
</tr>
<tr>
<td>Average aboveground carbon input, Mg ha(^{-1})</td>
<td>0.95</td>
<td>0.96</td>
</tr>
</tbody>
</table>
Testing: Pendleton OR summer fallow wheat

Treatment: 90 kg N ha\(^{-1}\), no residue burn

Projected soil carbon evolution from the beginning of agriculture in the area

Likely soil carbon evolution with residue input of 1.8 Mg C ha\(^{-1}\) year\(^{-1}\) under conventional tillage and summer fallow

Likely soil carbon evolution with residue input of 1.8 Mg C ha\(^{-1}\) year\(^{-1}\) under no-tillage and summer fallow
Testing: Rothamsted UK continuous wheat

Treatment: 144 kg N ha\(^{-1}\), no residue burn
1853 – 1926 continuous wheat
1927 – 1962 wheat – fallow
1963 – 2005 continuous wheat

Average aboveground carbon input: approximately 2.2 Mg ha\(^{-1}\) year\(^{-1}\)

Treatment: 0 kg N ha\(^{-1}\), no residue burn
1853 – 1926 continuous wheat
1927 – 1962 wheat – fallow
1963 – 2005 continuous wheat

Average aboveground carbon input: approximately 1.2 Mg ha\(^{-1}\) year\(^{-1}\)
C-FARM Rothamsted: carbon input and tillage system

Treatment: 144 kg N ha\(^{-1}\), no residue burn
Compare *till* vs. *no-till* (simulated) systems
Difference between systems: 6 Mg C ha\(^{-1}\)
Average aboveground carbon input: approximately 2.2 Mg ha\(^{-1}\) year\(^{-1}\)

Treatment: 0 kg N ha\(^{-1}\), no residue burn
Compare *till* vs. *no-till* (simulated) systems
Difference between systems: 7 Mg C ha\(^{-1}\)
Average aboveground carbon input: approximately 1.2 Mg ha\(^{-1}\) year\(^{-1}\)
C-FARM Concluding Remarks

- C-FARM carbon dynamic representation is scientifically sound
- The model has been successfully tested in two environments with different precipitation patterns and management systems
- The representation of tillage effects is tool-specific
- The interface and limited input requirements makes it useful for consultants and farmers, allowing a quick assessment of the soil carbon balance under different management systems

Future developments:
- simple N balance and estimations of denitrification and nitrous oxide emission
- estimation of erosion

Stand alone version + web-based simulation capabilities
Acknowledgements

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- Request more information and a trial version:
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  - stockle@wsu.edu