Studies of crop and soil management effects on soil organic matter constituents

Paul Voroney and Katelyn Congreves
School of Environmental Sciences
University of Guelph
Guelph, Ontario

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Outline of presentation

- What is soil organic matter (SOM) and why is it so important
- Past management
  - **Forest clearing and cropping effects on soil organic matter levels**
- Present management: Long-term studies of decomposition of crop residues and C stabilization in soil (soil C sequestration)
  - **Tillage practices**
  - **Cropping practices**
- Future management: Implications of crop residue removal for:
  - **Biofuels, bioproducts**
  - **Biochar**

SOM improves all soil properties

SOM: inherited from the past 10,000 yr of soil formation;
f (climate, parent material, vegetation, topography, time) *(Hans Jenny, 1941)*

- Physical
- Chemical
- Biological

SOM improves soil properties for plants

- Physical:
  - Central role in aggregation and soil structure: enhances soil tilth and resilience to compaction
  - Reduces bulk density and increases porosity
  - Increases water infiltration rates, aeration status and water holding capacity

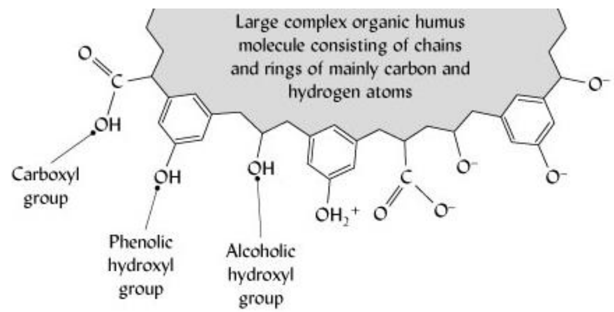
Soils from organic (right) and conventional (left) research plots are very different in appearance due to the increase in SOM

SOM improves soil properties for plants

- Chemical:
  - Storehouse of plant nutrients
    - Macronutrients in organic form (N, P, S)

Microbial mineralization →

100-200 kg N/ha/yr
10-20 kg P/ha/yr

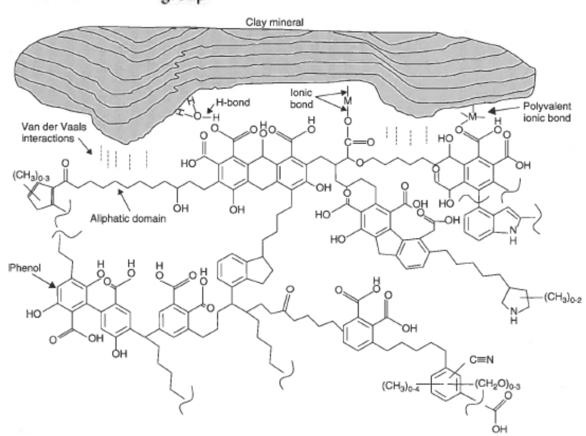


  - Cation (+) anion (-) exchange capacity

(4X more than clay)

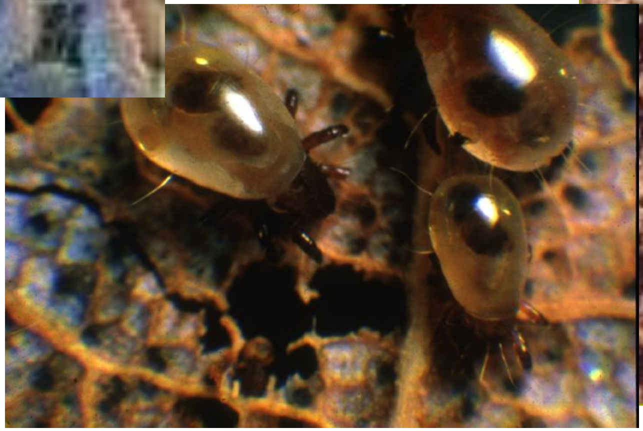
  - Organo-mineral complexes

(SOM stuck to minerals)



SOM improves soil properties for plants

- Biological:
  - Provides substrates (energy and nutrients) to support a large, biomass of soil organisms


Soil Food Web

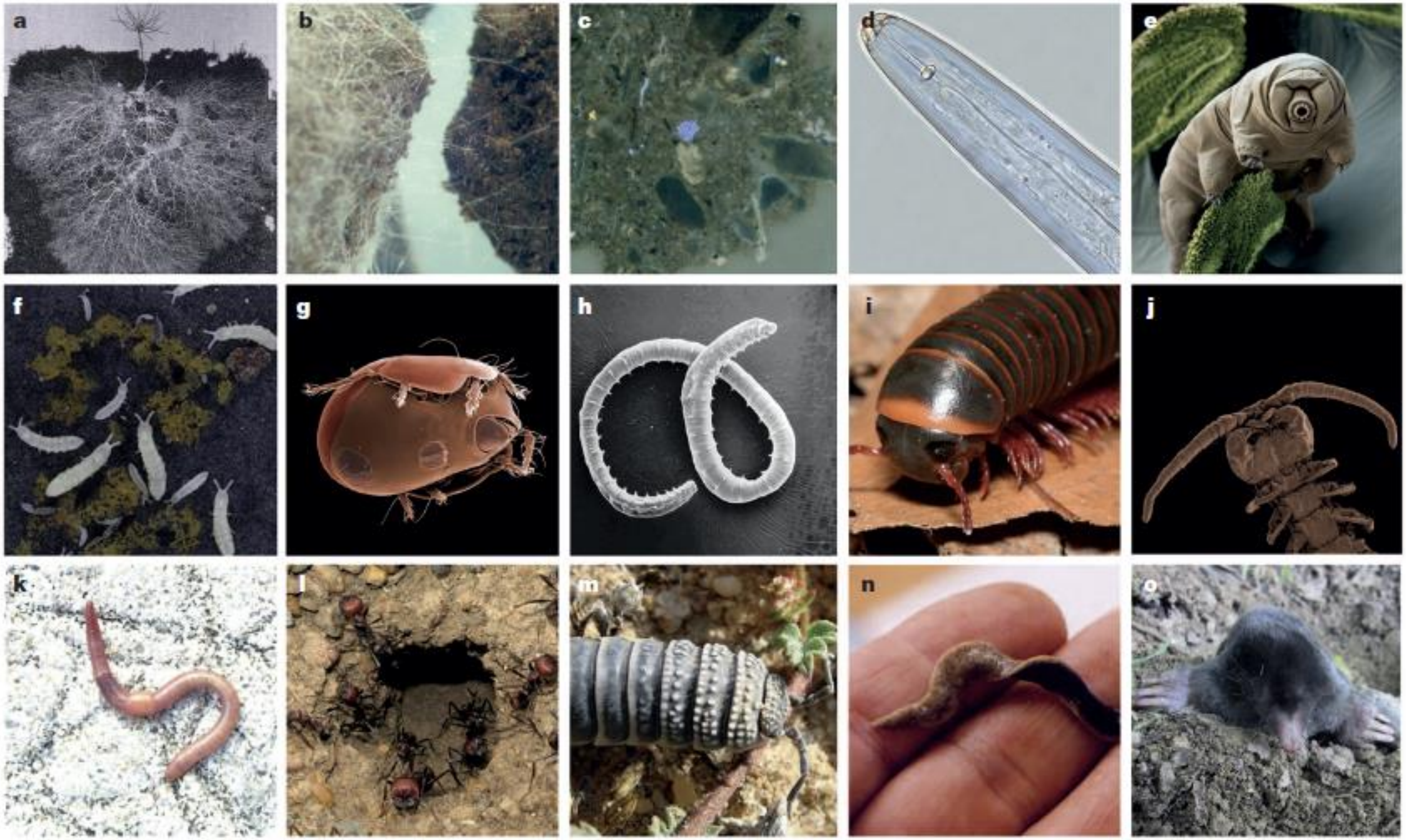


Figure 1 | A selection of organisms of the soil food web. **a–o**, The selection of organisms includes ectomycorrhizal (**a**) and decomposer fungi (**b**), bacteria (**c**), nematode (**d**), tardigrade (**e**), collembolan (**f**), mite (**g**), enchytraeid worm (**h**), millipede (**i**), centipede (**j**), earthworm (**k**), ants (**l**), woodlice (**m**), flatworm (**n**) and mole (**o**). All photographs are from the European Soil Biodiversity Atlas, courtesy of A. Jones; individual photo credits are: K. Ritz (**b**, **c**); H. van Wijnen (**d**); Water bear in moss, Eye of Science/Science Photo Library (**e**); P. Henning Krog (**f**); D. Walter (**g**); J. Rombke (**h**); J. Mourek (**i**, **j**); D. Cluzeau (**k**); European Soil Biodiversity Atlas, Joint Research Centre (**l**, **n**); S Taiti (**m**); and H. Atter (**o**).

Global Carbon Reservoirs

Carbon reservoirs	ppm	10^9 Mg carbon
Atmosphere		
1850	260	560
1986	360	760
2010	**388**	**820**
October 2016	**401.6**	**864.5**
Ocean		
Carbonates		20×10^6
Organics		3,600
Land		
Biota		**500**
SOM		**1,500**
Fossil fuel		10,000

Soil organic matter (SOM) levels: 1 - 5%

- How much organic matter is in soil in the **surface 30 cm** of a hectare?
- At a **4% SOM** content = 160,000 kg ha^{-1}
- Given that SOM is **~58% SOC**, then quantity of SOC =

  93,000 kg ha^{-1}

[Assumes that the mass of soil = 4,000,000 kg/ha]

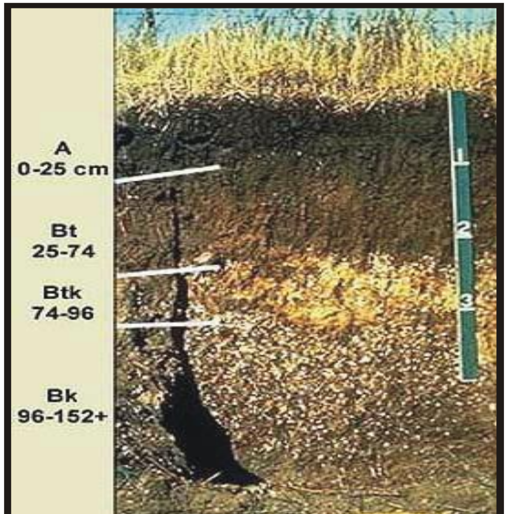
Soil organic matter (SOM)

'Average' soil (ha^{-1}):

100,000 kg organic C

10,000 kg organic N

2,000 kg organic P



What is SOM in mineral soils?

SOM is:

- Anything that is or once was living-recognizable structures:
  - Plant and animal residues in various stages of decay (10-15%)
  - Cells and tissues of soil organisms, the soil microbial biomass (5-8%)
- Plant residues measured by hand picking, sieving, sedimentation (light fraction)
- Microbial biomass by fumigation extraction-biomass C, N, P, S

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Active fraction

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- Biopolymers released during decay of plant and microbial residue
- Plant and microbial carbohydrates, proteins, lipids, lignins, etc.

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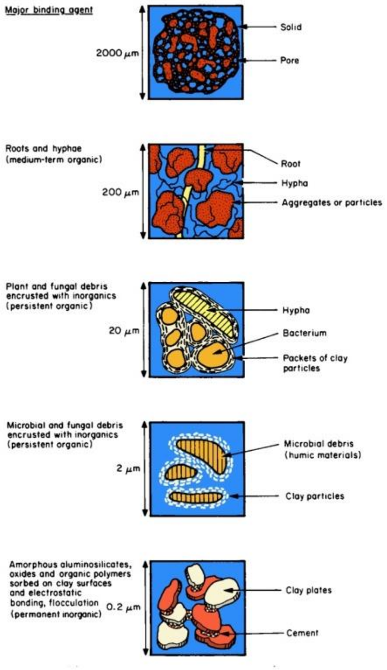
SOM is:

- Biopolymers released during decay of plant and microbial residue
- Plant and microbial carbohydrates, proteins, lipids, lignins, etc.
  - stabilized by adsorption to surfaces of soil minerals
  - stabilized by protection within soil aggregates
  - soil matrix slows reactions



Tisdale and Oades (1982)

What is SOM in mineral soils?

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  - 40- 100% of total soil organic matter
- Chemistries of these biopolymers and their degradation products are well understood

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Physically-stabilized SOM

What is SOM in mineral soils?

SOM is:

- Humic substances formed abiotically from the products of microbial decay (0 – 50%)
  - Brown - black coloured, spongy amorphous material
  - High molecular weight (1000 Da)
  - Chemically-complex
  - 1000s yr mean residence time

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Chemically-stabilized SOM

Roth C model

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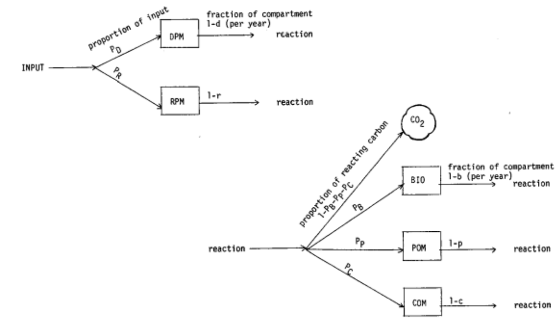

FIG. 6. Flow of C through model from unitary input of plant C into the 0–23 cm layer of soil.

Pool	Proportion of total %	Decay rate yr^{-1}	$T_{1/2}$ yr
Microbial biomass	1.1	0.41	1.69
Physical stab.	47.5	0.014	49.5
Chemical stab.	51.3	0.00035	1980

(Jenkinson and Rayner, 1977)

Past management in southern Ontario

- Forest clearing and cropping effects
  - Land cleared in mid-1800s and planted to pastures, for dairy, and for cereal production
  - Soil organic matter levels not an important concern

Why don’t we hear more about SOM levels in southern Ontario

- Effects of losses of SOM are not as dramatic as those resulting in prairie dust storms

  (There were dust storms during the ’30s on the tobacco sands)

- Southern Ontario has a favourable climate for crop production

Long-term studies of tillage and cropping effects on crop residue decay and SOC turnover

- Changes in soil organic matter levels
  - SOM is relatively large pool
  - Difficult to detect changes due to soil variability
  - Changes in SOM distribution in profile
  - Changes in soil bulk density

Long-term studies of tillage and cropping effects on crop residue decay and SOC turnover

- **Changes in soil organic matter levels**
  - **SOM is relatively large pool**
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  - **Changes in soil bulk density**

- **Measure total N instead!**

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- **Delta ^{13}C studies (switch from C_3 crop to C_4 crop)**
  - **Delta $^{13}C/^{12}C$ of C_3 = -26; C_4 = -12**

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- **^{14}C enrichment studies**

Long-term tillage and cropping experiment at Delhi, Ontario set out in 1990

^{14}C-labelled crop residues were prepared *in situ* by applying repeated pulses of ^{14}C-CO_2 to the plants 12 times over the growing season

Hypothesis #1: *'Tillage fuels the fires of decay'*

alters:

- decay rate of crop residues
- proportion of residue becoming stabilized SOM
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Different mechanisms controlling each process

Hypothesis #2: ***Conservation tillage 'per se' increases SOM levels***

Good reasons to adopt conservation tillage methods:

- erosion control
- conservation of soil moisture
- less fuel consumption
- timeliness of farming operations

Total SOC at Delhi, ON under continuous corn cropping after 6 yr of no-tillage (g m^{-2})

Soil depth (cm)	Tobacco/ rye	Corn CT	Corn NT	Forest
0 - 5	456	427	465	2083
5 - 10	427	402	382	420
10 - 15	405	420	378	244
15 - 30	633	778	681	524
30 - 50	402	310	305	397
Total	2324	2338	2211	3668

38% decline

Total SOC at Elora, ON under continuous corn cropping after 29 yr of minimal-tillage (g m^{-2})

Soil depth (cm)	CT	MT	Forest
0 - 5	1224	1347	2784
5 - 10	1251	1385	1982
10 - 15	1245	1469	1921
15 - 30	2366	2159	3798
30 - 50	1131	806	2698
Total	7217	7167	13184

45% decline

Forest conversion to cropland

Table 3. Meta-analysis of the effect of forest (control) conversion to long-term cropland (treatment) on the mean change in soil organic C in the 0- to 30-cm or 0- to 40-cm depth at 17 sites in Ontario

	Mean change in soil organic C[z]	
Site	Net (Mg ha^{-1}) ($n=27$)	Relative (%) ($n=28$)
Bond Head[y]	−22.0*ab*	−24.3*abcd*
C Blondeau	−27.7*abc*	−20.3*abc*
Delhi	−30.4*abc*	−55.3*cd*
Edwards	−91.1*c*	−68.2*d*
Elora	−42.6*abc*	−40.7*bcd*
Exeter	−36.1*abc*	−37.9*abcd*
Fonthill	−18.7*ab*	−23.5*abcd*
Highgate	−15.1*ab*	−7.7*ab*
Kapuskasking	−3.30*ab*	−4.2*ab*
Kemptville	−24.9*ab*	−30.5*abcd*
Ottawa	−8.10*a*	−3.0*a*
Panmure	−20.0*ab*	−23.6*abcd*
Plainfield	−42.4*abc*	−40.3*bcd*
Ste. Anne	−37.0*abc*	−34.2*abcd*
Vineland	−16.4*ab*	−29.0*abcd*
Winchester	−43.8*abc*	−34.8*bcd*
Woodslee	−45.1*bc*	−30.6*bc*
Mean	−32.7	−27.6
95% confidence interval	−41.5 to −24.0	−34.4 to −20.8
Standard error	4.46	3.46

Congreves et al., 2014

Tillage vs no-tillage

Table 4. Meta-analysis of the effect of tillage (treatment) compared to no-tillage (control) on the mean change of soil organic C in three soil depths in Ontario

	Soil depth (cm)								
	0–10 (n = 23)			0–20 (n = 23)			0–45 (n = 62)		
	Mean change in soil organic C[z]								
Site	Net (Mg C ha^{-1})	Relative (%)	Rate (g C m^{-2} yr^{-1})	Net (Mg C ha^{-1})	Relative (%)	Rate (g C m^{-2} yr^{-1})	Net (Mg C ha^{-1})	Relative (%)	Rate (g C m^{-2} yr^{-1})
Clinton[y]	−6.8*a*	−14*ab*	−34*ab*	−11*a*	−9.9*b*	−55*ab*	−13*b*	−8.2*bc*	−68*bc*
Dresden							−1.3*ab*	−5.2 *abc*	−8.8*abc*
Elora	−1.2*a*	−4.5*a*	−6.0*a*	1.8*a*	4.7*a*	5.1*a*	4.6*a*	6.5*ab*	18*a*
Paris							0.30*a*	−3.0*bc*[x]	2.0*ab*
Ridgetown	−7.4*a*	−22*b*	−49*b*	−10*a*	−16*b*	−67*b*	−16*b*	−15*c*	−104*c*
Strathroy							7.8*a*	16*a*	52*a*
Thorndale							4.9*a*	1.8*abc*	32*a*
Woodslee	−6.9*a*	−20*ab*	−43*ab*	−3.4*a*	−5.7*ab*	−21*ab*	−4.3*ab*	−6.9*abc*	−28*abc*
Mean	−5.5	−15	−33	−6.5	−8.0	−41	−1.2	−0.83	−6.9
95% Confidence Interval	−8.0 to −3.1	−19 to −10	−47 to −19	−11 to −1.8	−13 to −2.7	−66 to −15	−4.8 to 2.5	−5.7 to 4.1	−29 to 15
Standard error	1.23	2.4	7.1	2.43	2.69	13.2	1.85	2.51	11.17

[z]Negative values indicate lower soil organic C with tillage compared with no-till.
[y]Publications include: Gregorich et al. (1996), Wanniarachchi et al. (1999) Yang and Kay (2001b), Gregorich et al. (2001), VandenBygaart et al. (2010), Deen and Kataki (2003), VandenBygaart and Kay (2004), Yang et al. (2008), Shi et al. (2011) and Van Eerd et al. (2014).
[x]An outlier was detected within the Paris data for soil organic C relative change (%) based on Lund's test and was not discarded (the presence of the outlier explains the incongruence in sign among integers for the 0–45 cm data at Paris).
a–c In each column, means followed by different letters indicate a significant difference among sites with a LSD test at $P < 0.05$.

Congreves et al., 2014

Rotational cropping vs continuous corn

Table 5. Meta-analysis of the effect rotational cropping (treatment) compared to continuous corn (control) on the mean change of soil organic C in three soil depths in Ontario

	Soil depth (cm)								
	0–10 ($n=15$)			0–20 ($n=15$)			0–45 ($n=20$)		
	Mean change in soil organic C[z]								
Site	Net ($Mg\ C\ ha^{-1}$)	Relative (%)	Rate ($g\ C\ m^{-2}\ yr^{-1}$)	Net ($Mg\ C\ ha^{-1}$)	Relative (%)	Rate ($g\ C\ m^{-2}\ yr^{-1}$)	Net ($Mg\ C\ ha^{-1}$)	Relative (%)	Rate ($g\ C\ m^{-2}\ yr^{-1}$)
Elora[y]	0.60*a*	2.0*a*	3.0*a*	1.4*a*	2.4*a*	6.9*a*	2.3*b*	2.9*b*	11*a*
Ridgetown	0.42*a*	2.9*a*	2.8*a*	0.63*a*	2.3*a*	4.2*a*	−1.0*b*	0.78*b*	−6.9*a*
Woodslee	2.5*a*	11*a*	7.0*a*	2.9*a*	5.6*a*	8.3*a*	19*a*	23*a*	55*a*
Mean	0.75	3.6	3.5	0.95	2.4	5.0	2.7	4.1	8.5
95% Confidence Interval	−0.61 to 2.1	−1.1 to 8.4	−4.8 to 12	−1.5 to 3.4	−2.1 to 6.8	−10 to 20	−1.8 to 7.1	−1.0 to 9.1	−16 to 33
Standard error	0.697	2.41	4.24	1.246	2.27	7.78	2.28	2.58	12.53

[z]Positive values indicate a higher soil organic C with rotating crops compared to continuous corn.
[y]Publications include: Gregorich et al. 2001; Yang and Kay (2001a); Meyer-Aurich et al. 2006; Van Eerd et al. (2014).
a–b For each column, means followed by different letters indicate a significant difference among sites with a LSD test at $P < 0.05$.

Congreves et al., 2014

Crop inputs* (Mg C ha^{-1}) at Delhi, ON

Crop	Above-ground residues	Roots	Extra-root (soil)	Total annual C input
Corn	2.78	1.50	0.20	4.48
Winter wheat	1.47	1.06	0.37	2.90
Soybeans	1.60	1.45	0.29	3.34
Winter rye	1.63	1.33	0.44	3.40
Tobacco	0.68	0.87	0.12	1.67

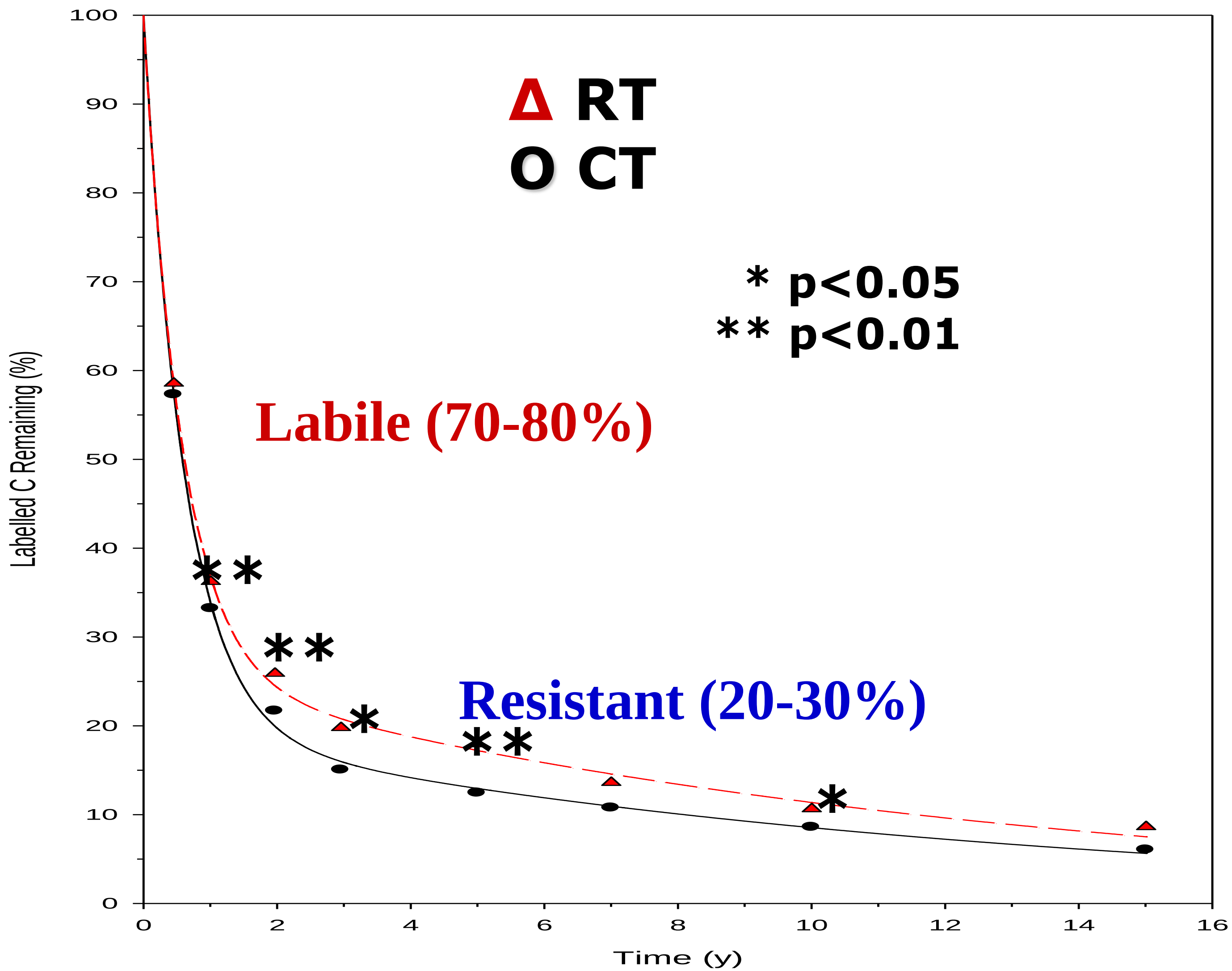
***Estimated from the distribution of assimilated $^{14}C-CO_2$ at harvest**

Decay of ^{14}C-labelled above- and -below ground crop residues during the first 3 yr at Delhi, ON

Location	Labile	Corn	Soy bean	Winter wheat	Fall rye	Tobacco	Mean
Above-ground	%	72	77	75	77	72	75
	T½ (yr)	0.48	0.39	0.36	0.36	0.55	0.43
Below-ground	%	73	65	71	73	66	70
	T½ (yr)	0.52	0.34	0.53	0.52	0.50	0.48

Below-ground labile-C: 7% smaller; decay rate 12% slower

^{14}C-labelled stover decomposition during 15 yr of continuous corn cropping



Decay of the labile component of above-ground crop residues

Tillage	Labile	Corn	Soy beans	Winter wheat	Fall Rye	Tobacco	Mean
CT	%	84	82	81	80	79	81
	T½ (yr)	0.49	0.20	0.43	0.48	0.45	0.41
RT	%	75	75	70	70	71	72
	T½ (yr)	0.52	0.30	0.57	0.64	0.64	0.53

Under RT: labile-C 11% smaller; decay rate 29% slower

Decay of the resistant component of above-ground crop residues

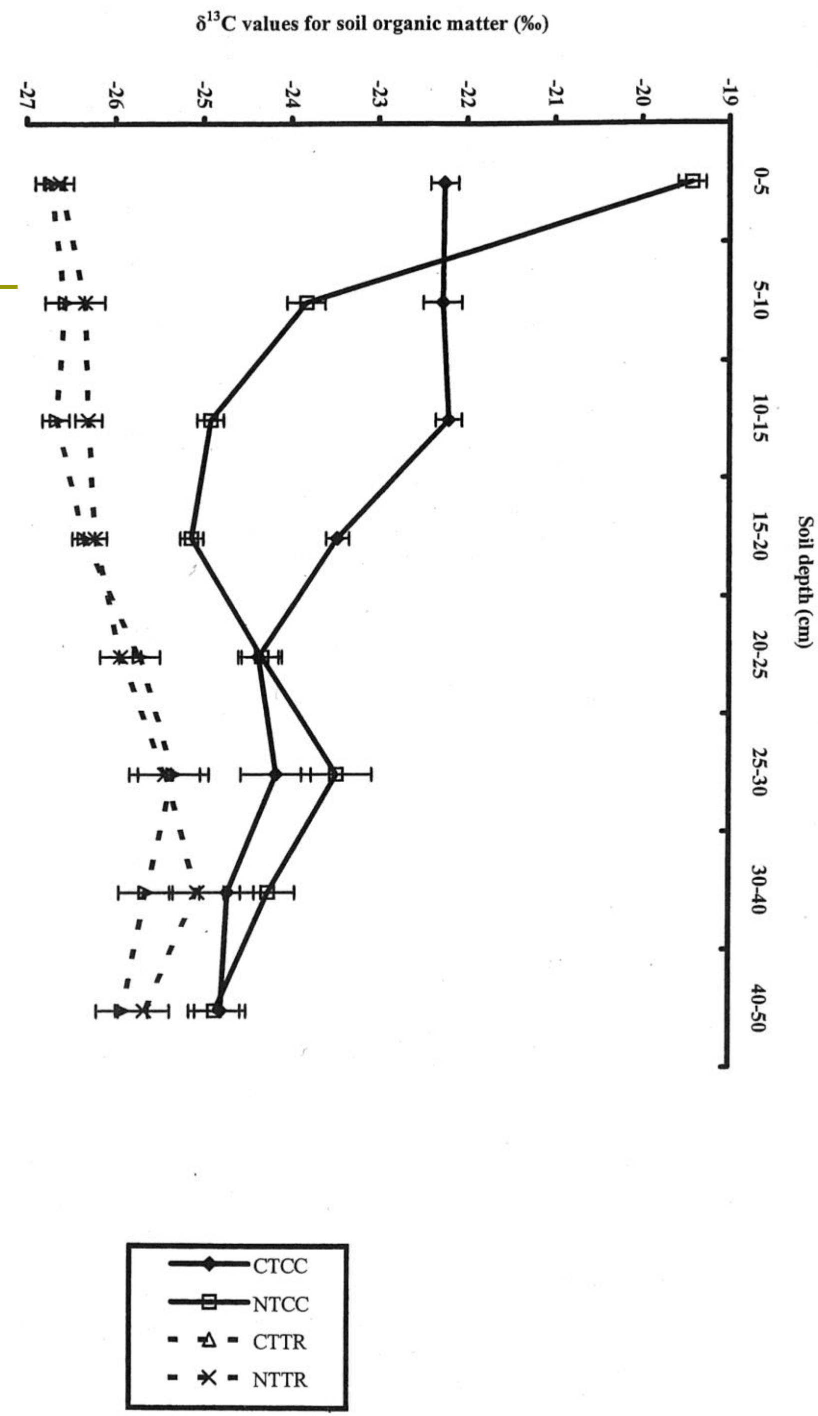
Tillage	Resistant	Corn	Soy beans	Winter wheat	Fall Rye	Tobacco	Mean
CT	%	16	18	19	20	21	19
	T½ (yr)	10.3	8.7	9.4	7.7	8.6	8.9
RT	%	25	25	30	30	29	28
	T½ (yr)	9.0	7.2	7.7	6.7	7.1	7.5

Under RT: resistant-C 47% larger; decay rate 16% faster

Changes in SOC content (0-50 cm) at Delhi, ON after 15 yr due to changes in crop C inputs

	Tobacco /w. rye	Soybeans/ w. wheat	Cont. corn
Annual crop residue inputs (Mg C ha^{-1})	2.54	3.12	4.48
Soil organic C	29.68	31.13	33.22
C input/SOC	0.08	0.10	0.13

Soil profile $\delta^{13}C$ of SOM after 11 yr continuous corn following tobacco/rye under CT and NT



Corn-derived C in SOC (g m^{-2}) at Delhi, ON after 11 yr continuous corn cropping

Soil depth (cm)	CT	NT
0 – 5	162	361*
5 – 10	156 *	80
10 – 15	163 *	41
15 – 20	95 *	29
20 – 30	40	51
30 – 50	30	22
Total	646	585

Tillage effect on the decay rates of C_3-derived C in SOC after 11 yr corn cropping

	CT	NT
A_0 (Mg ha^{-1})	19.8	
A_{11} (Mg ha^{-1})	15.2	15.0
k (yr^{-1})	0.024	0.025
T½ (yr)	28.6	27.8

Corn-derived C in SOC (Mg ha^{-1}) at Elora after 29 yr continuous corn cropping

Soil depth (cm)	CT	MT
0 – 5	3.2	4.4*
5 – 10	3.3	3.9*
10 – 15	3.3	3.5
15 – 30	6.0*	4.4
30 – 50	3.0	1.6
Total	18.9	17.8

Relic C_3-derived C in SOC (Mg ha^{-1}) at Elora, ON after 29 yr continuous corn cropping

Soil depth (cm)	CT	MT
0 – 5	9.0	9.1
5 – 10	9.2	9.9
10 – 15	9.2	11.2
15 – 30	17.6	17.2
30 – 50	8.4	6.5
Total	53.3	53.9

Organic C and N content of whole soil and light fraction (LF) after 6 yr at Elora, ON

Ramnarine et al. 2015

Element and soil depth	Conventional tillage	No-tillage	LSD†	*P* value‡
cm	—— C or N (g m^{-2} soil) ——			
0–10				
C	2838 (138)§	3134 (60)	301	0.054
N	227 (11)	247 (5)	24	0.099
0–20				
C	5626 (252)	5736 (68)	521	0.673
N	451 (20)	456 (5)	41	0.818
0–30				
C	7544 (297)	7526 (79)	615	0.954
N	613 (23)	606 (7)	48	0.770
	—— LFC or N (g m^{-2} soil) ——			
0–10				
C	138.8 (4.6)	193.4 (5.6)	14.4	<0.001
N	7.7 (0.3)	9.6 (0.4)	1.0	<0.001
10–20				
C	132.1 (4.2)	146.1 (6.6)	5.6	0.079
N	6.9 (0.2)	7.3 (0.4)	0.8	0.451
20–30				
C	83.3 (2.8)	89.2 (4.3)	10.4	0.264
N	4.2 (0.2)	4.1 (0.2)	0.6	0.815
0–30				
C	354.3 (8.9)	428.7 (11.0)	28.4	<0.001
N	18.8 (0.5)	21.0 (0.7)	1.7	0.014

C/N ~20

Conclusions

- **Conservation tillage reduces the size and slows the decay rate of the labile component of crop residues**
  - % labile and half-life

    CT = ~81% $T_{1/2}$ = 0.41 yr

    RT = ~72% $T_{1/2}$ = 0.53 yr

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- Conservation tillage reduces the size and slowa the decay rate of the labile component of crop residues
  - % labile and half-life

    CT = ~81% T½ = 0.41 yr

    RT = ~72% T½ = 0.53 yr
- **Conservation tillage increases the size of the resistant component derived from crop residues but its decay rate is faster**
  - % resistant and half-life

    CT = ~19% T½ = 8.9 yr

    RT = ~28% T½ = 7.5 yr

Conclusions

- **Proportion of crop residues becoming stabilized in soil, 5-8% of added, is significantly affected by annual crop type**

  corn ~50-60% less than SBWW=TWR

How much crop residue can be removed for bio-products or biochar?

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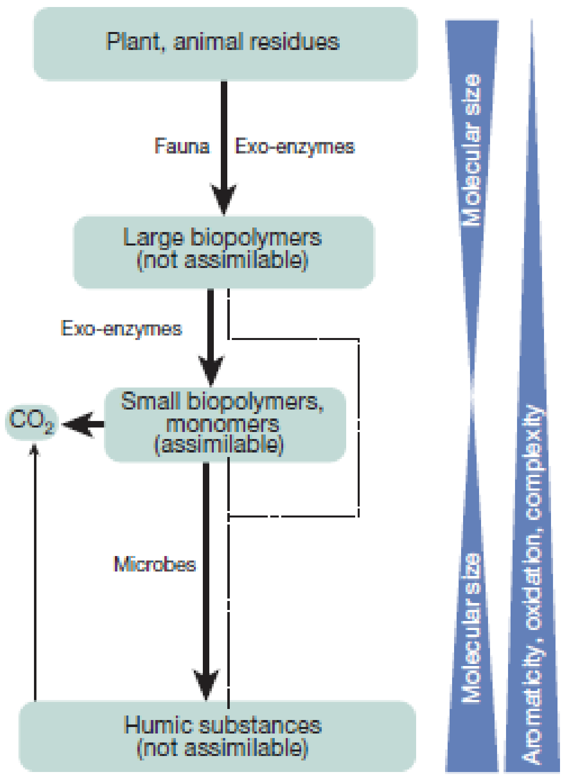
- **None!**

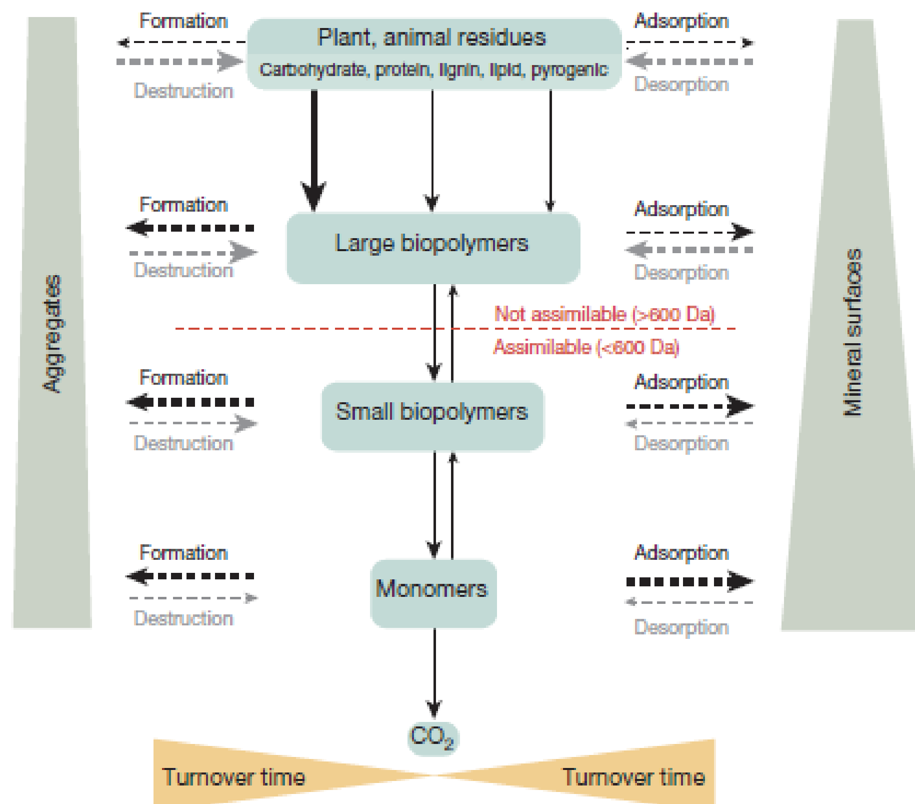
Acknowledgements:
Julien Winter
Ron Beyaert
Sudas Wanniarrachchi
Evah Murage
Ravindra Ramnarine

Thank you for your attention

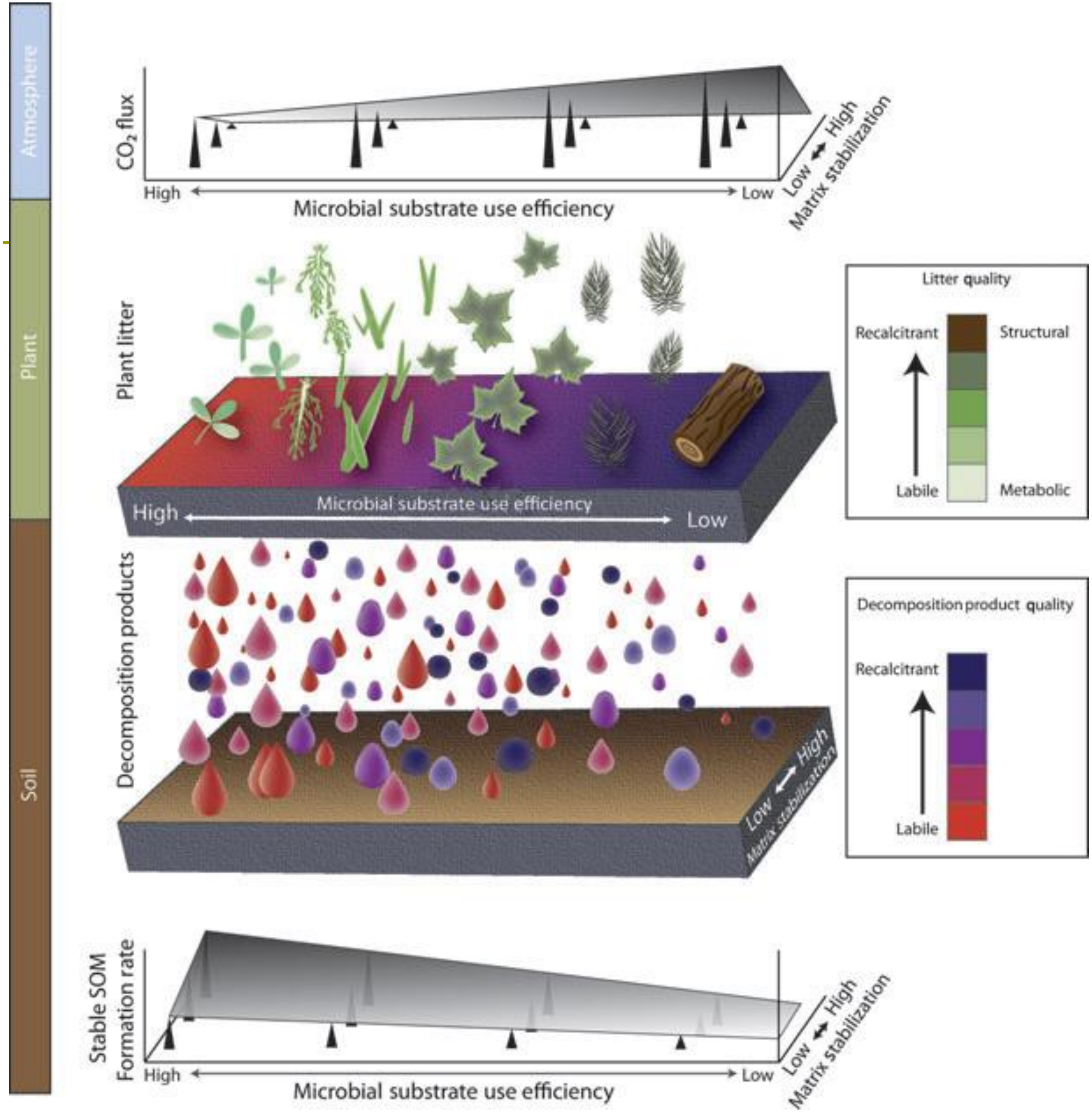
Humification

Emerging view





Microbial Efficiency-Matrix Stabilization (MEMS) framework



Cotrufo et al. (2013). Global Change Biology 19(4):988-995.