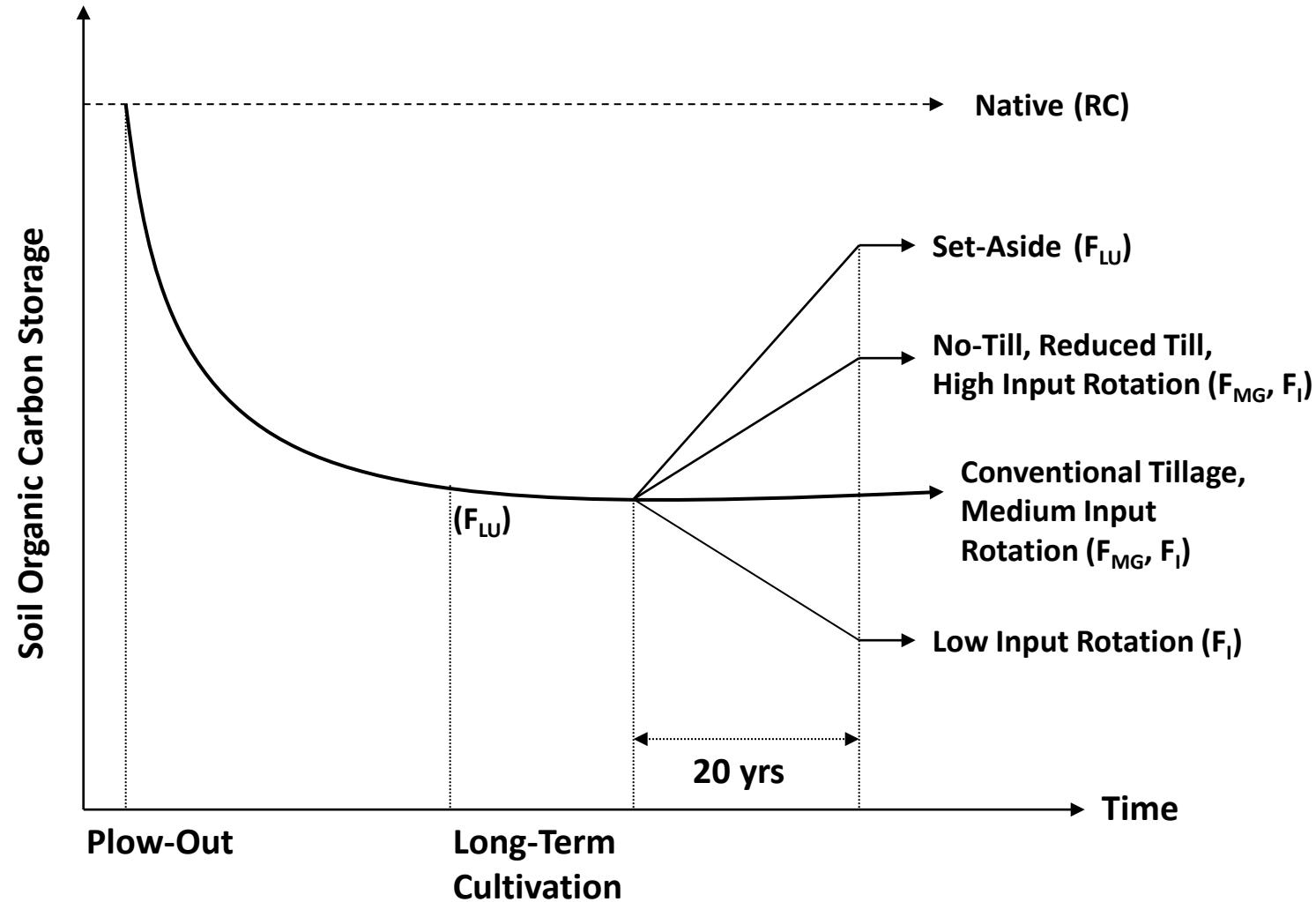


IPCC 2019 Refinement: Tier 2 Steady State Soil Carbon Method

Stephen M. Ogle, Ph.D.
Department of Ecosystem Science and Sustainability
Natural Resource Ecology Laboratory
Colorado State University

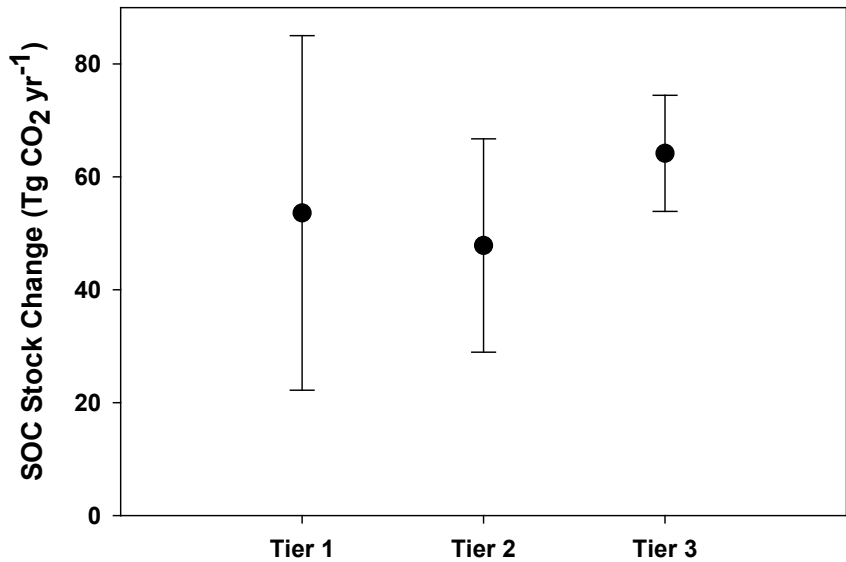


IPCC Tier 1 Method for Mineral Soil Carbon



Ogle, S.M., F.J. Breidt and K. Paustian. 2005. Agricultural Management Impacts on Soil Organic Carbon Storage under Moist and Dry Climatic Conditions of Temperate and Tropical Regions. *Biogeochemistry* 72:87-121.

IPCC Tier 1 Method for Mineral Soil Carbon



IPCC 2006 GL, IPCC 2019 Refinement

EQUATION 2.25 ANNUAL CHANGE IN ORGANIC CARBON STOCKS IN MINERAL SOILS

$$\Delta C_{\text{Mineral}} = \frac{(SOC_0 - SOC_{(0-T)})}{D}$$

$$SOC = \sum_{c,s,i} (SOC_{\text{REF},c,s,i} \cdot F_{\text{LU},c,s,i} \cdot F_{\text{MG},c,s,i} \cdot F_{\text{I},c,s,i} \cdot A_{c,s,i})$$

(Note: T is used in place of D in this equation if T is ≥ 20 years, see note below)

Where:

$\Delta C_{\text{Mineral}}$ = annual change in carbon stocks in mineral soils, tonnes C yr⁻¹

SOC_0 = soil organic carbon stock in the last year of an inventory time period, tonnes C

$SOC_{(0-T)}$ = soil organic carbon stock at the beginning of the inventory time period, tonnes C

SOC_0 and $SOC_{(0-T)}$ are calculated using the SOC equation in the box where the reference carbon stocks and stock change factors are assigned according to the land-use and management activities and corresponding areas at each of the points in time (time = 0 and time = 0-T)

T = number of years over a single inventory time period, yr

D = Time dependence of stock change factors which is the default time period for transition between equilibrium SOC values, yr. Commonly 20 years, but depends on assumptions made in computing the factors F_{LU} , F_{MG} and F_{I} . If T exceeds D, use the value for T to obtain an annual rate of change over the inventory time period (0-T years).

c = represents the climate zones, s the soil types, and i the set of management systems that are present in a country.

SOC_{REF} = the reference carbon stock, tonnes C ha⁻¹ (Table 2.3)

F_{LU} = stock change factor for land-use systems or sub-system for a particular land-use, dimensionless

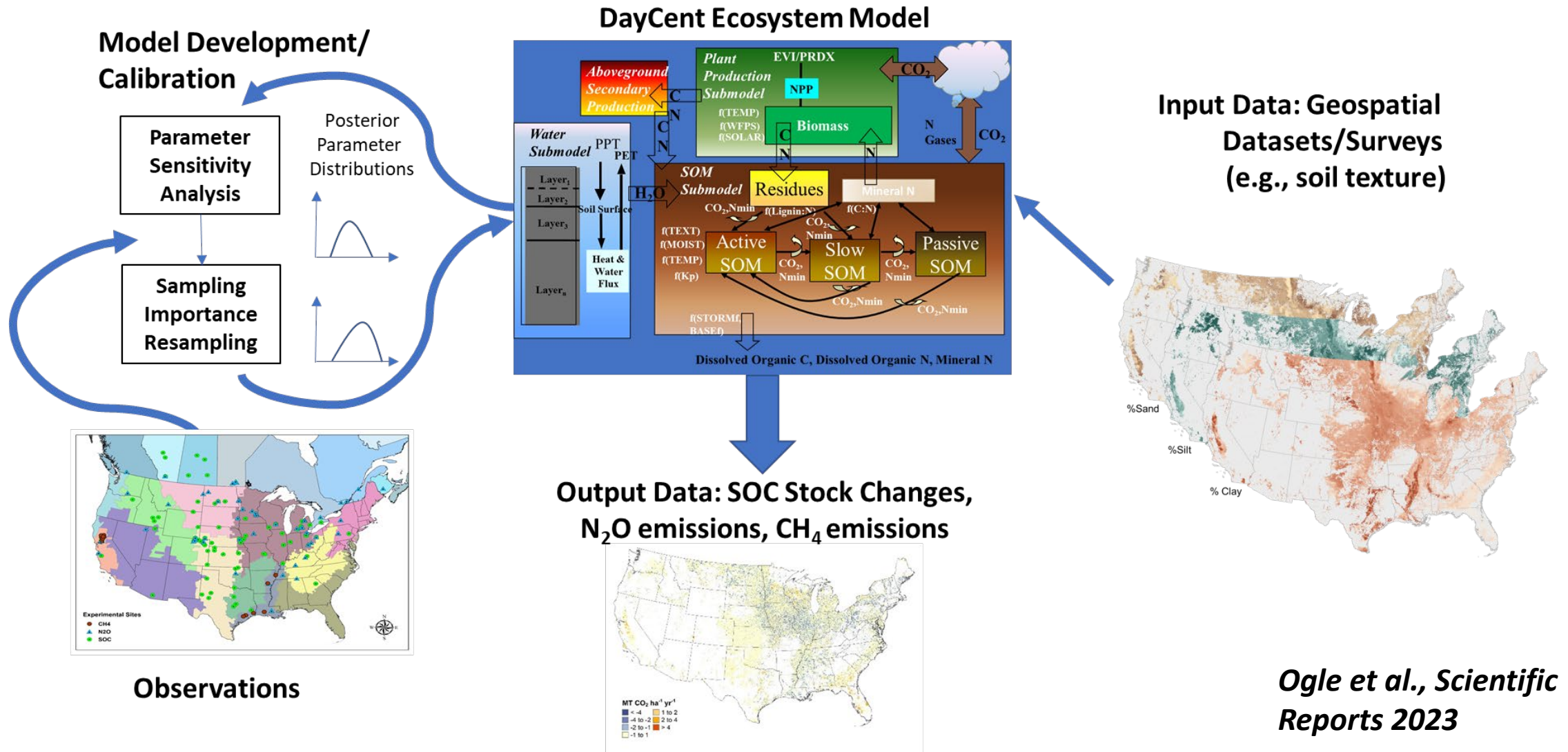
[Note: F_{ND} is substituted for F_{LU} in forest soil C calculation to estimate the influence of natural disturbance regimes.

F_{MG} = stock change factor for management regime, dimensionless

F_{I} = stock change factor for input of organic matter, dimensionless

A = land area of the stratum being estimated, ha. All land in the stratum should have common biophysical conditions (i.e., climate and soil type) and management history over the inventory time period to be treated together for analytical purposes.

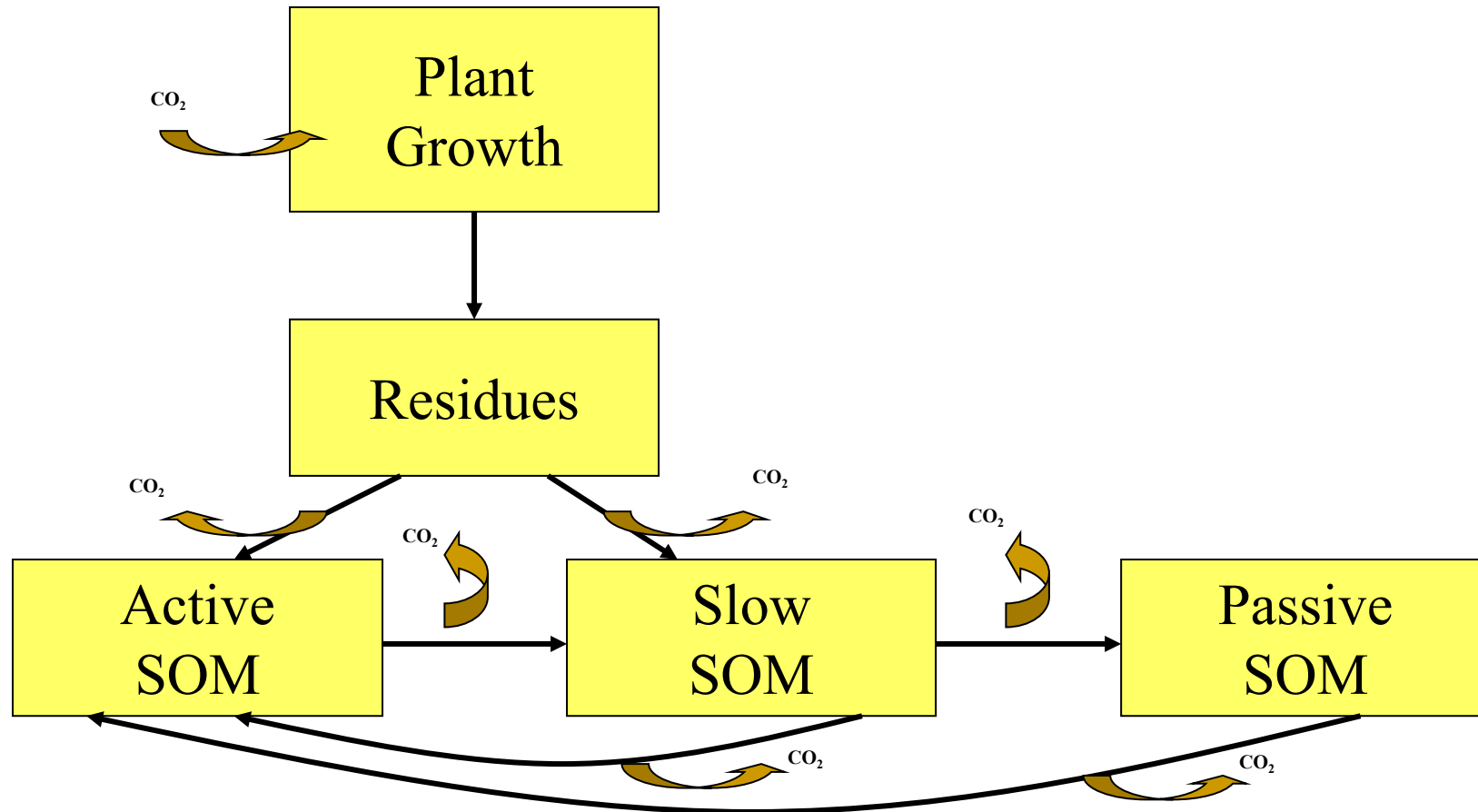
Tier 3 DayCent Ecosystem Modeling Platform



Roadmap for Presentation

- **Steady State Model Background**
- **Model Structure**
- **Model Calibration, Inputs, and Outputs**
- **Advantages and Disadvantages**

Century Ecosystem Model



Parton, W.J., Schimel, D.S., Cole, C.V., Ojima, D.S., 1987. Analysis of factors controlling soil organic matter dynamics in an agroecosystem. Soil Science Society of America Journal 51, 1173–1179.

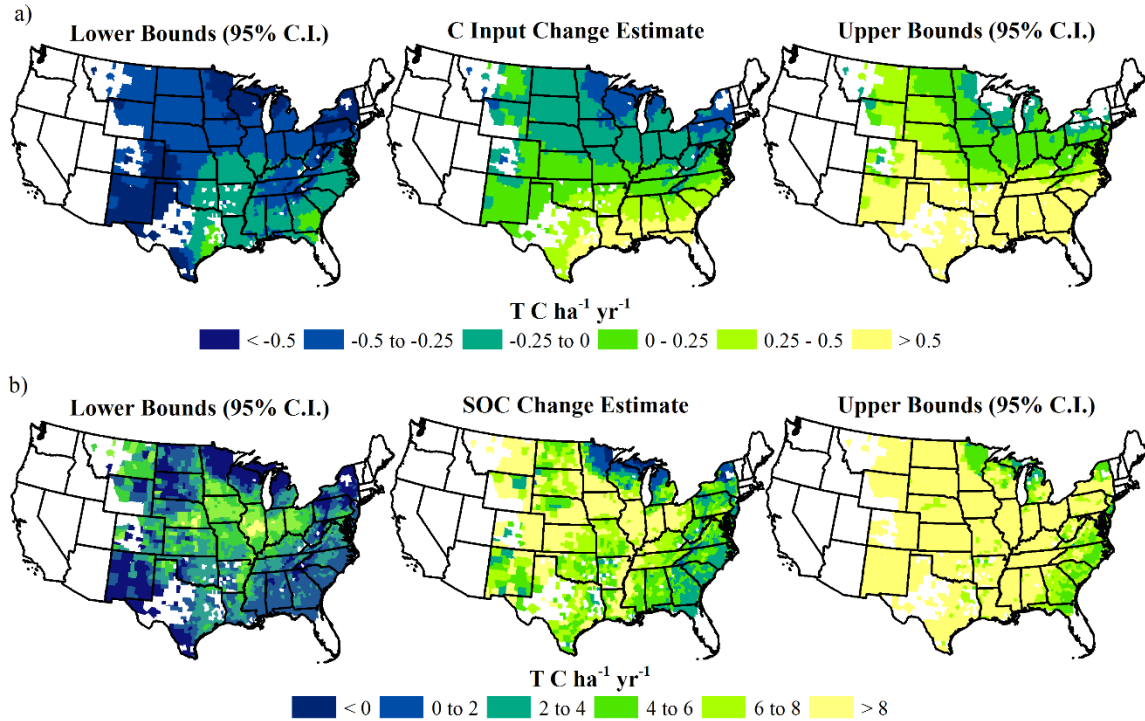
Steady State Solution

$$X_{\text{tot}}^* = I \left\{ \frac{\beta}{k_1} + \frac{(1-\beta)}{k_2} \left[\frac{1}{k_3} + \frac{f_4}{k_4} + \frac{f_5 + f_4 f_6}{k_5} \right] \alpha + \left[\frac{1}{k_4} + \frac{f_6}{k_5} \right] f_3 \lambda (1-\beta) \right\}$$

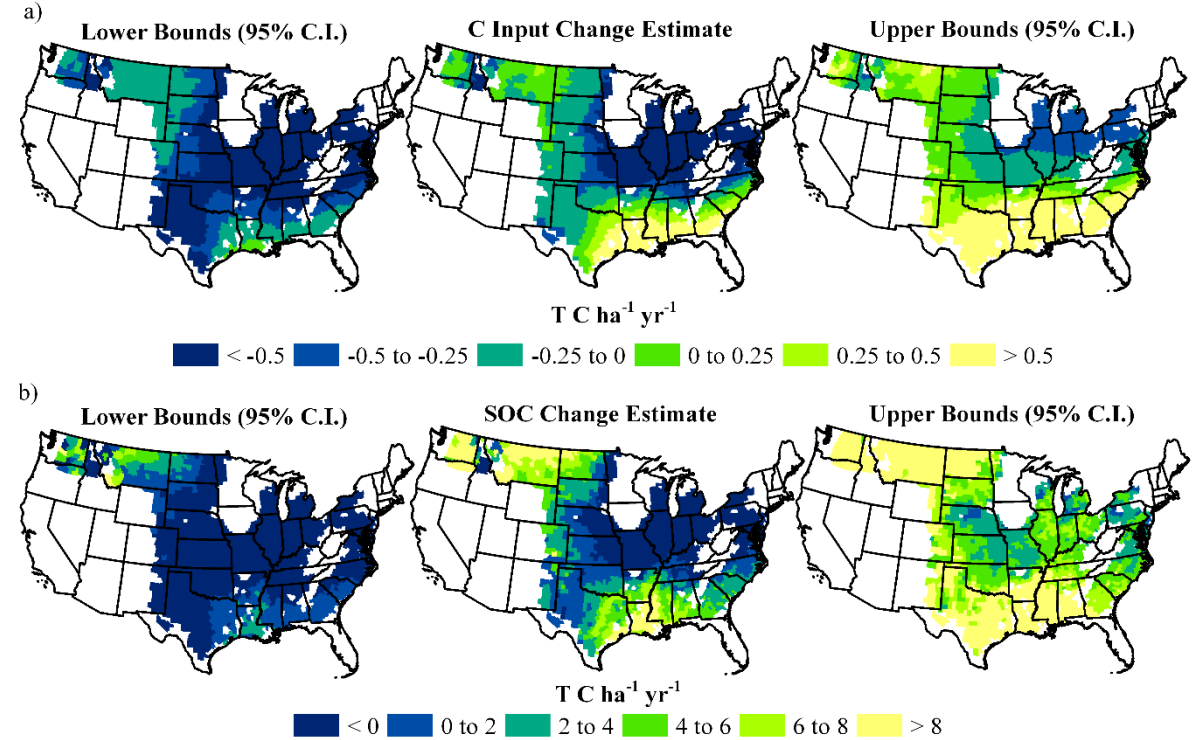
$$\alpha = \frac{f_1 \beta + [f_2(1-\lambda) + f_3 \lambda (f_7 + f_6 f_8)](1-\beta)}{(1 - f_4 f_7 - f_5 f_8 - f_4 f_6 f_8)}$$

Paustian et al., 1997, Modeling litter quality effects on decomposition and soil organic matter dynamics. In: Cadisch, G., Giller, K.E. (Eds.), Driven by Nature: Plant Litter Quality and Decomposition. CAB International, UK, pp. 316–336.

Corn

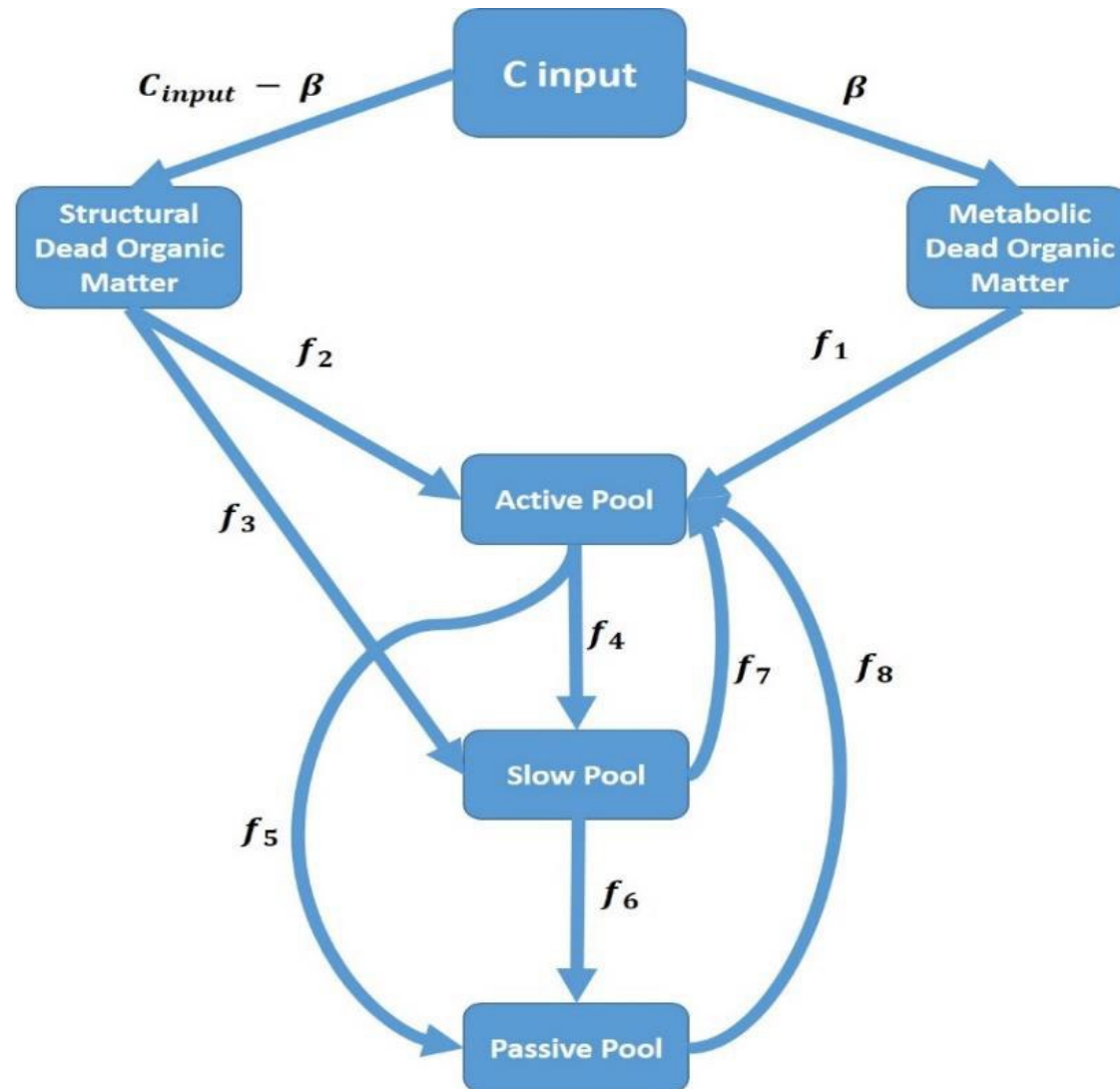


Wheat



Ogle, S.M., A. Swan and K. Paustian. 2012. No-till management impacts on crop productivity, carbon input and soil carbon sequestration. *Agriculture, Ecosystems and Environment* 149:37-49.

Steady State Model

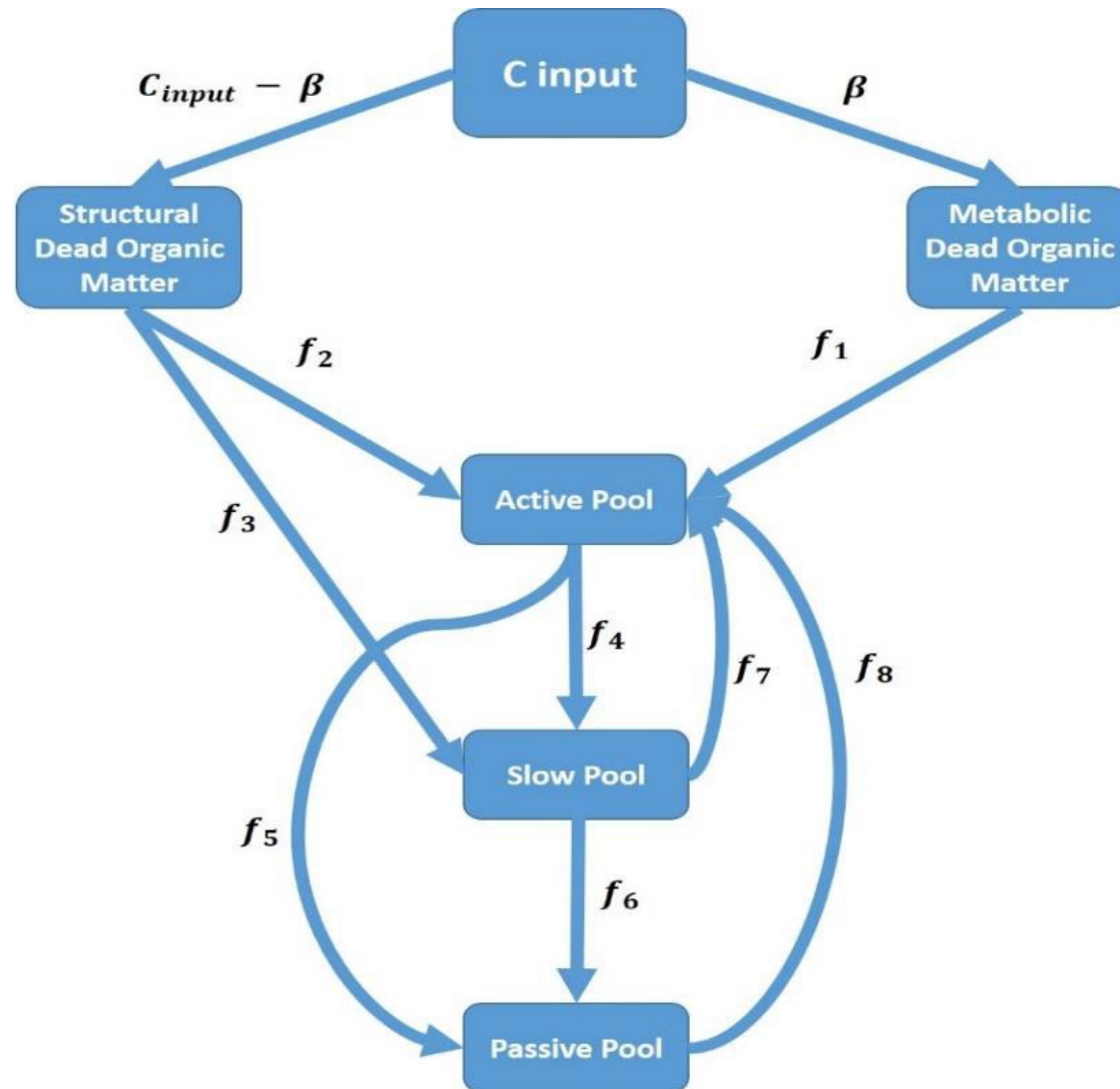


IPCC 2019 Refinement

Roadmap for Presentation

- **Steady State Model Background**
- **Model Structure**
- **Model Calibration, Inputs, and Outputs**
- **Advantages and Disadvantages**

Steady State Model



IPCC 2019 Refinement

Change in SOC Stock

EQUATION 5.0A (NEW)

ANNUAL CHANGE IN SOIL C STOCK FOR MINERAL SOILS USING THE STEADY STATE METHOD

$$\Delta C_{Mineral} = \sum_i F_{SOC_i} \cdot A_i$$

$$F_{SOC_i} = SOC_{yi} - SOC_{(y-1)i}$$

$$SOC_{yi} = ACTIVE_{yi} + SLOW_{yi} + PASSIVE_{yi}$$

IPCC 2019 Refinement

Active SOC Pool

EQUATION 5.0B (NEW)

ACTIVE SUB-POOL SOIL C STOCK FOR MINERAL SOILS USING THE STEADY-STATE METHOD

$$ACTIVE_y = ACTIVE_{y-1} + (ACTIVE_{y^*} - ACTIVE_{y-1}) \cdot 1yr \cdot k_a$$

$$ACTIVE_{y^*} = \frac{\alpha}{k_a}$$

$$k_a = k_{fac_a} \cdot t_{fac} \cdot w_{fac} \cdot (0.25 + (0.75 \cdot sand)) \cdot till_{fac}$$

Where:

$ACTIVE_y$ = active sub-pool SOC stock in year y, tonnes C ha⁻¹

$ACTIVE_{y-1}$ = active sub-pool SOC stock in previous year, tonnes C ha⁻¹

$ACTIVE_{y^*}$ = steady state active sub-pool SOC stock given conditions in year y, tonnes C ha⁻¹

k_a = decay rate for active SOC sub-pool, year⁻¹

α = C input to the active SOC sub-pool, tonnes C ha⁻¹ year⁻¹ (see Equation 5.0g)

k_{fac_a} = decay rate constant under optimal conditions for decomposition of the active SOC sub-pool, year⁻¹ (see Table 5.5a)

t_{fac} = temperature effect on decomposition, dimensionless (see Equation 5.0e)

w_{fac} = water effect on decomposition, dimensionless (see Equation 5.0f)

$till_{fac}$ = tillage disturbance modifier on decay rate for active and slow sub-pools, dimensionless (see Table 5.5a)

$sand$ = fraction of 0-30 cm soil mass that is sand (0.050 – 2mm particles), dimensionless

IPCC 2019 Refinement

Slow SOC Pool

EQUATION 5.0C (NEW)
SLOW SUB-POOL SOIL C STOCK FOR MINERAL SOILS USING THE STEADY-STATE METHOD

$$SLOW_y = SLOW_{y-1} + (SLOW_{y^*} - SLOW_{y-1}) \cdot 1yr \cdot k_s$$

$$SLOW_{y^*} = \frac{[(C_{input} \cdot LC) \cdot f_3] + [(ACTIVE_{y^*} \cdot k_a) \cdot f_4]}{k_s}$$

$$k_s = k_{fac_s} \cdot t_{fac} \cdot w_{fac} \cdot till_{fac}$$

$$f_4 = 1 - f_5 - (0.17 + 0.68 \cdot sand)$$

Where:

$SLOW_y$ = slow sub-pool SOC stock in y, tonnes C ha⁻¹

$SLOW_{y-1}$ = slow sub-pool SOC stock in previous year, tonnes C ha⁻¹

$SLOW_{y^*}$ = steady state slow sub-pool SOC stock given conditions in year y, tonnes C ha⁻¹

k_s = decay rate for slow SOC sub-pool, year⁻¹

C_{input} = total carbon input, tonnes C ha⁻¹ year⁻¹

LC = lignin content of carbon input, proportion (see Table 5.5b and 5.5c) for default values, otherwise compile country-specific values)

$ACTIVE_{y^*}$ = steady state active sub-pool SOC stock given conditions in year y, tonnes C ha⁻¹

k_a = decay rate for active carbon sub-pool in the soil, year⁻¹

k_{fac_s} = decay rate constant under optimal condition for decomposition of the slow carbon sub-pool, year⁻¹ (see Table 5.5a)

t_{fac} = temperature effect on decomposition, dimensionless (see Equation 5.0e)

w_{fac} = water effect on decomposition, dimensionless (see Equation 5.0f)

$till_{fac}$ = tillage disturbance modifier on decay rate for active and slow sub-pools, dimensionless (see Table 5.5a)

f_3 = fraction of structural component decay products transferred to the slow sub-pool, proportion (see Table 5.5a)

f_4 = fraction of active sub-pool decay products transferred to the slow sub-pool, proportion (see Equation 5.0c)

f_5 = fraction of active sub-pool decay products transferred to the passive sub-pool, proportion (see Table 5.5a)

$sand$ = fraction of 0-30 cm soil mass that is sand (0.050 – 2mm particles), proportion

IPCC 2019 Refinement

Passive SOC Pool

EQUATION 5.0D (NEW)
 PASSIVE SUB-POOL SOIL C STOCK FOR MINERAL SOILS USING THE STEADY-STATE METHOD

$$PASSIVE_y = PASSIVE_{y-1} + (PASSIVE_y^* - PASSIVE_{y-1}) \cdot 1yr \cdot k_p$$

$$PASSIVE_y^* = \frac{[(ACTIVE_y^* \cdot k_a) \cdot f_5] + [(SLOW_y^* \cdot k_s) \cdot f_6]}{k_p}$$

$$k_p = k_{fac_p} \cdot t_{fac} \cdot w_{fac}$$

Where:

$PASSIVE_y$ = passive sub-pool SOC stock in year y, tonnes C ha⁻¹

$PASSIVE_{y-1}$ = passive sub-pool SOC stock in previous year, tonnes C ha⁻¹

$PASSIVE_y^*$ = steady state passive sub-pool SOC given conditions in year y, tonnes C ha⁻¹

k_p = decay rate for passive SOC sub-pool, year⁻¹

$ACTIVE_y^*$ = steady state active sub-pool SOC stock given conditions in year y, tonnes C ha⁻¹

k_a = decay rate for active carbon sub-pool, year⁻¹

$SLOW_y^*$ = steady state slow sub-pool SOC stock given conditions in year y, tonnes C ha⁻¹

k_s = decay rate for slow carbon sub-pool, year⁻¹

k_{fac_p} = decay rate constant under optimal conditions for decomposition of the slow carbon sub-pool, year⁻¹ (see Table 5.5a)

t_{fac} = temperature effect on decomposition, dimensionless (see Equation 5.0e)

w_{fac} = water effect on decomposition, dimensionless (see Equation 5.0f)

f_5 = fraction of active sub-pool decay products transferred to the slow sub-pool, proportion(see Table 5.5a)

f_6 = fraction of slow sub-pool decay products transferred to the passive sub-pool, proportion(see Table 5.5a)

IPCC 2019 Refinement

Temperature Effect on Decomposition

EQUATION 5.0E (NEW)
TEMPERATURE EFFECT ON DECOMPOSITION FOR MINERAL SOILS USING THE STEADY-STATE
METHOD

$$t_{fac} = \frac{1}{12} \sum_{i=1}^{12} T_i$$
$$T_i = \left(\frac{t_{max} - temp_i}{t_{max} - t_{opt}} \right)^{0.2} \bullet exp \left\{ 0.076 \bullet \left[1 - \left(\frac{t_{max} - temp_i}{t_{max} - t_{opt}} \right)^{2.63} \right] \right\}$$

Where:

- t_{fac} = annual average air temperature effect on decomposition, dimensionless
- T_i = monthly average air temperature effect on decomposition, dimensionless ($i = 1, 2, \dots, 12$)
- t_{max} = maximum monthly air temperature for decomposition, degrees C (see Table 5.5a)
- $temp_i$ = monthly average air temperature ($i = 1, 2, \dots, 12$), degrees C
- t_{opt} = optimum air temperature for decomposition, degrees C (see Table 5.5a)

IPCC 2019 Refinement

Moisture Effect on Decomposition

EQUATION 5.0F (NEW)
WATER EFFECT ON DECOMPOSITION FOR MINERAL SOILS USING THE STEADY-STATE METHOD

$$w_{fac} = 1.5 \cdot \left(\frac{1}{12} \sum_{i=1}^{12} w_i \right)$$

$$w_i = 0.2129 + (w_s \cdot mappet_i) - (0.2413 \cdot mappet_i^2)$$

$$mappet_i = \min \left(1.25, \frac{precip_i}{PET_i} \right)$$

Where:

- w_{fac} = annual water effect on decomposition, dimensionless
- w_i = monthly water effect on decomposition, dimensionless
- w_s = modifier for $mappet_i$, dimensionless (see Table 5.5a)
- $mappet_i$ = ratio of total precipitation to total potential evapotranspiration (dimensionless) for month i ($i = 1, 2, \dots, 12$)
- $precip_i$ = total precipitation for month i , mm
- PET_i = total potential evapotranspiration for month i , mm

IPCC 2019 Refinement

Carbon Input

EQUATION 5.0G (NEW)

C INPUT TO THE ACTIVE SOIL C SUB-POOL FOR MINERAL SOILS USING THE STEADY-STATE METHOD

$$\alpha = \frac{[\beta \cdot f_1] + [(C_{input} \cdot (1 - LC) - \beta) \cdot f_2] + [(C_{input} \cdot LC) \cdot f_3 \cdot (f_7 + f_6 \cdot f_8)]}{1 - (f_4 \cdot f_7) - (f_5 \cdot f_8) - (f_4 \cdot f_6 \cdot f_8)}$$

$$\beta = C_{input} \cdot \left[0.85 - 0.018 \cdot \left(\frac{LC}{NC} \right) \right]$$

IPCC 2019 Refinement

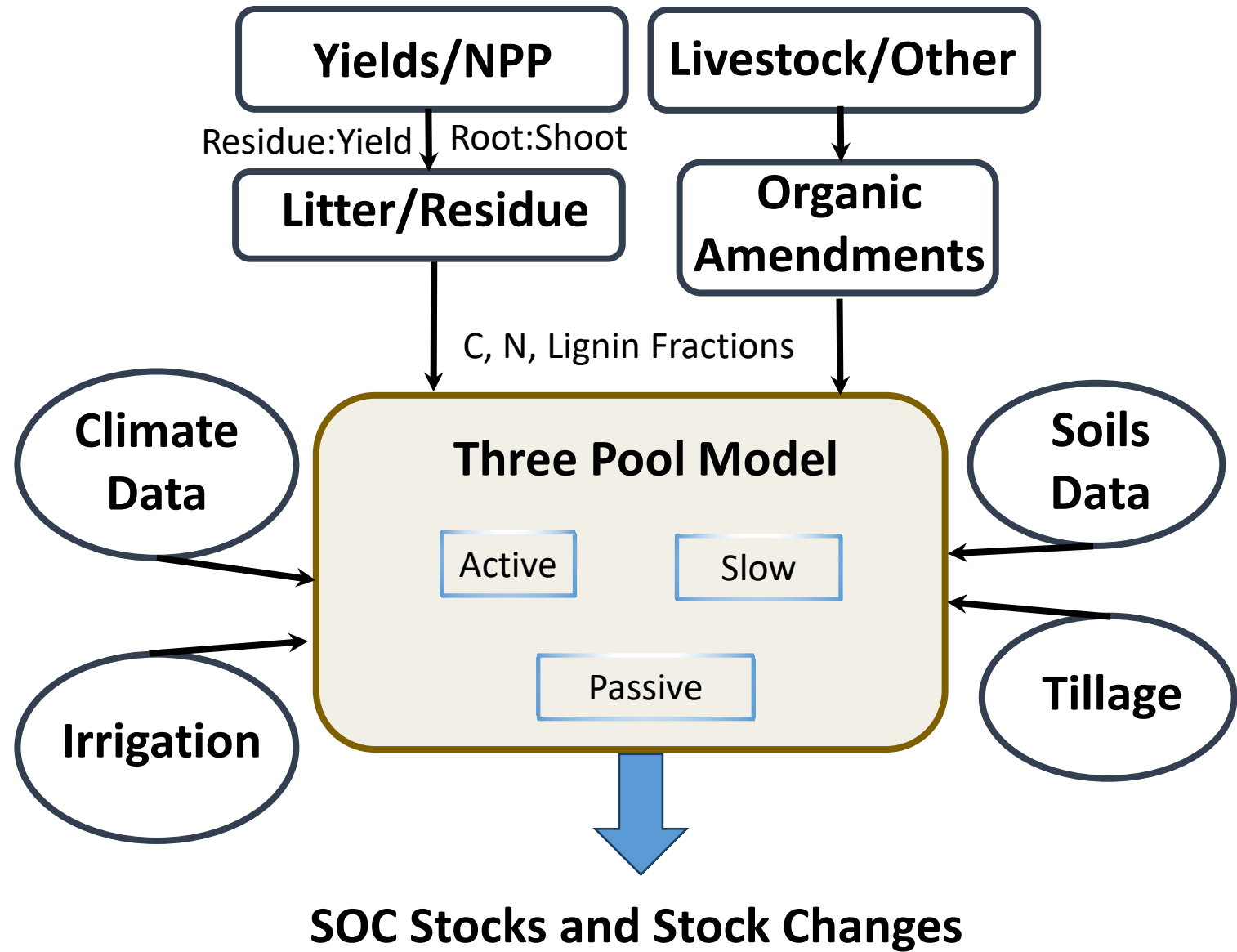
Where:

- α = C input to the active soil carbon sub-pool, tonnes C ha⁻¹
- β = C input to the metabolic dead organic matter C component, tonnes C ha⁻¹ year⁻¹
- C_{input} = total carbon input, tonnes C ha⁻¹year⁻¹
- f_1 = fraction of metabolic dead organic matter decay products transferred to the active sub-pool, proportion (see Table 5.5a)
- f_2 = fraction of structural dead organic matter decay products transferred to the active sub-pool, proportion (see Table 5.5a)
- f_3 = fraction of structural dead organic matter decay products transferred to the slow sub-pool, proportion (see Table 5.5a)
- f_4 = fraction of active sub-pool decay products transferred to the slow sub-pool, proportion, (see Equation 5.0c)
- f_5 = fraction of active sub-pool decay products transferred to the passive sub-pool, proportion (see Table 5.5a)
- f_6 = fraction of slow sub-pool decay products transferred to the passive sub-pool, proportion (see Table 5.5a)
- f_7 = fraction of slow sub-pool decay products transferred to the active sub-pool, proportion (see Table 5.5a)
- f_8 = fraction of passive sub-pool decay products transferred to the active sub-pool, proportion (see Table 5.5a)
- LC = lignin content of carbon input, proportion (see Tables 5.5b and 5.5c for default values, otherwise compile country-specific values)
- NC = nitrogen fraction of the carbon input, proportion (see Tables 5.5b and 5.5c) for default values, otherwise compile country-specific values)

Roadmap for Presentation

- **Steady State Model Background**
- **Model Structure**
- **Model Calibration, Inputs, and Outputs**
- **Advantages and Disadvantages**

Steady State Model Inputs and Outputs



IPCC 2019 Refinement

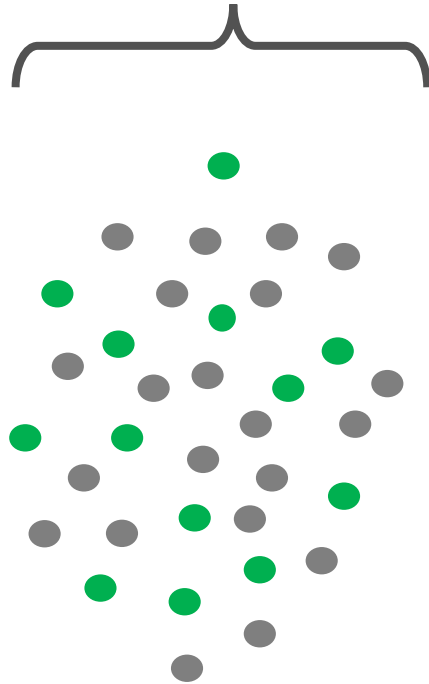
Bayesian Calibration (Sampling Importance Resampling)

Step 1

Step 2

Step 3

“Initial Sample”
from Prior



Run the model and estimated
likelihood (importance weights)
for each sample



Re-sample with probability
= importance Weights
(Posterior)



*Gurung et al. 2020,
Geoderma*

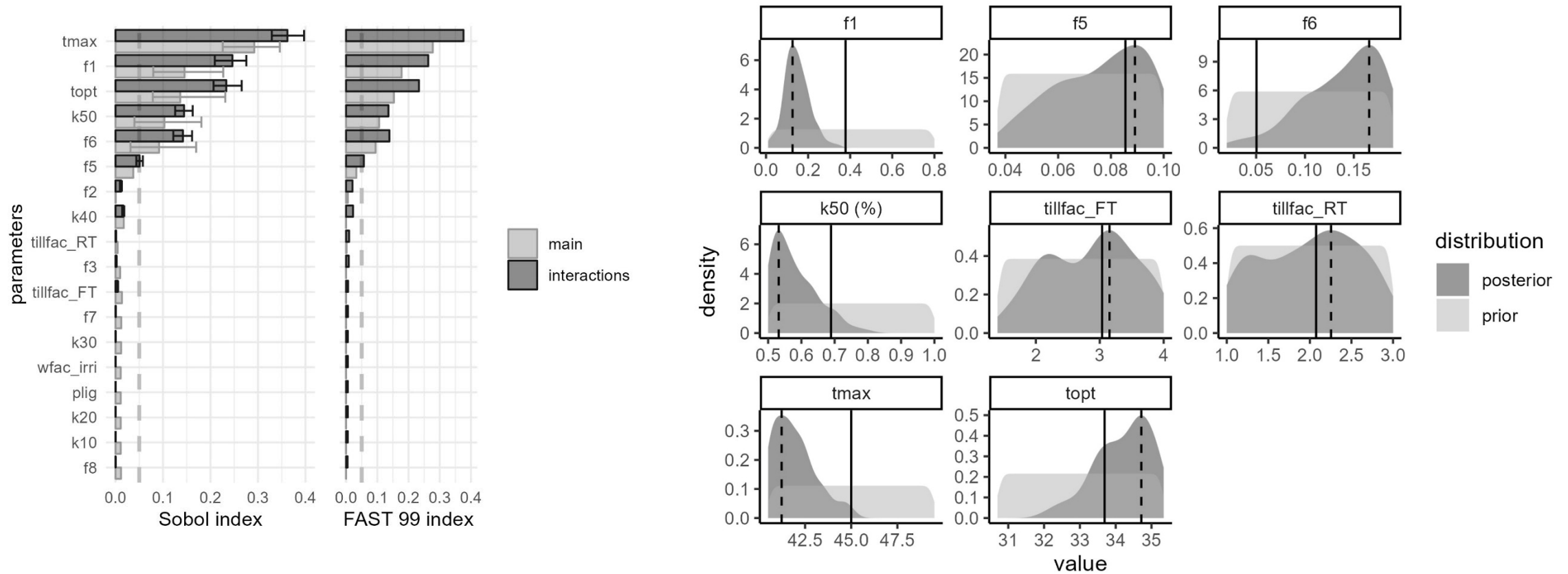
Steady State Model Parameters

IPCC 2019 Refinement

TABLE 5.5A (NEW)
GLOBALLY CALIBRATED MODEL PARAMETERS TO BE USED TO ESTIMATE SOC CHANGES FOR MINERAL SOILS WITH THE
TIER 2 STEADY-STATE METHOD

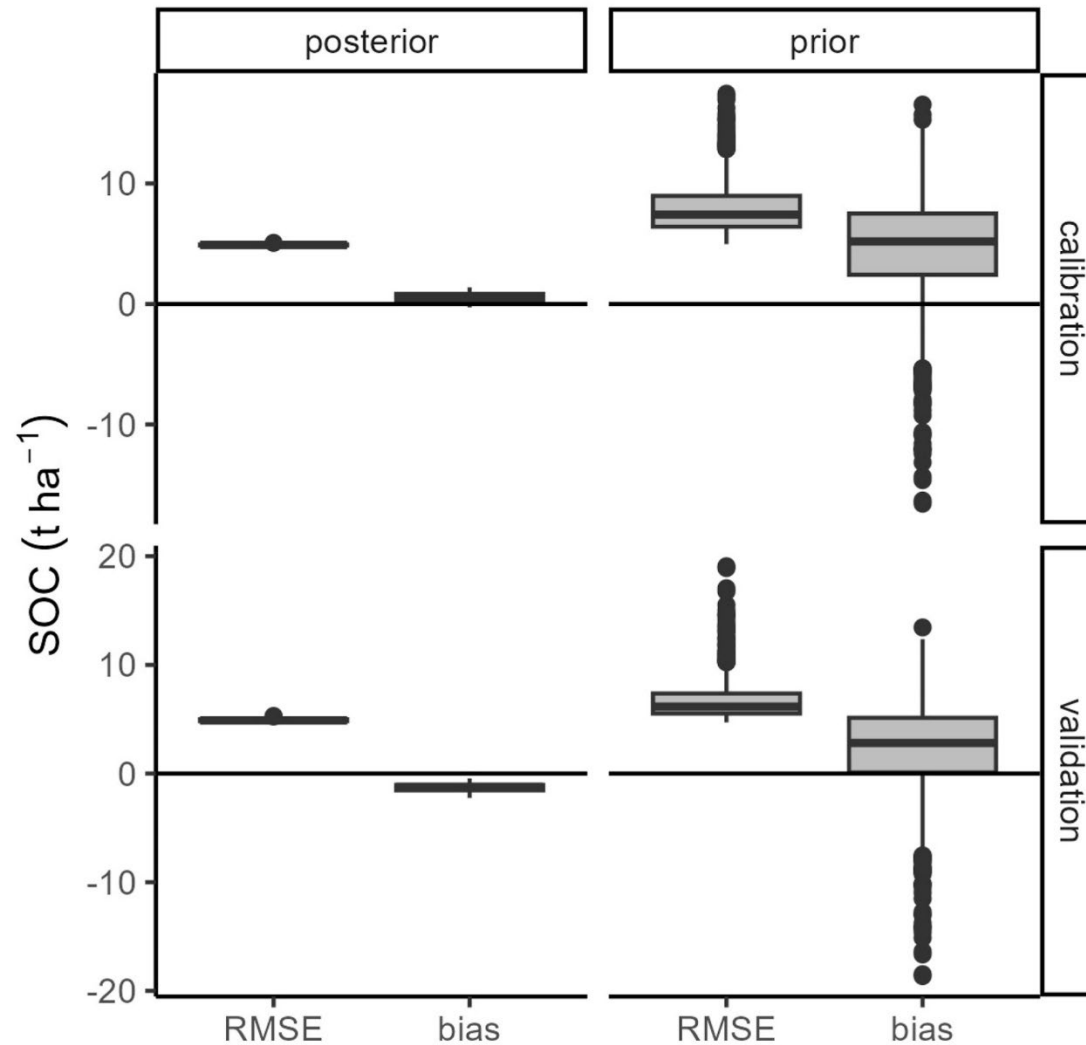
Parameter	Practice	Value (min, max)	Standard Deviation	Description
$till_{fac}$	Full-till	3.036 (1.4, 4.0)	0.579	Tillage disturbance modifier for decay rates
	Reduced-till	2.075 (1.0, 3.0)	0.569	
	No-till	1		
w_s	All	1.331 (0.8, 2.0)	0.386	slope parameter for $mappet_i$ term to estimate W_{fac}
k_{fac_a}	All	7.4	n/a	Decay rate constant under optimal conditions for decomposition of the active sub-pool
k_{fac_s}	All	0.209 (0.058, 0.3)	0.566	Decay rate constant under optimal conditions for decomposition of the slow sub-pool
k_{fac_p}	All	0.00689 (0.005, 0.01)	0.00125	Decay rate constant under optimal conditions for decomposition of the passive sub-pool
f_1	All	0.378 (0.01, 0.8)	0.0719	Fraction of metabolic dead organic matter decay products transferred to the active sub-pool
f_2	Full-till	0.368 (0.007, 0.5)	0.0998	Fraction of structural dead organic matter decay products transferred the active sub-pool
f_3	All	0.455 (0.1, 0.8)	0.201	Fraction of structural dead organic matter decay products transferred to the slow sub-pool
f_5	All	0.0855 (0.037, 0.1)	0.0122	Fraction of active sub-pool decay products transferred to the passive sub-pool
f_6	All	0.0504 (0.02, 0.19)	0.0280	Fraction of slow sub-pool decay products transferred to the passive sub-pool
f_7	All	0.42	n/a	Fraction of slow sub-pool decay products transferred to the active sub-pool
f_8	All	0.45	n/a	Fraction of passive sub-pool decay products transferred to the active sub-pool
t_{opt}	All	33.69 (30.7, 35.34)	0.66	Optimum temperature to estimate temperature modifier on decomposition
t_{max}	All	45	n/a	Maximum monthly average temperature for decomposition.

Canada Application



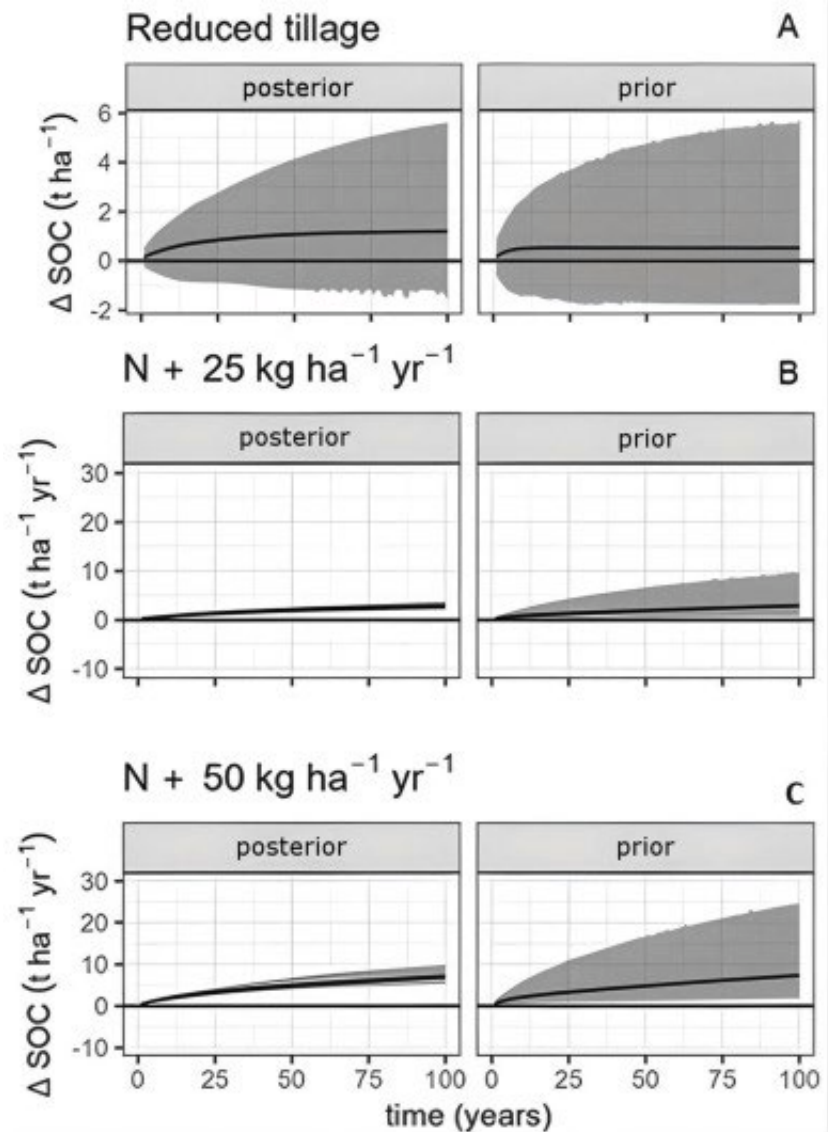
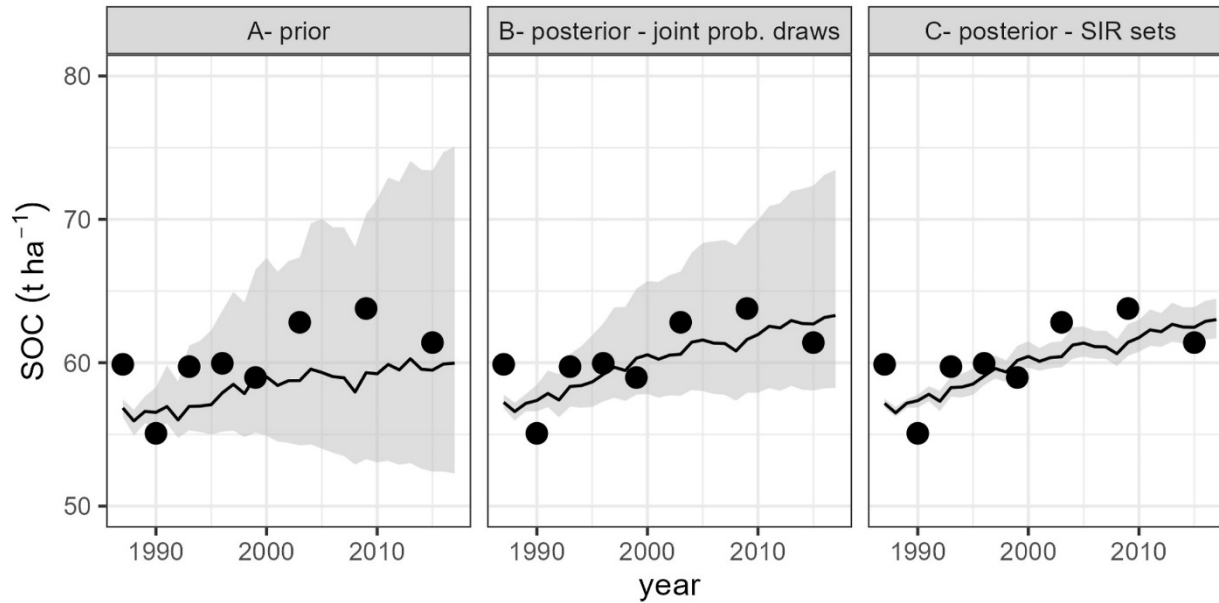
Pelletier, N., A. Thiagarajan, F. Durnin-Vermette, B. C. Liang, D. Choo, D. Cerkwoniak, A. Elkhoury, D. MacDonald, W. Smith and A. J. VandenBygaart (2025). "Approximate Bayesian inference for calibrating the IPCC tier-2 steady-state soil organic carbon model for Canadian croplands using long-term experimental data." *Environmental Modelling & Software* 190: 106481.

Canada Application



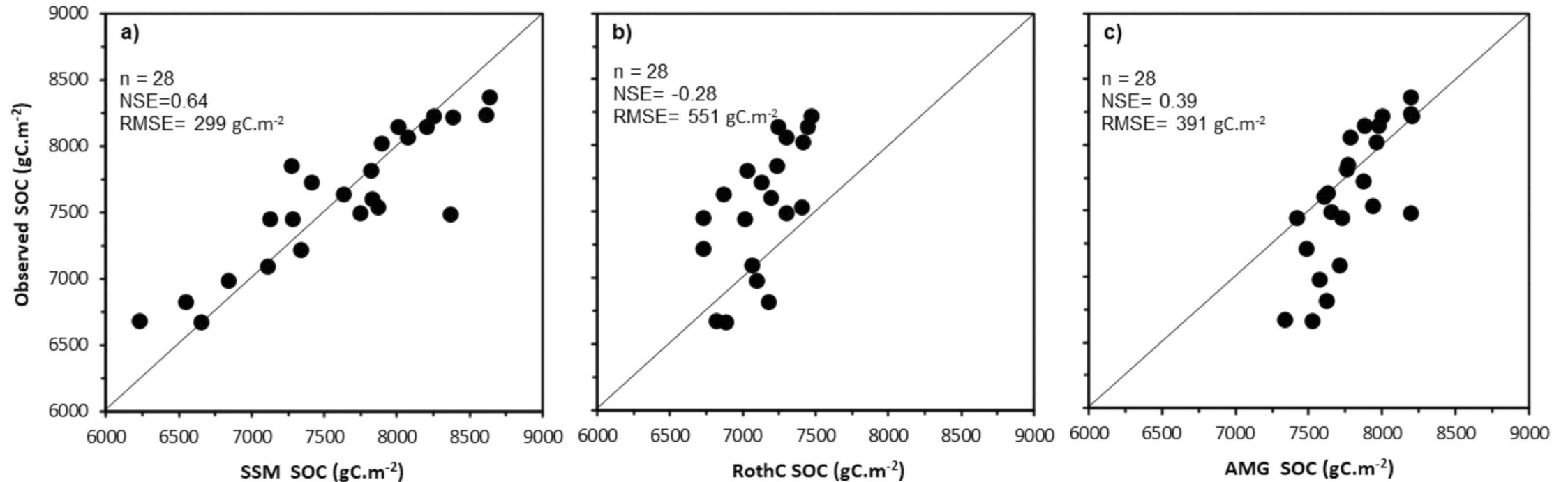
Pelletier, N., A. Thiagarajan, F. Durnin-Vermette, B. C. Liang, D. Choo, D. Cerkowniak, A. Elkhoury, D. MacDonald, W. Smith and A. J. VandenBygaart (2025). "Approximate Bayesian inference for calibrating the IPCC tier-2 steady-state soil organic carbon model for Canadian croplands using long-term experimental data." Environmental Modelling & Software 190: 106481.

Canada Application



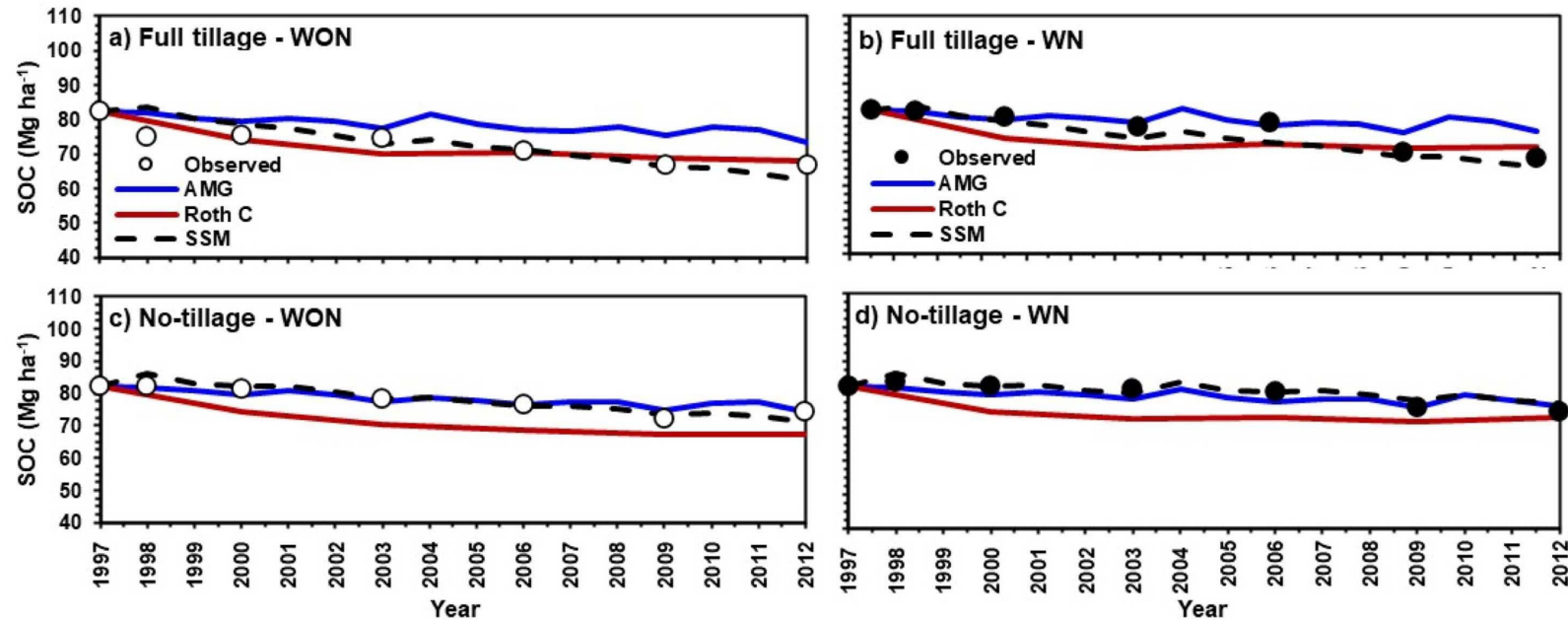
Pelletier, N., A. Thiagarajan, F. Durnin-Vermette, B. C. Liang, D. Choo, D. Cerkowniak, A. Elkhoury, D. MacDonald, W. Smith and A. J. VandenBygaart (2025). "Approximate Bayesian inference for calibrating the IPCC tier-2 steady-state soil organic carbon model for Canadian croplands using long-term experimental data." Environmental Modelling & Software 190: 106481.

Argentina Application – Tillage Experiment



Amabile, G.V., Studdert, G., Ogle, S.M., Beltrán, M., Said, A.D., Galbusera, S., Montiel, F., Moreno, F., and Ricard, M.F. 2024. An evaluation of soil carbon models and their role on finding ways to net-zero in agricultural systems. Soil & Tillage Research 246:106342.

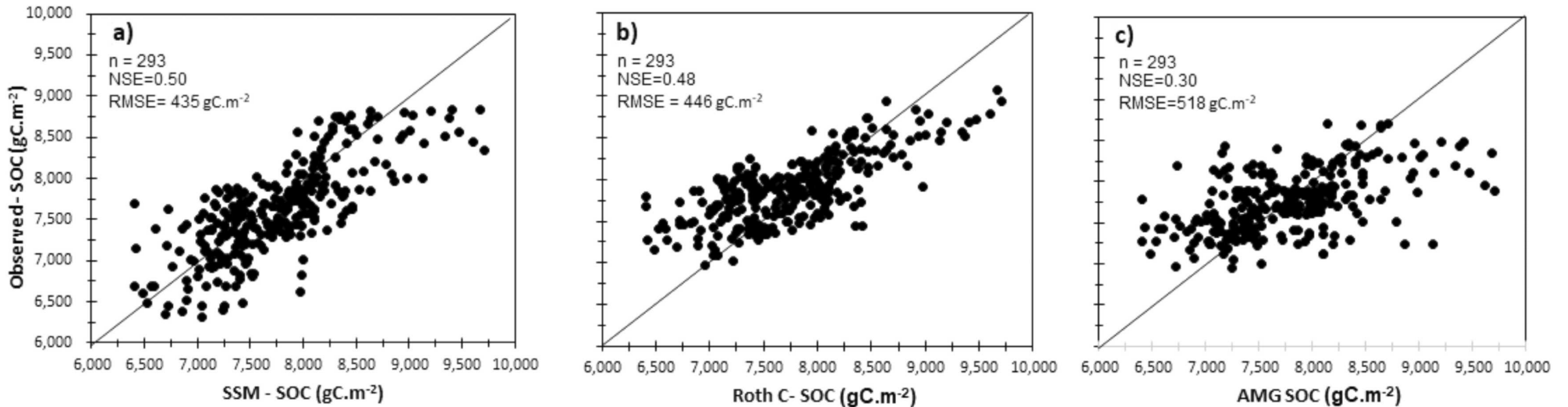
Argentina Application – Tillage Experiment



Tillage systems		n	NSE			RMSE ($\text{g C}\cdot\text{m}^{-2}$)		
Plot id.	Description		Models			SSM	AMG	RothC
a & b	Full tillage	14	0.45	-0.09	0.33	374	526	388
c & d	No-tillage	14	0.70	0.77	-3.16	199	172	677

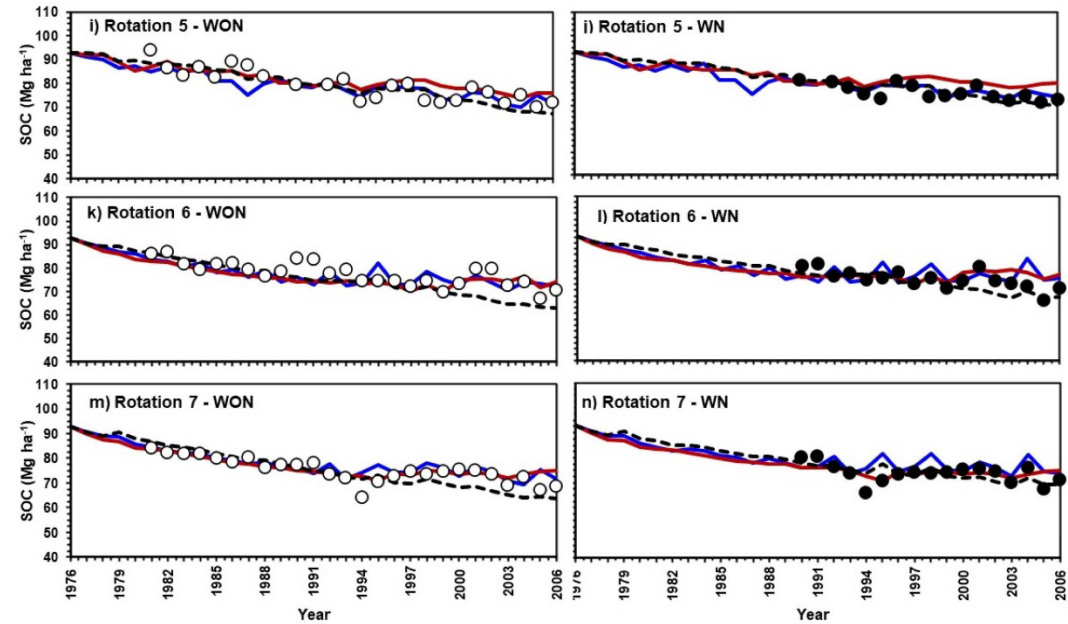
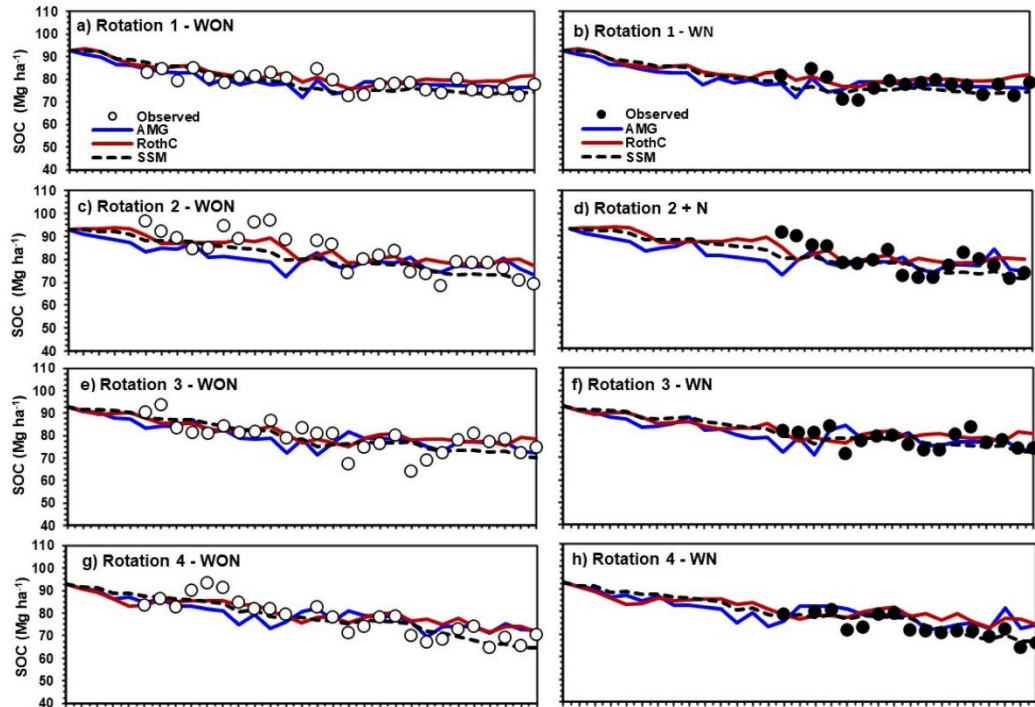
Amabile, G.V., Studdert, G., Ogle, S.M., Beltrán, M., Said, A.D., Galbusera, S., Montiel, F., Moreno, F., and Ricard, M.F. 2024. An evaluation of soil carbon models and their role on finding ways to net-zero in agricultural systems. Soil & Tillage Research 246:106342.

Argentina Application – Crop/Pasture Rotation



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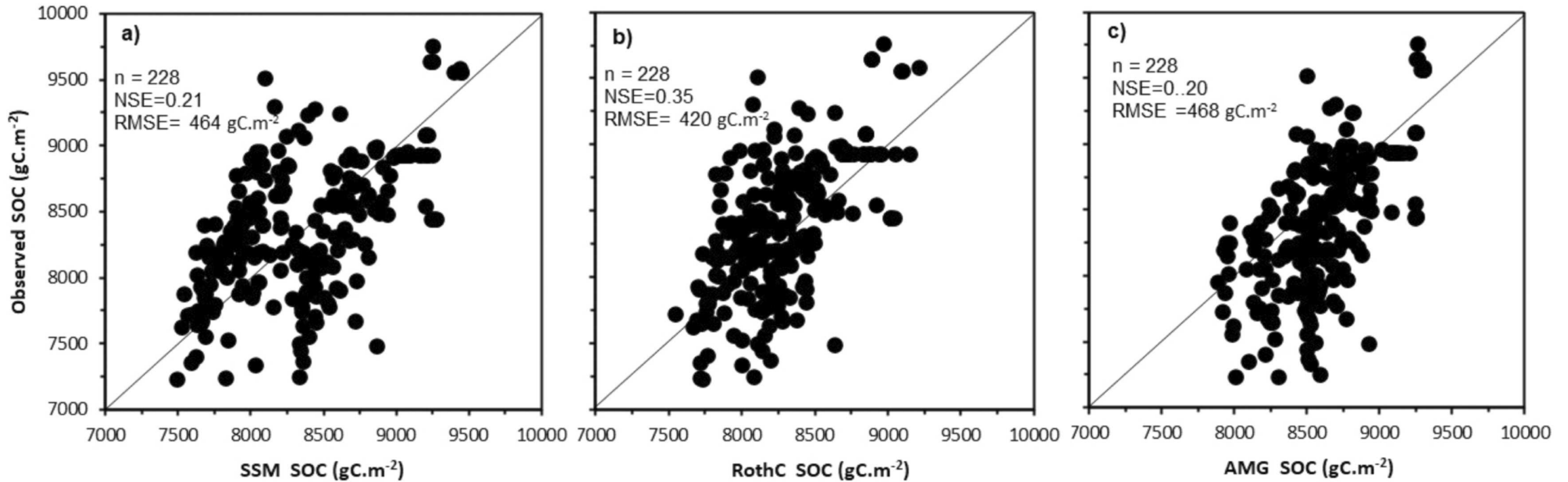
Argentina Application – Crop/Pasture Rotation



Num.	Rotation Description	n	NSE			RMSE (g C.m ⁻²)		
			SSM	AMG	RothC	SSM	AMG	RothC
1	Pasture 60%-Crop Full Tillage 40%	41	0.15	0.25	0.05	351	331	372
2	Pasture 50%-Crop Full Tillage 50%	42	0.45	0.05	0.55	583	767	527
3	Pasture 35%-Crops 65% (Full Tillage 70%/ No Tillage 30%)	43	0.31	0.02	0.24	468	560	492
4	Pasture 30%-Crop Full Tillage 70%	41	0.72	0.36	0.42	363	555	526
5	Pasture 25%-Crops 75% (Full Tillage 60%/ No Tillage 40%)	40	0.72	0.64	0.47	334	378	461
6	Continuous Crop-Full Tillage 100%	43	0.25	0.30	0.51	493	476	398
7	Continuous Crop-Full Till 60%-No Tillage 40%	43	0.87	0.84	0.92	384	419	298

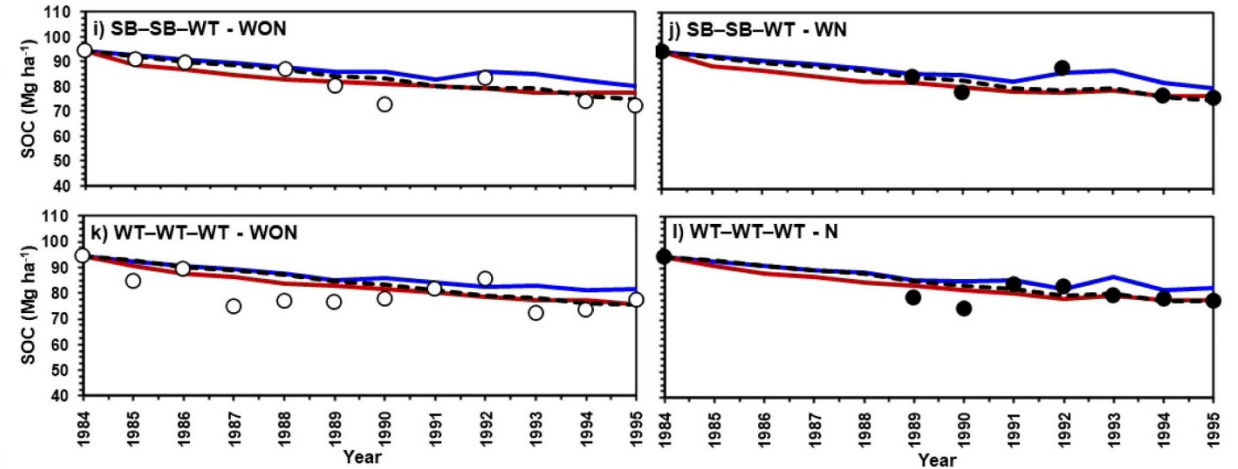
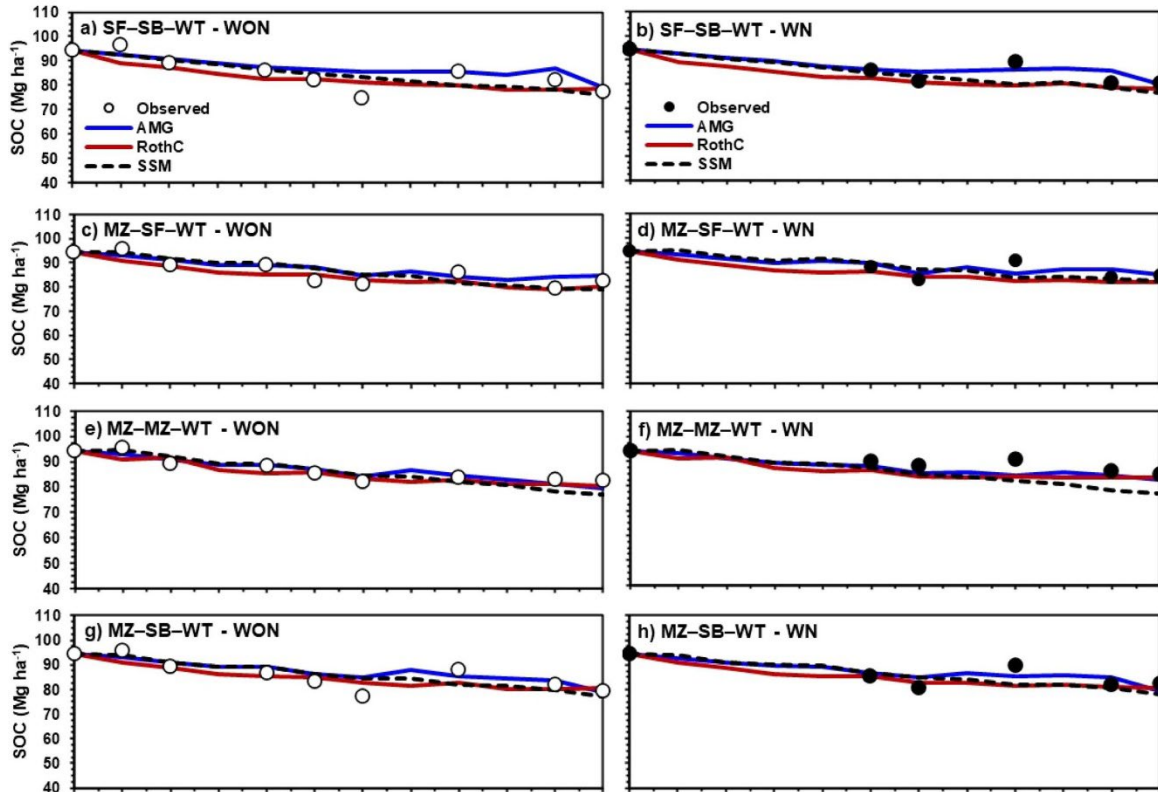
Amabile, G.V., Studdert, G., Ogle, S.M., Beltrán, M., Said, A.D., Galbusera, S., Montiel, F., Moreno, F., and Ricard, M.F. 2024. An evaluation of soil carbon models and their role on finding ways to net-zero in agricultural systems. *Soil & Tillage Research* 246:106342.

Argentina Application – Continuous Crop Rotation



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Argentina Application – Continuous Crop Rotation



Crop sequence		n	NSE			RMSE (g C.m ⁻²)		
Plot id.	Description		Models			SSM	AMG	RothC
a & b	SF-SB-WT*	15	0.37	0.38	0.32	436	430	453
c & d	MZ-SF-WT*	15	0.36	0.43	0.39	349	328	341
e & f	MZ-MZ-WT*	15	-0.06	0.52	0.31	392	263	315
g & h	MZ-SB-WT*	15	0.26	0.49	0.46	415	346	354
i & j	SB-SB-WT*	15	0.48	0.11	0.49	451	587	446
k & l	WT-WT-WT*	20	-0.96	-1.81	-0.33	620	742	510

* SF: sunflower; SB: soybean; WT: spring wheat; MZ: maize

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Roadmap for Presentation

- Steady State Model Background
- Model Structure
- Model Calibration, Inputs, and Outputs
- **Advantages and Disadvantages**

Advantages

- Advance beyond Tier 1 method to produce more accurate estimates
- May be as accurate as a Tier 3 method in some circumstances
- Moderate level of data requirements (similar to the Tier 1 method)
- Fewer parameters and less complexity than a Tier 3 method

Disadvantages

- Needs to be tested and possibly calibrated
- Probably not as dynamic and accurate as a Tier 3 method across a range of environmental conditions
- Only set up for application in cropland systems

Thanks for your attention!



Colorado State University

N A T U R A L R E S O U R C E E C O L O G Y L A B O R A T O R Y