SLU

Modelling dynamics interactions between soil structure and soil organic matter storage

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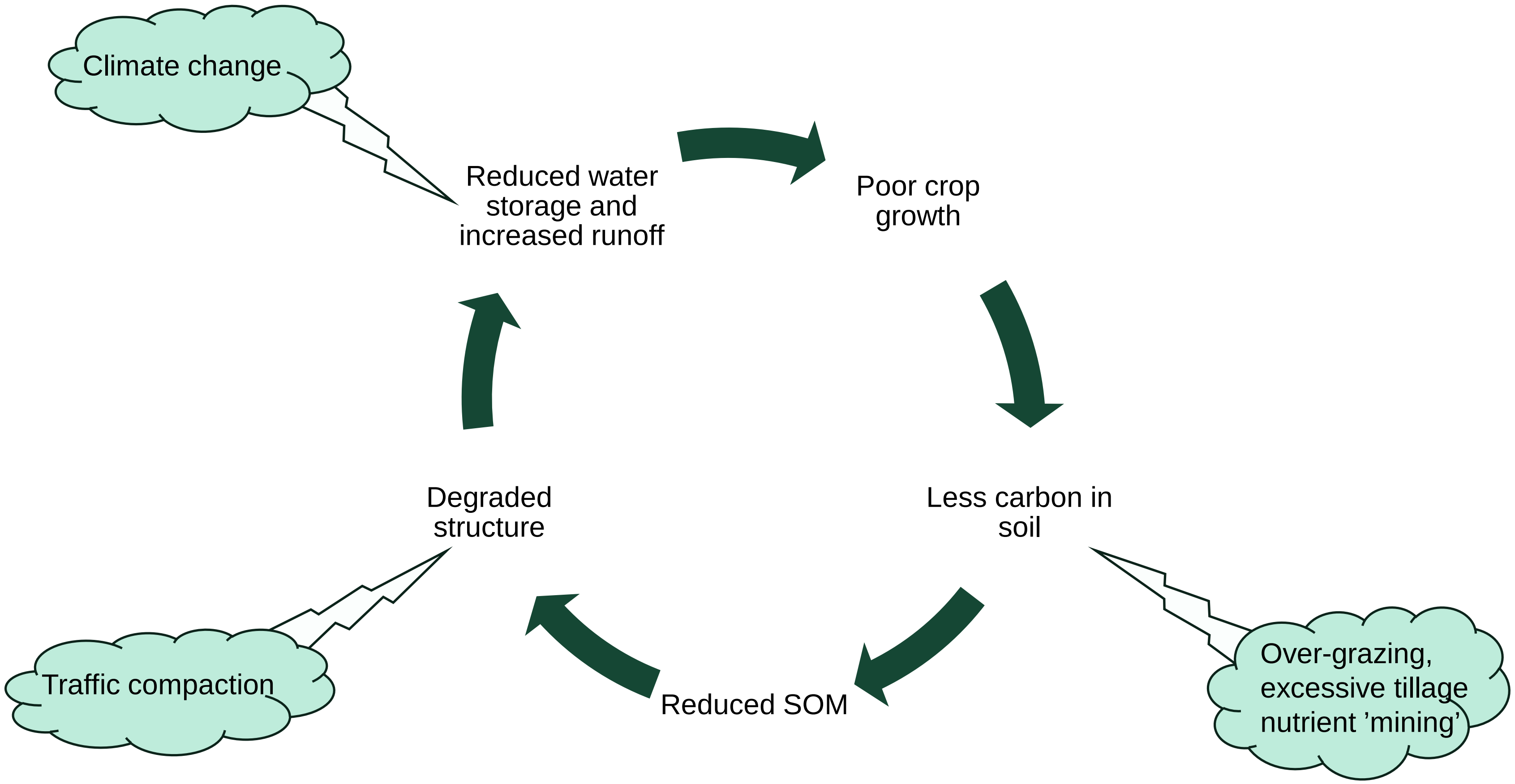
Soil degradation

- ”the decline in soil quality caused through its misuse by humans”[1]
- every year, 12 million hectares are lost worldwide because of soil degradation[2]
  - considered a global threat
- determined by soil structure, i.e. the spatial arrangement and stability of soil solids and pore space[3]
  - controls all key soil processes, e.g. air and water movement, microbial activity, carbon and nitrogen cycling, root growth[4]

[1] Lal & Stewart (1990) Soil degradation: A global threat. In: R Lal & BA Stewart, Advances in Soil Sciences, Volume 11, Soil Degradation, Springer-Verlag
[2] FAO/ITPS. 2015. FAO/ITPS, Rome, Italy
[3] Dexter, A (1988) Advances in characterization of soil structure. Soil & Till. Res., 11, 199-238.
[4] Rabot et al. (2018) Soil structure as an indicator of soil functions: A review. Geoderma, 314, 122-137.

The vicious circles of soil degradation



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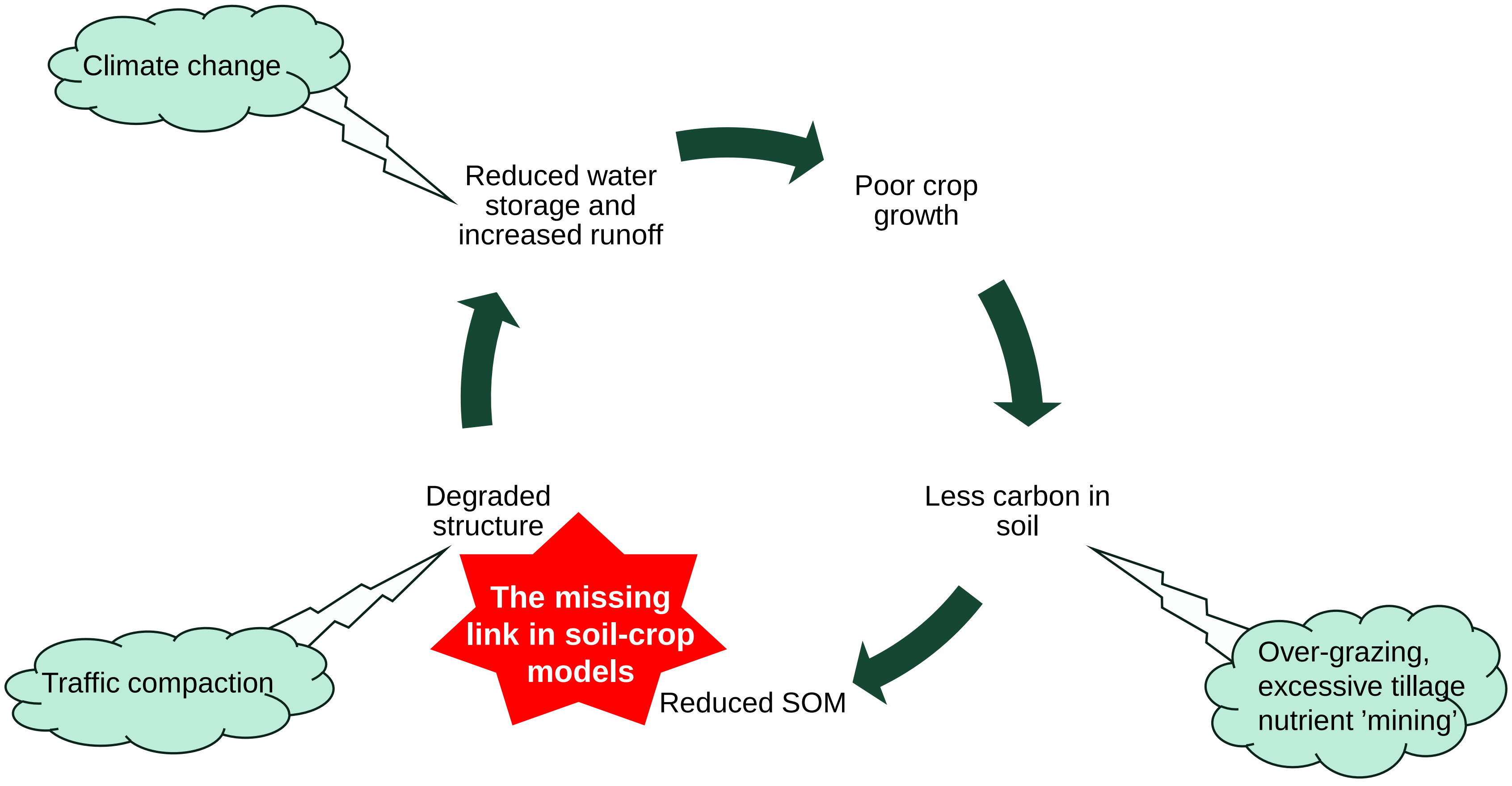
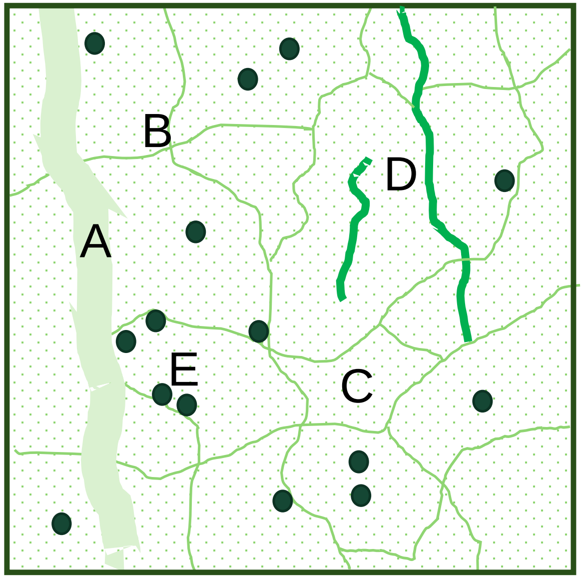


Dynamic changes in soil hydraulic properties that affect soil water balance, crop growth and soil carbon storage at decadal to centennial time-scales

Coupled modelling of soil organic matter dynamics and soil structure



A) macropores (> 300 µm)

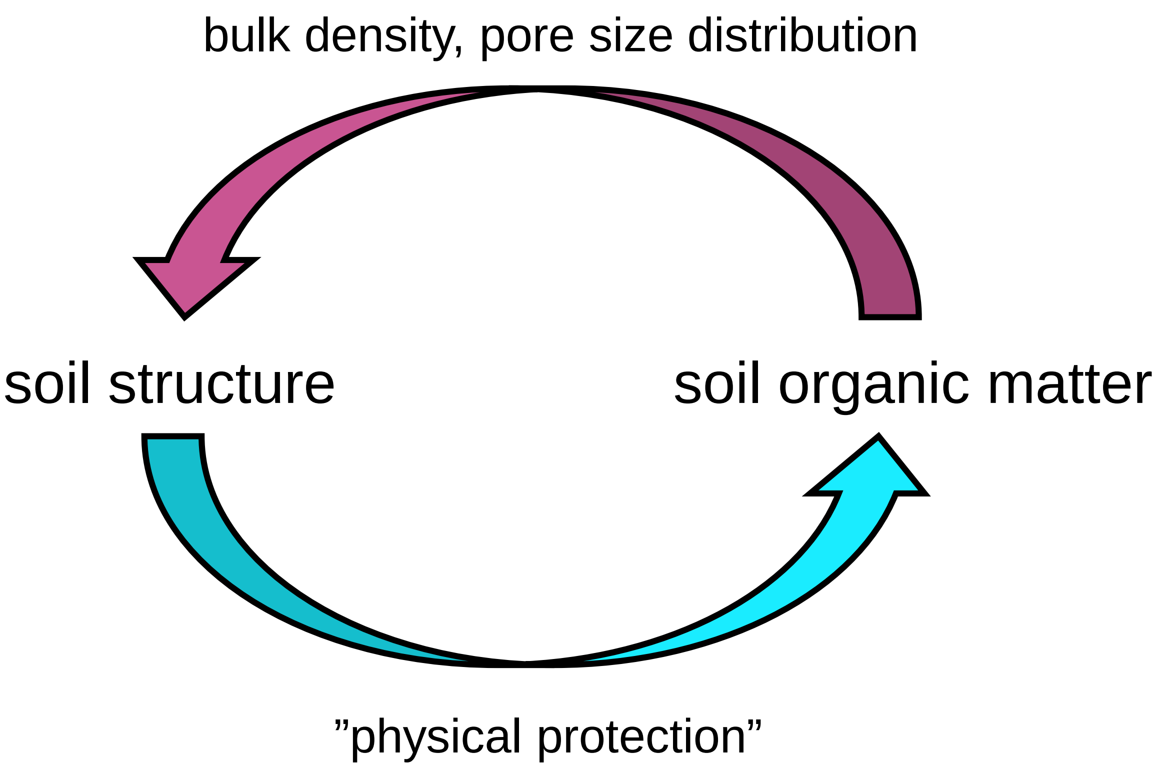
B) mesopores (30 – 300 µm)

C) micropores (< 30 µm)

D) POM e.g. decaying roots

E) microbially-processed organic matter

Two-way interaction between soil structure and SOM



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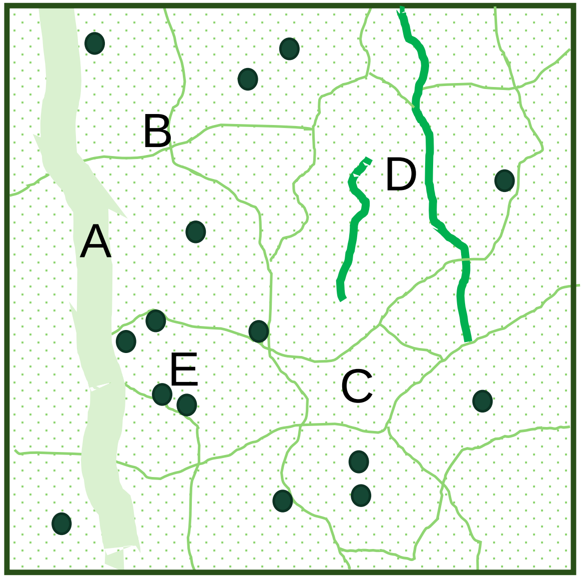

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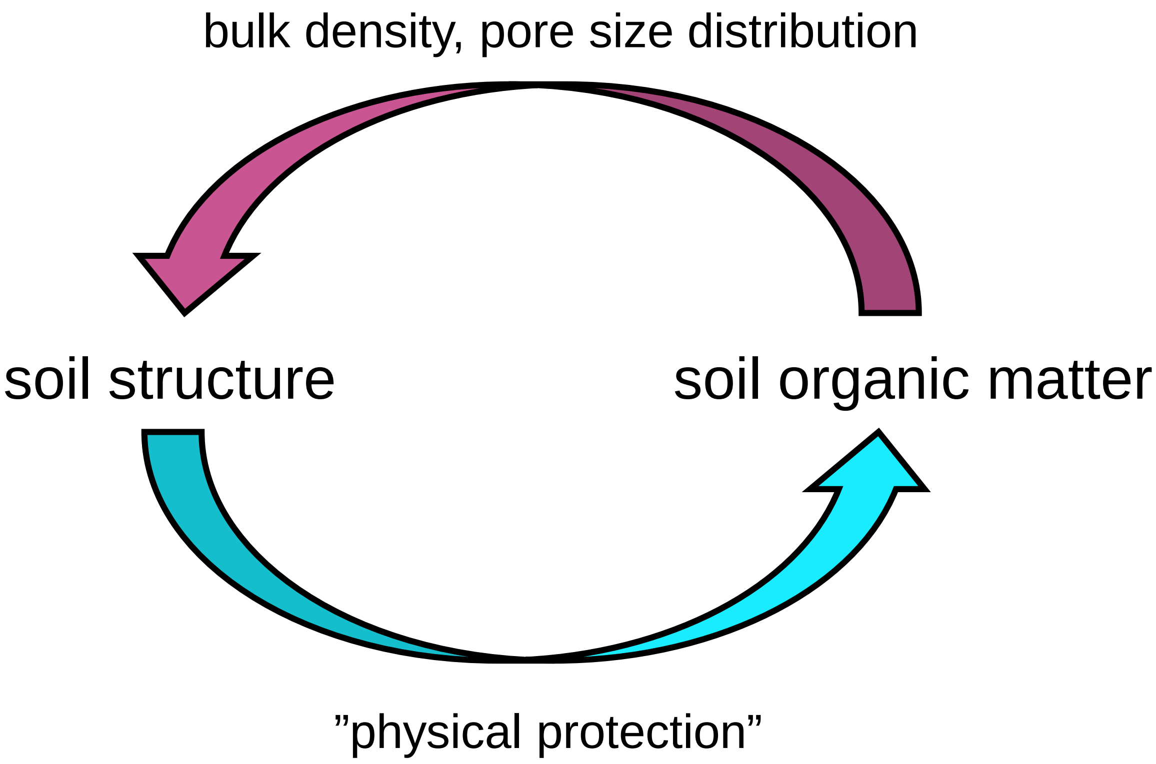
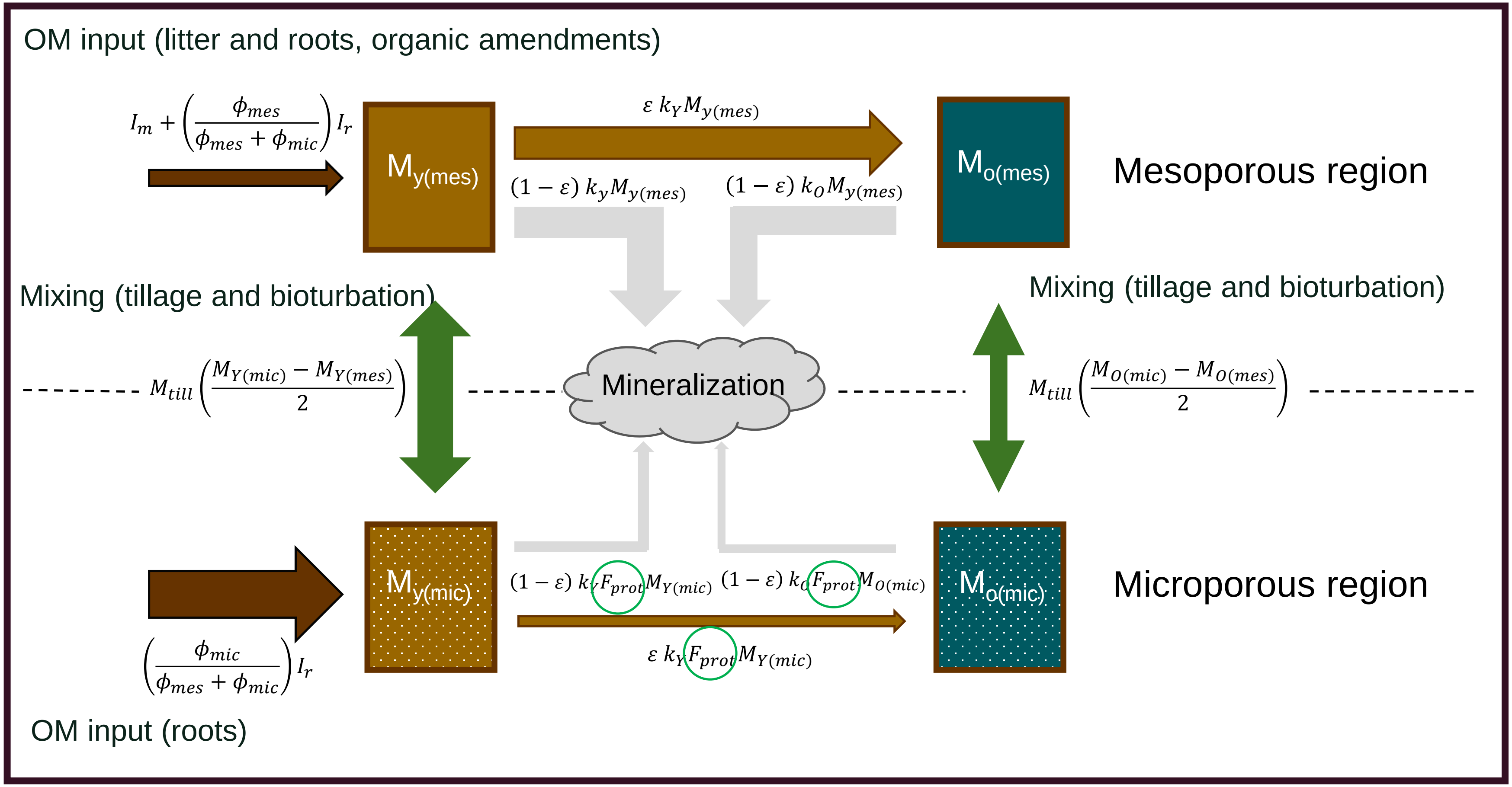


The influence of soil structure on SOM turnover and storage (extended ICBM model[1])



[1]Andrén, O., Kätterer, T. 1997. ICBM: the introductory carbon balance model for exploration of soil carbon balances. Ecological Applications, 7, 1226-1236.

Modelling dynamics in soil structure

Soil bulk density

$$\gamma_b = \frac{\gamma_{b(max)}}{\left\{\left(\frac{\gamma_{b(max)}}{\gamma_{som}}\right)(1+f_{agg})f_{som}\right\} + (1-f_{som})}$$

Total porosity

Aggregation pores *Textural pores*

$$\phi = \frac{\left\{\left(\frac{M_{som}}{\gamma_{som}}\right) f_{agg}\right\} + \left\{\Delta z_{min}\left(1+\left(\frac{\gamma_{b(max)}}{\gamma_{min}}\right)\right)\right\}}{\left\{\left(\frac{M_{som}}{\gamma_{som}}\right)(1+f_{agg})\right\} + \Delta z_{min}}$$

f_{som} = SOM concentration

M_{som} = SOM mass

γ_{som} = SOM density

Microporosity

$$\phi_{mic} == \frac{\left\{\left(M_{Y(mic)} + M_{O(mic)}\right)\left(\frac{f_{agg}}{\gamma_{som}}\right)\right\} + f_{text(mic)}\left\{\Delta z_{min}\left(1-\left(\frac{\gamma_{b(max)}}{\gamma_{min}}\right)\right)\right\}}{\left\{\left(\frac{M_{som}}{\gamma_{som}}\right)(1+f_{agg})\right\} + \Delta z_{min}}$$

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f_{som} = SOM concentration

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γ_{som} = SOM density

Microporosity

$$\phi_{mic} == \frac{\left\{\left(M_{Y(mic)} + M_{O(mic)}\right)\left(\frac{f_{agg}}{\gamma_{som}}\right)\right\} + f_{text(mic)}\left\{\Delta z_{min}\left(1 - \left(\frac{\gamma_{b(max)}}{\gamma_{min}}\right)\right)\right\}}{\left\{\left(\frac{M_{som}}{\gamma_{som}}\right)(1 + f_{agg})\right\} + \Delta z_{min}}$$

Testing the model

1. Sensitivity analysis

f_{som} = SOM concentration
γ_b = soil bulk density
f_{mic} = fraction of micropores

Parameter	Sampled range	Partial correlation coefficients, r		
		f_{som}	γ_b	f_{mic}
1st order rate coefficient, k_y [$year^{-1}$]	0.1 – 1.0	**-0.54**	**0.37**	-0.10
1st order rate coefficient, k_o [$year^{-1}$]	0.01 – 0.05	**-0.82**	**0.70**	**0.32**
Physical protection factor, F_{prot} [-]	0.05 – 0.20	**-0.46**	**0.28**	-0.08
OM Retention coefficient, ε [-]	0.1 – 0.5	**0.92**	**-0.82**	**-0.30**
Mixing coefficient, k_{mix} [$year^{-1}$]	0 – 0.2	**-0.68**	**0.50**	**-0.60**
Fraction of textural micropores, $F_{text(mic)}$ [-]	0.5 – 0.9	**0.24**	**-0.16**	**0.96**
Density of mineral matter, γ_{min} [$g\ cm^{-3}$]	2.6 – 2.7	-0.09	**0.37**	0.01
Density of organic matter, γ_{som} [$g\ cm^{-3}$]	1.1 – 1.4	-0.03	**0.33**	-0.01
Minimum porosity, ϕ_{min} [$cm^3\ cm^{-3}$]	0.3 – 0.4	**0.162**	**-0.85**	0.02
Aggregation factor, f_{agg} [-]	2 – 4	0.0	**-0.50**	0.02

Testing the model

1. Sensitivity analysis
2. Parameter identifiability

- Created synthetic data by running the model for 50 years given two scenarios with different OM inputs: (i) no input (bare fallow), (ii) constant input of 0.06 g cm^{-2} $year^{-1}$

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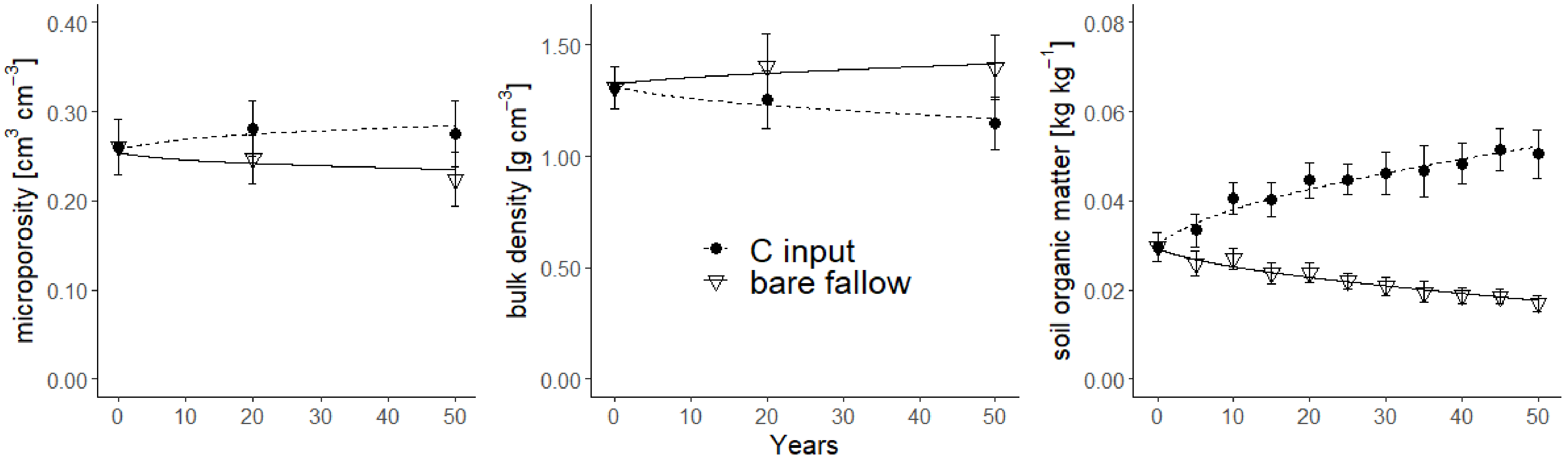
Parameters	Value used for data generation (true value)	Sampled range during calibration
1^{st} order rate coefficient, k_y [$year^{-1}$]	0.40	0.1 – 1.0
1^{st} order rate coefficient, k_o [$year^{-1}$]	0.02	0.005 – 0.1
Mixing coefficient, k_{mix} [$year^{-1}$]	0.05	0 – 0.3
Microbial efficiency, ε [-]	0.3	0.1 – 0.6
Physical protection factor, F_{prot} [-]	0.3	0.05 – 1.0
Fraction of textural micropores, $F_{text(mic)}$ [-]	0.5	0.2 – 0.8
Density of mineral matter, γ_{min} [g cm^{-3}]	2.7	
Density of organic matter, γ_{som} [g cm^{-3}]	1.2	
Minimum layer thickness, $\Delta z_{(min)}$ [cm]	16	
Minimum porosity, ϕ_{min} [cm^3 cm^{-3}]	0.4[a)]/0.41[b)]	
Aggregation factor, f_{agg} [-]	5.0[a)]/4.92[b)]	

Testing the model – parameter identifiability



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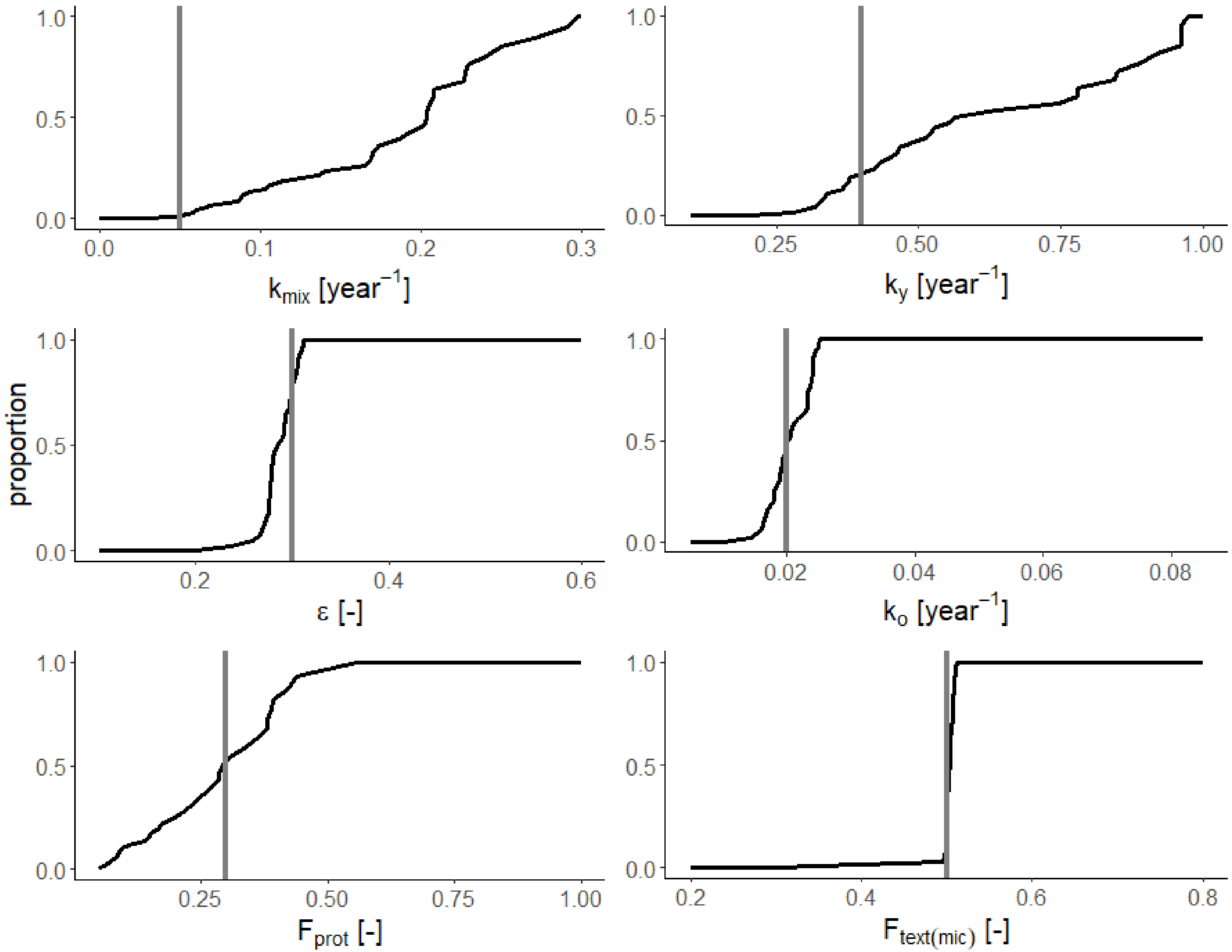

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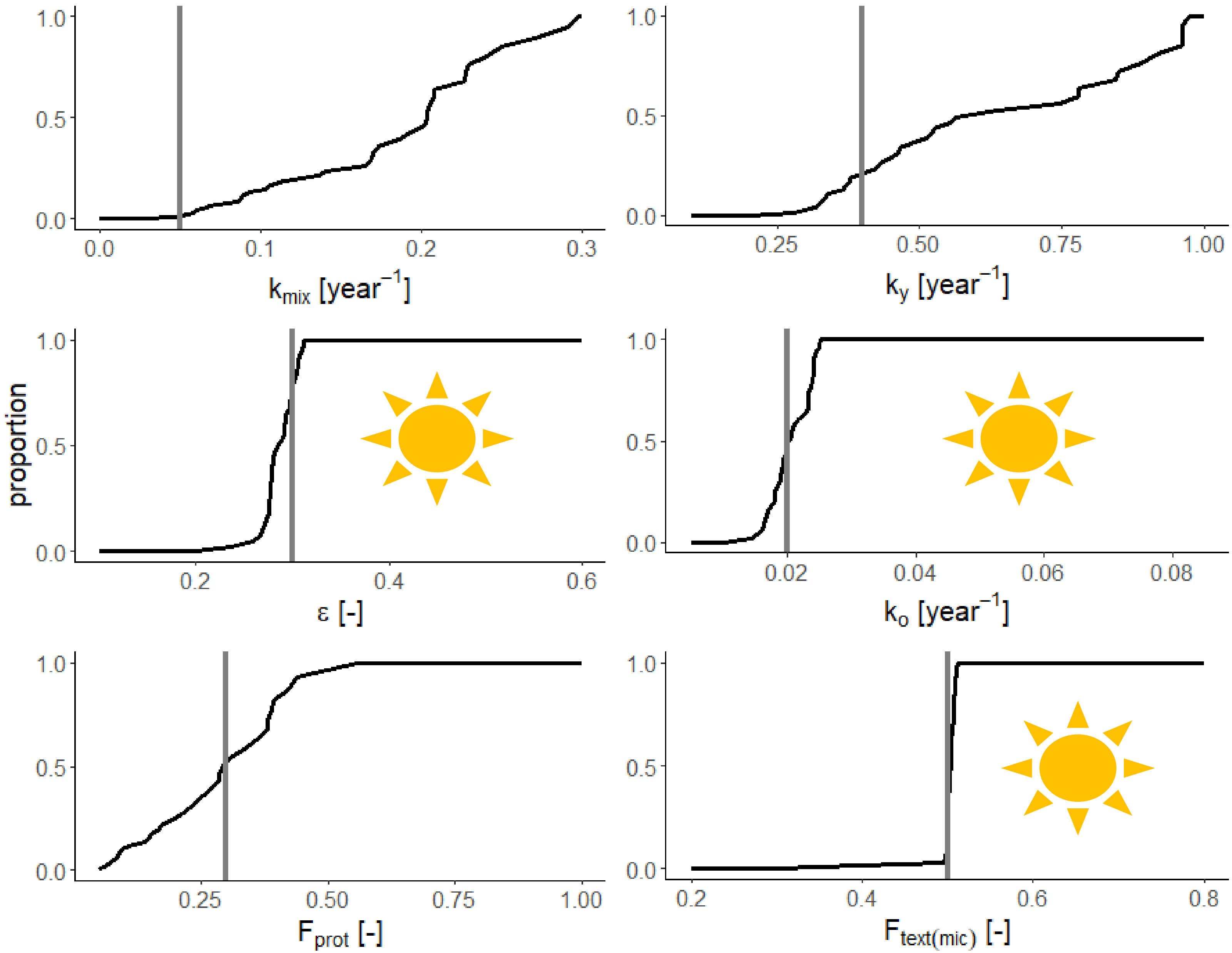

Application to the Ultuna long-term ”frame” trial

RAM-56 Organic matter trial

Treatment	Mineral fertilizer [kg N ha^{-1} yr^{-1}]	Organic material [t C ha^{-1}] *
bare fallow (A)	0	0
No-N (B)	0	0
$Ca(NO_3)_2$ (C)	80	0
$(NH_4)_2SO_4$ (D)	80	0
kkv (E)	80	0
straw (F)	0	4
straw (G)	80	4
green manure (H)	0	4
peat (I)	0	4
animal manure (J)	0	4
animal manure (K)	0	4
saw dust (L)	0	4
peat (M)	80	4
saw dust (N)	80	4
sewage sludge (O)	0	4

* applied every other year

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saw dust (N)	80	4
sewage sludge (O)	0	4
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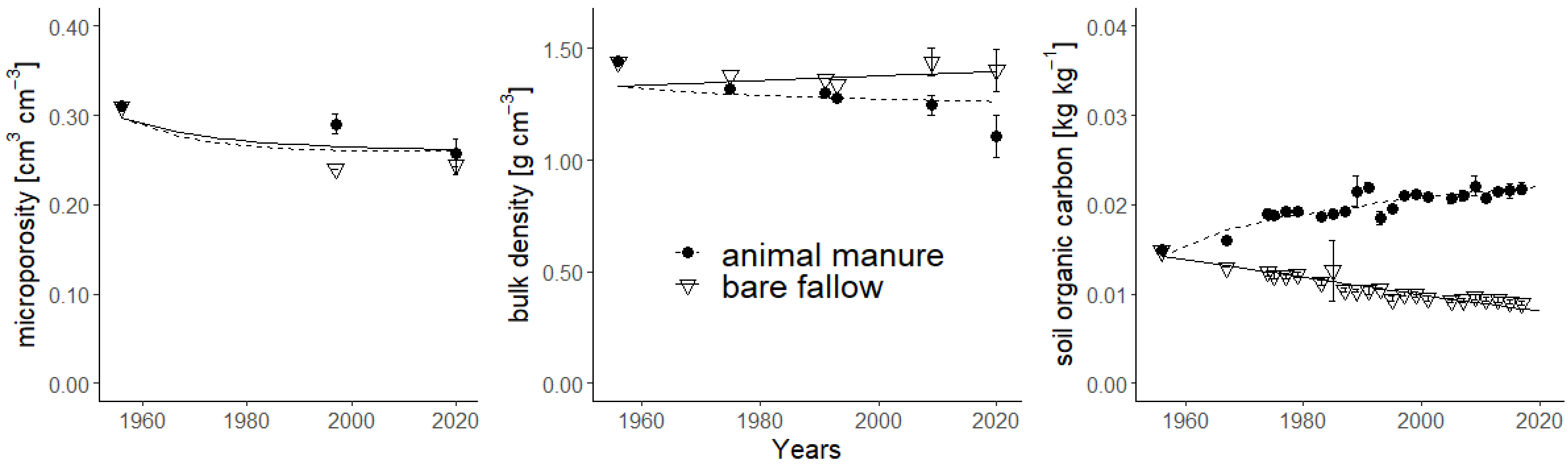
Application to the Ultuna long-term "frame" trial

Parameter	Value	Variation
1st order rate coefficient, k_o ($year^{-1}$)	0.036	0.031 – 0.039
OM retention coefficient, ε	0.37	0.35 – 0.39
OM input spin-up ($g\ cm^{-2}\ year^{-1}$)	0.0064	0.0061 – 0.0066
Fraction of textural micropores, $f_{text(mic)}$	0.85	0.84 – 0.87



Data from:

Kirchmann, H. et al., 1994. Dept. Soil Sciences, Reports and Dissertations 17, Swedish University of Agricultural Sciences, Uppsala, Sweden.

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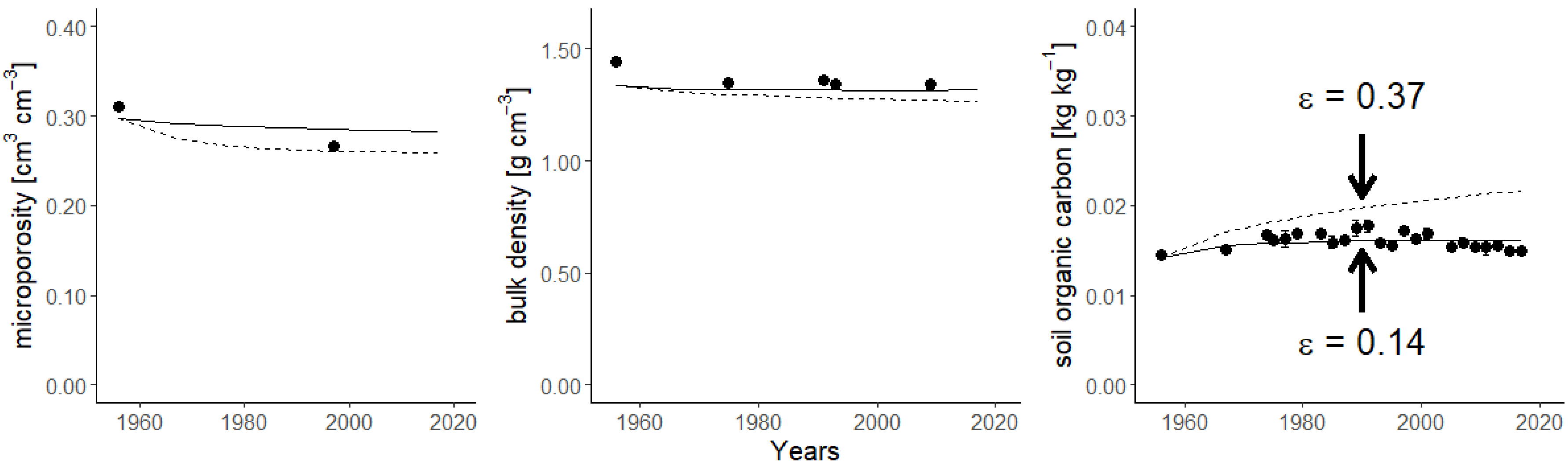
Application to the Ultuna long-term ”frame” trial

Predictions for the green manure treatment

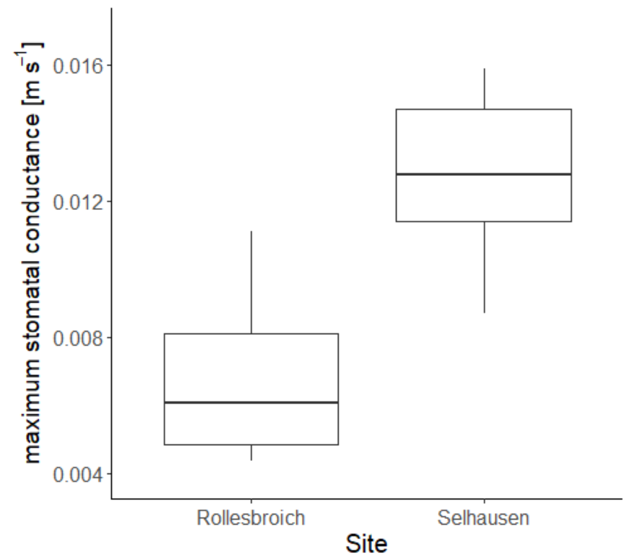


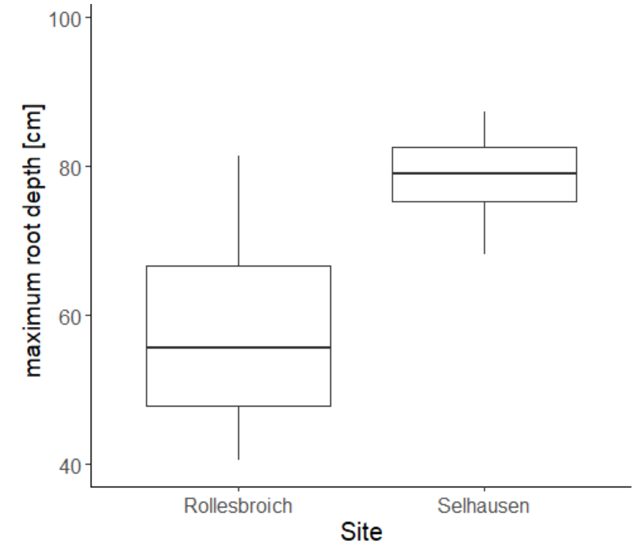
Outlook and plans

- A promising approach to model the interactions between SOM storage and turnover and soil structure
- Ongoing and future model development
  - Physical processes (e.g. swell/shrink, freeze/thaw)
  - Coupling to modules for soil hydrology and plant growth
    - Integration within an overall soil-crop modelling framework?

Ongoing and future work

- Increased frequency of severe drought will impact many important agricultural regions of the world
- Strong interaction between soil water status and plant growth hardly covered by models
  - TERENO SOILCan (lysimeter) network
  - Rhine valley (Germany): Rollesbroich (wetter) and Selhausen (drier)
  - Coupling hydrological processes and grassland production in two contrasting climates *(Jarvis et al. under review)*
- Greater stomatal conductance, increase in dry matter allocation below-ground and larger maximum root depth in drier climate
- Plant plasticity (adaptation) introduced significant additional uncertainties into model predictions of crop growth in response to climate change





Ongoing and future work

- 3 internal projects:
  - MixRoot and MaxRoot
    - Effect of root systems on carbon flow and organic matter accumulation in European agricultural soils
  - EnergyLink
    - Linking crop diversification to microbial energy allocation and organic carbon storage in soils

- Field experiment on the impacts of drought on grassland production and SOC stocks in a future climate (Uppsala, Sweden)

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Thank you for your attention!

SCIENCE AND EDUCATION FOR SUSTAINABLE LIFE

Research project:

”Soil structure and soil degradation: improved model tools to meet sustainable development goals under climate and land use change”

A multi-disciplinary approach, integrating all relevant disciplines:

- Soil physics/mechanics, biogeochemistry, ecology
- Hydrology
- Crop science
- Socio-economics

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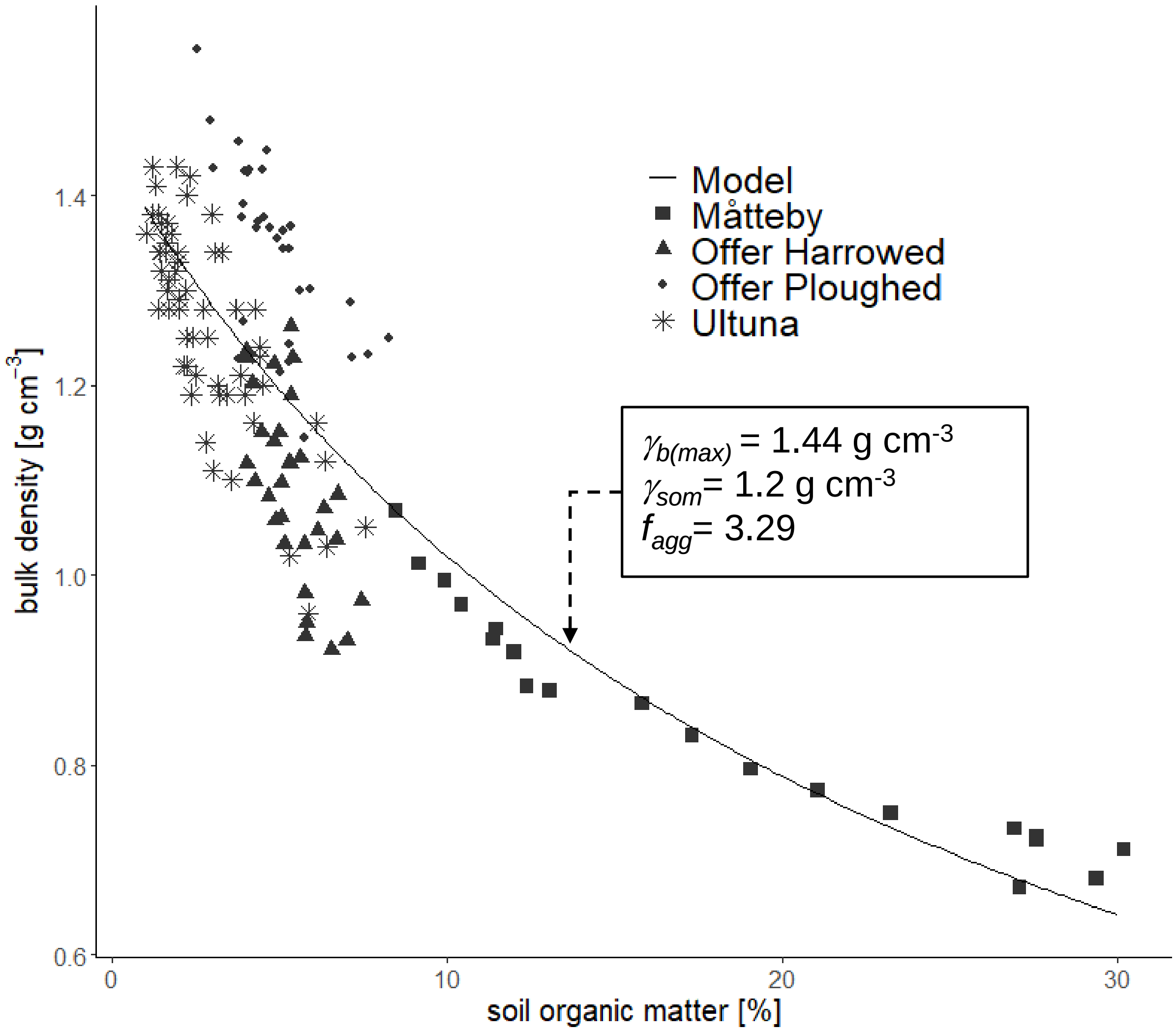

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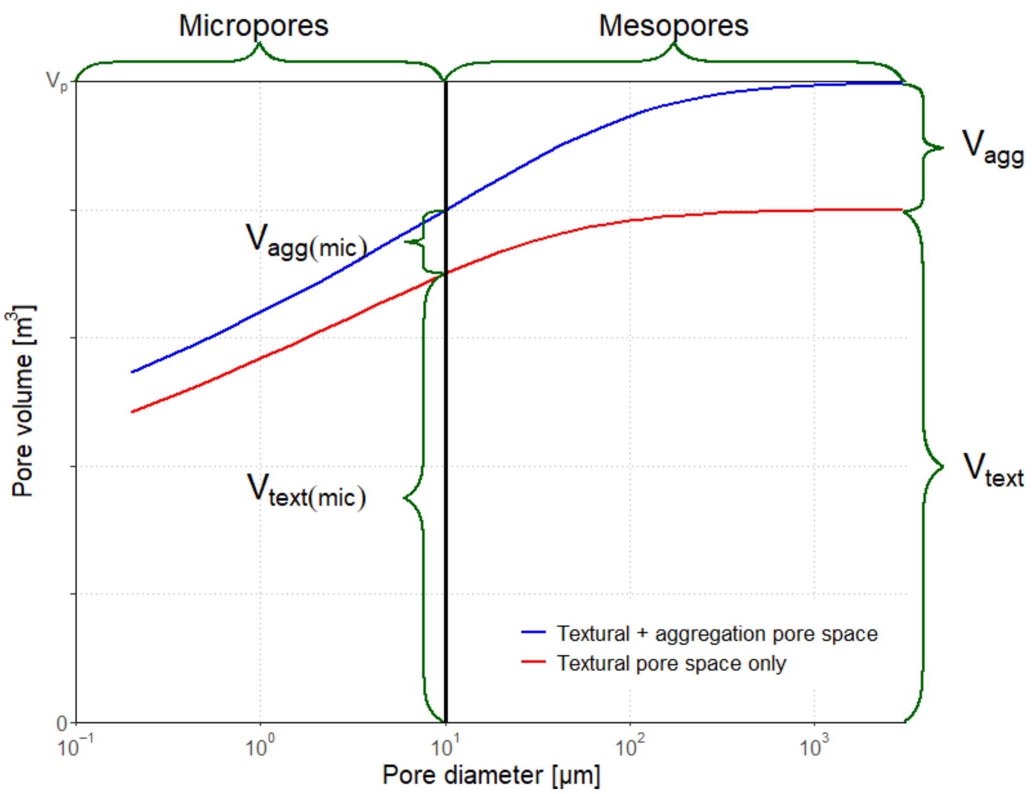
Larsbo et al. (2016) Vadose Zone Journal, doi:10.2136/vzj2016.03.0021.

The influence of SOM on soil pore size distribution and porosity



- The total soil pore volume comprises a constant volume of "textural pores" and an aggregation pore volume, V_{agg}, which is assumed to be a linear function of the volume of stored organic matter[1-3]

$$V_{agg} = f_{agg}\left(\frac{M_{som}}{\gamma_{som}}\right)$$

$$V_{text} = \Delta z_{min}\left(1 + \left(\frac{\gamma_{b(max)}}{\gamma_{min}}\right)\right)$$

- The textural porosity is partitioned between the micropores and mesopores (as a function of the particle size distribution)

[1]Emerson, W., McGarry, D. 2003. Australian Journal of Soil Research, 41, 107-118
[2]Boivin, P., et al. 2009. European Journal of Soil Science, 60, 265-275
[3]Johannes A., et al. 2017. Geoderma, 302, 14-21.

Testing the model – sensitivity analysis

- 500 simulations over a period of 2000 years (each)
  - Different parameter values obtained by Latin hypercube sampling
- How are the targeted outputs (f_{som}, γ_b, f_{mic}) influenced by parameter changes?
  - Partial rank correlation coefficients

Parameter	**Sampled range**	**Partial correlation coefficients, r**		
		f_{som}	γ_b	f_{mic}
1st order rate coefficient, k_y [year^{-1}]	0.1 – 1.0	**-0.54**	**0.37**	-0.10
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Aggregation factor, f_{agg} [-]	2 – 4	0.0	**-0.50**	0.02

Testing the model – parameter identifiability

! Sensitive parameters are not necessarily identifiable in a calibration procedure, since their effects on the target outputs may be correlated !

- Created synthetic data by running the model for 50 years given two scenarios with different OM inputs:
  - (i) no input (bare fallow), (ii) constant input of 0.06 g cm^{-2} $year^{-1}$
    - Outputs: SOM concentration (every 5^{th} year), bulk density and microporosity (at three occasions)
- Stella-internal calibration method (Powell) to check if the parameters can be identified

Parameters	Value used for data generation (true value)	Sampled range during calibration
1^{st} order rate coefficient, k_y [$year^{-1}$]	0.40	0.1 – 1.0
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