Representation of Soil Carbon Dynamics and Nitrogen Limitation of Decomposition in Terrestrial Ecosystem Models: Present and Future Directions

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Do Climate Models Need Soil C-N Dynamics?

- Latent heat simulation requires stomatal conductance calculation – depends, in part on leaf N concentration.
- Carbon stocks in soil show sensitivity to inclusion of N dynamics.
- Models that include N dynamic in soil C decomposition show a tendency for reduced heterotrophic respiration.

OCN Changes in C stocks (kg C m^{-2}) 1860-2100

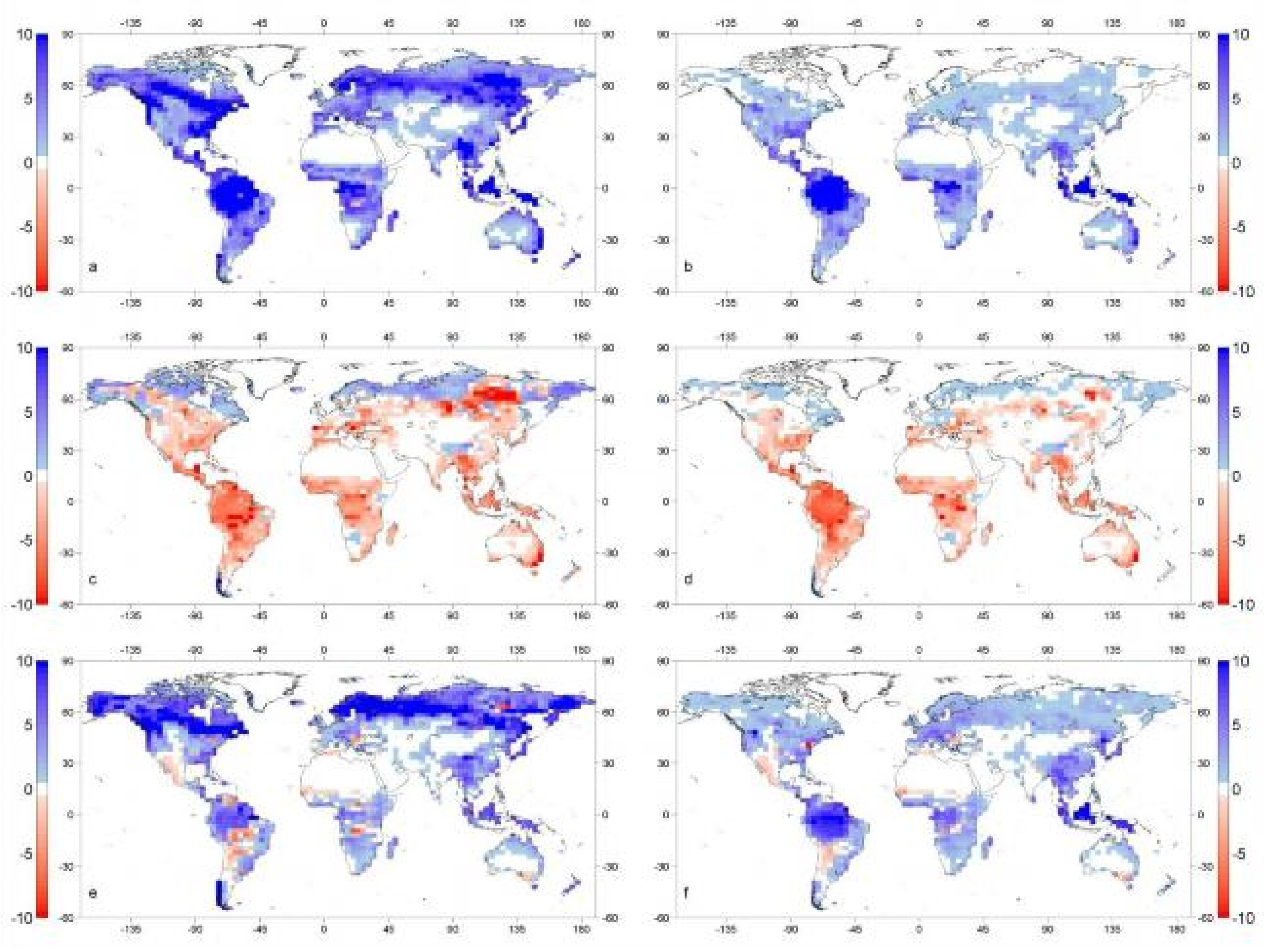
Carbon Only

Carbon –Nitrogen Model

CO_2

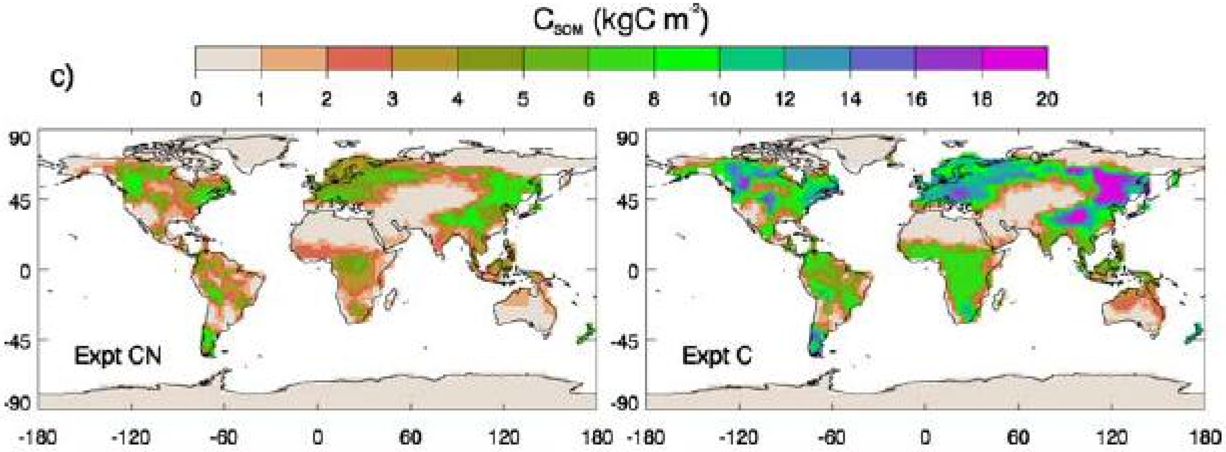
Climate

All Factors - Including N deposition



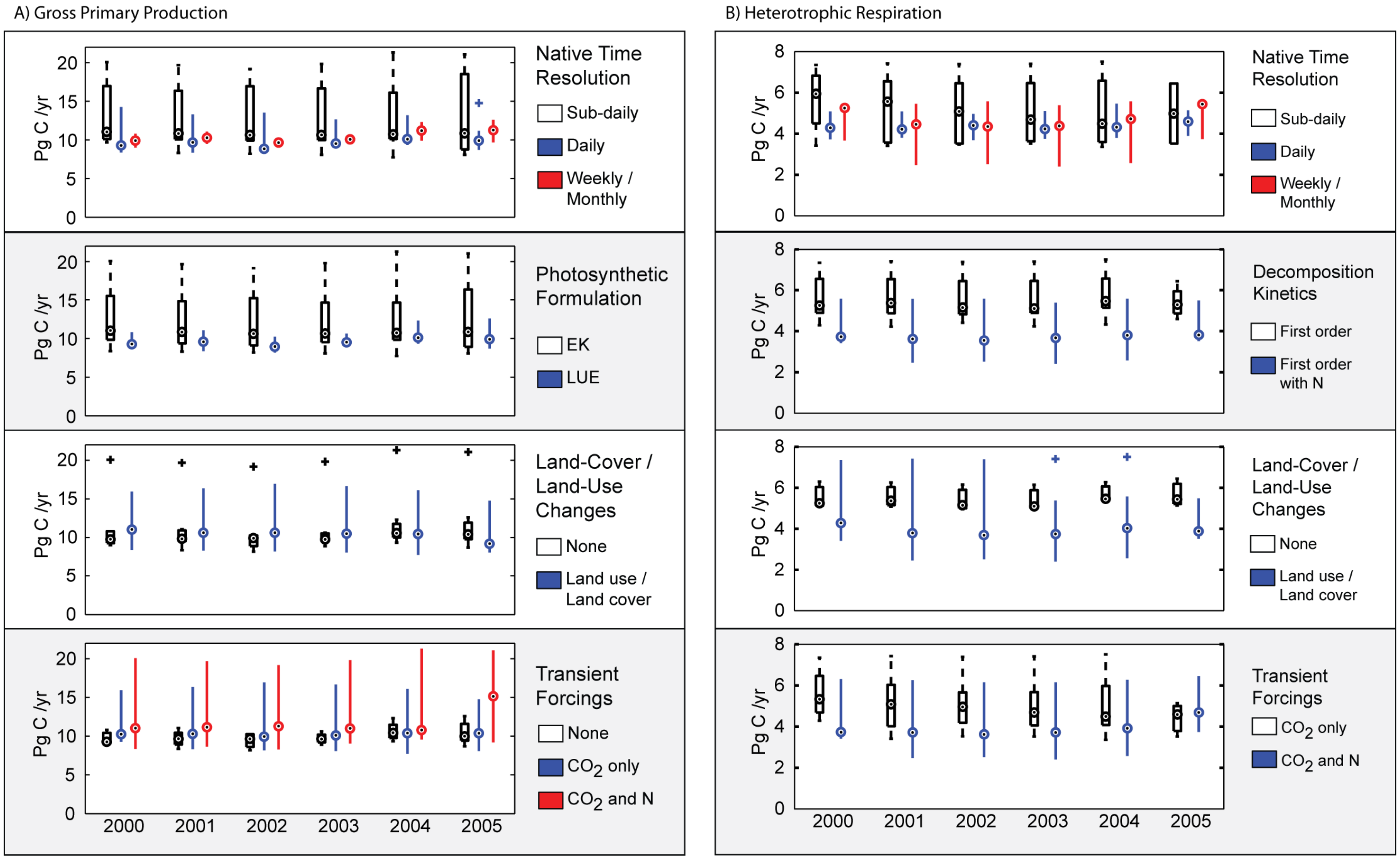
From Zaehle et al. 2010.

CLM-CN



Experiment	Wood C[b]	Veg. C	CWD C[c]	Litter C	SOM C[d]	Total C
			Control			
CN	613 (53)	653 (57)	147 (13)	16 (1)	334 (29)	1150
C	943 (47)	1014 (50)	247 (12)	28 (1)	736 (36)	2026
C_T	712 (49)	771 (53)	167 (11)	19 (1)	496 (34)	1452
			Years 1976–2000			
CN+co2	649 (54)	690 (58)	153 (13)	16 (1)	339 (28)	1199
CN+ndep	619 (53)	660 (57)	149 (13)	16 (1)	339 (29)	1163
CN+co2ndep	656 (54)	698 (57)	155 (13)	17 (1)	344 (28)	1213
C+co2	1047 (48)	1125 (51)	269 (12)	31 (1)	776 (35)	2201
C_T+co2	803 (50)	870 (54)	184 (11)	22 (1)	537 (33)	1612
			Years 2076–2100			
CN+co2	801 (57)	845 (60)	176 (13)	18 (1)	357 (26)	1397
CN+ndep	642 (53)	684 (57)	154 (13)	17 (1)	352 (29)	1206
CN+co2ndep	847 (57)	895 (60)	186 (13)	19 (1)	379 (26)	1480
C+co2	1527 (52)	1625 (55)	363 (12)	39 (1)	936 (32)	2963
C_T+co2	1225 (54)	1309 (57)	263 (12)	28 (1)	683 (30)	2284

NACP Regional Synthesis


A) Gross Primary Production

B) Heterotrophic Respiration

Climate Models Need Accurate Representations of Soil C-N Dynamics

- Soil C decomposition representations have not principally changed in 30 years.
- While soil models differ in many details,
  - N dynamics generally follow C dynamics,
  - N becomes available as a result of stoichiometry constraints.
- All climate models, to my knowledge, used at global scale use first order “donor control” kinetics.

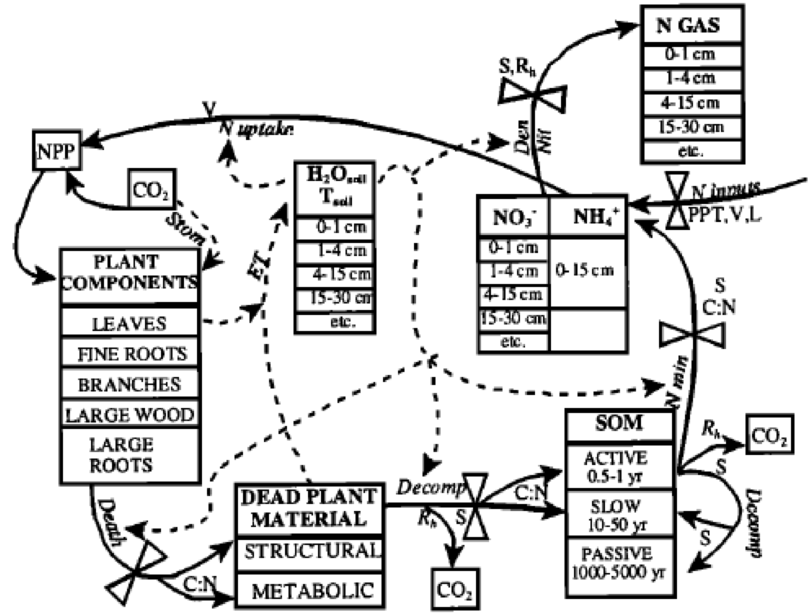
Jenny/Olson (1963) Paradigm

$$dC / dt = I - kC$$

- CENTURY/DAYCENT in OCN, CASA-CNP, CASA-GFED, LM3V, many others at regional scales
- RothC/SUNDIAL in ISAM,
- Biome-BGC in CLM-CN
- In each model the associated N turnover is determined by C dynamics among various C pools and stoichiometry.

Decomposition Model Structures

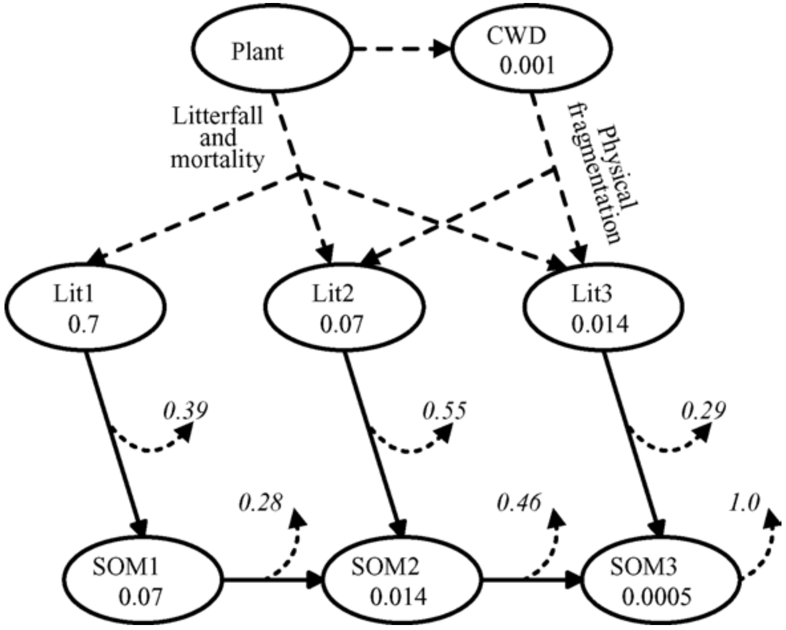
CENTURY/DAYCENT



= C, N flows
= Feedbacks, information flows
= Control on process
H_2O_{soil} = Soil water content
T_{soil} = Soil temperature
S = Soil texture
C:N = Carbon:Nitrogen ratio of material
V = Vegetation type
SOM = Soil Organic Matter
L = Land use
R_h = Heterotrophic respiration

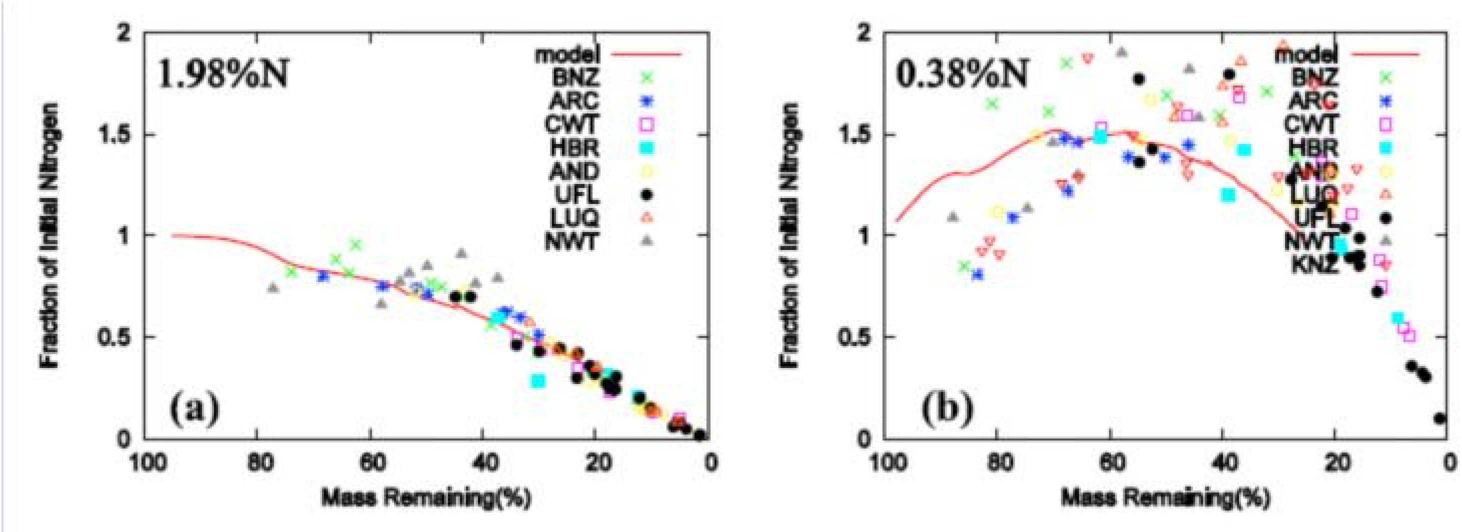
N GAS = N_2O, NO_X, N_2
Processes designated by *italics*
Stom = Stomatal conductance
Death = Plant component death
Decomp = Decomposition
N inputs = N Fixation, N deposition, N fertilization
Nit = Nitrification
Den = Denitrification
N min = N mineralization
ET = Evapotranspiration

CLM-CN (after Biome-BGC)



Converging cascade model of litter and soil organic matter decomposition. The model includes three litter pools (Lit1, Lit2, and Lit3, see text) and three soil organic matter pools (SOM1, SOM2, and SOM3).

ISAM



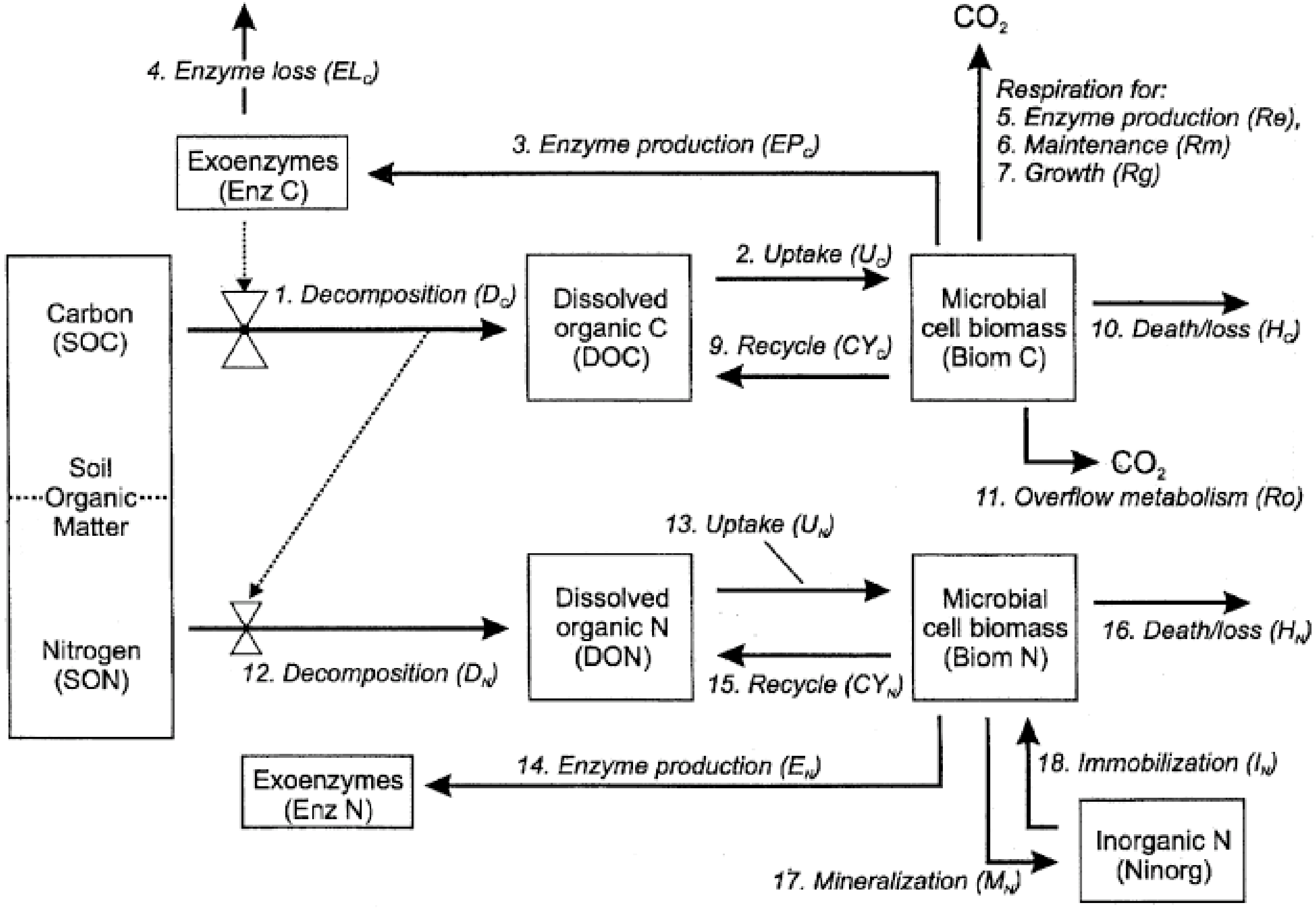
Fraction of initial litter N remaining as a function of the leaf litter mass remaining, with (a) high N litter with 1.98% N and (b) low N litter with 0.38% N. The lines in the graphs are model simulations averaged across all LIDET sites involved.

(Yang et al. 2009)

Why Do We Need to Consider a New Approach?

- Substrate supply models are immensely useful:
  - Capture major components of observed soil C spatial patterns
  - Kinetics generally consistent with long-term experimental finding
- However, there are important phenomena that are not directly addressed:
  - Priming (Wutzler and Reichstein 2007)
  - Divergent results from N fertilization experiment
  - Mineral soil interactions (Heal et al. in press)
  - Complicated temperature responses (Davidson and Janssens 2006)

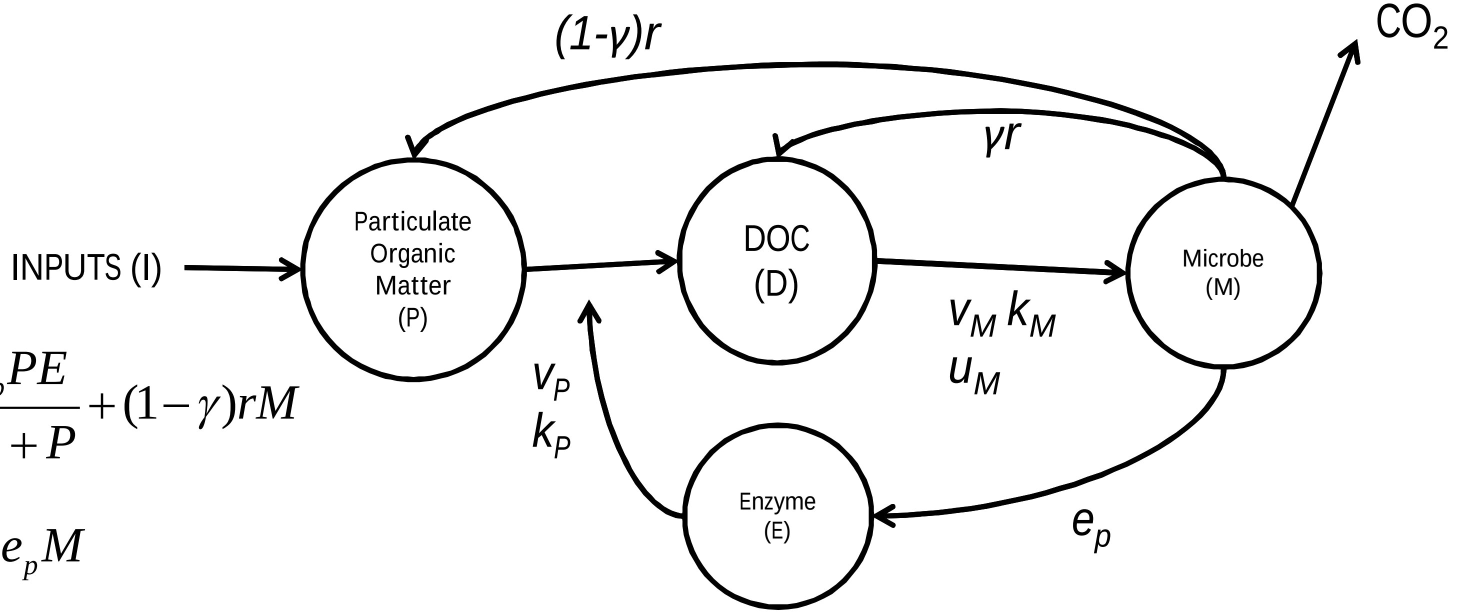
Decomposition is an Enzyme Kinetic Process



from Schimel and Weintraub (1993)

Carbon Equations

After Allison et al. (2010)



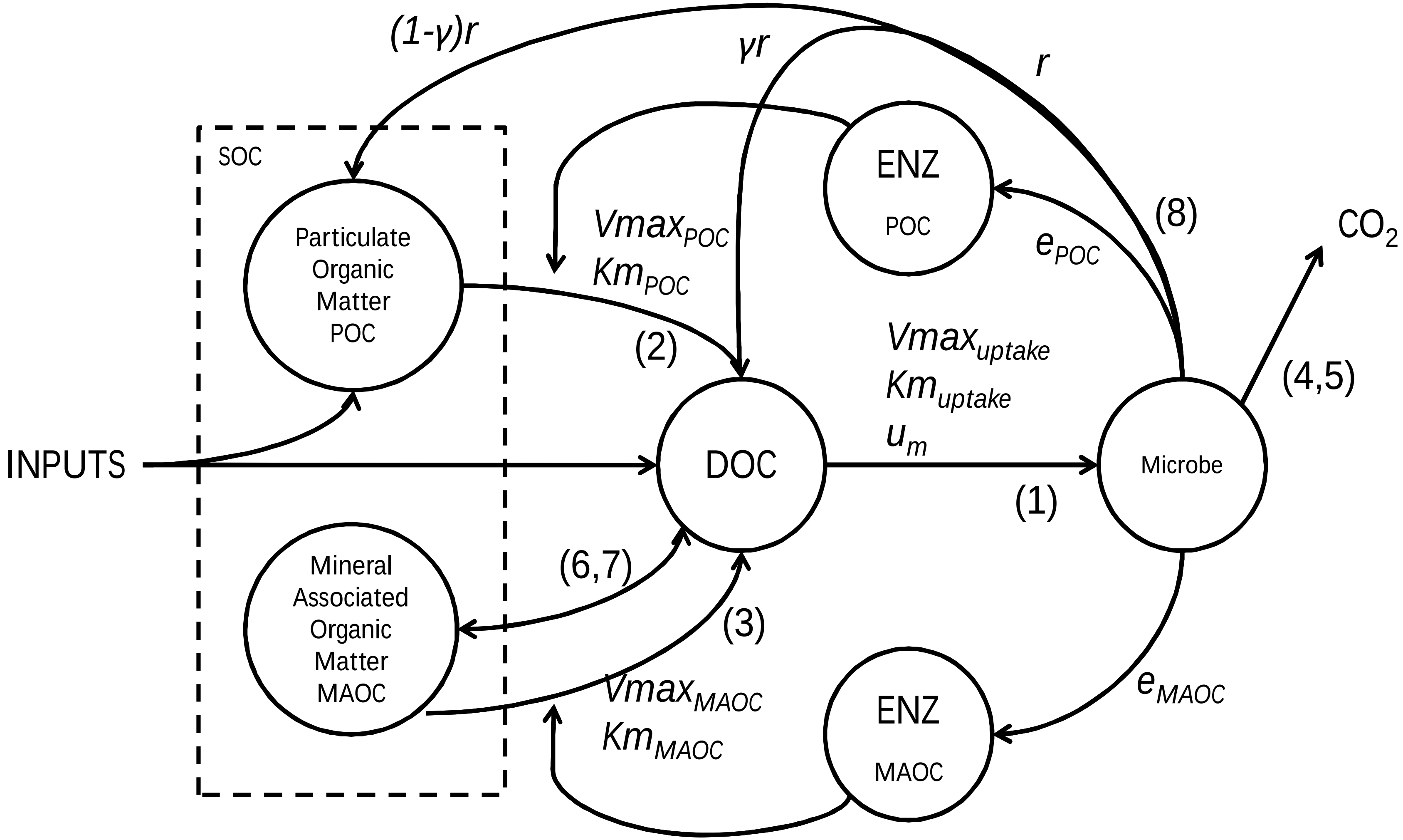
$$\frac{dP}{dt} = I_P - \frac{v_p PE}{k_P + P} + (1-\gamma)rM$$

$$\frac{dE}{dt} = -pE + e_p M$$

$$\frac{dD}{dt} = \frac{v_P PE}{k_P + P} - \frac{v_M MD}{k_m + D}$$

$$\frac{dM}{dt} = u_M \frac{v_M MD}{k_M + D} - rM - e_p M - m_r M$$

Include Representation of Mineral Interactions

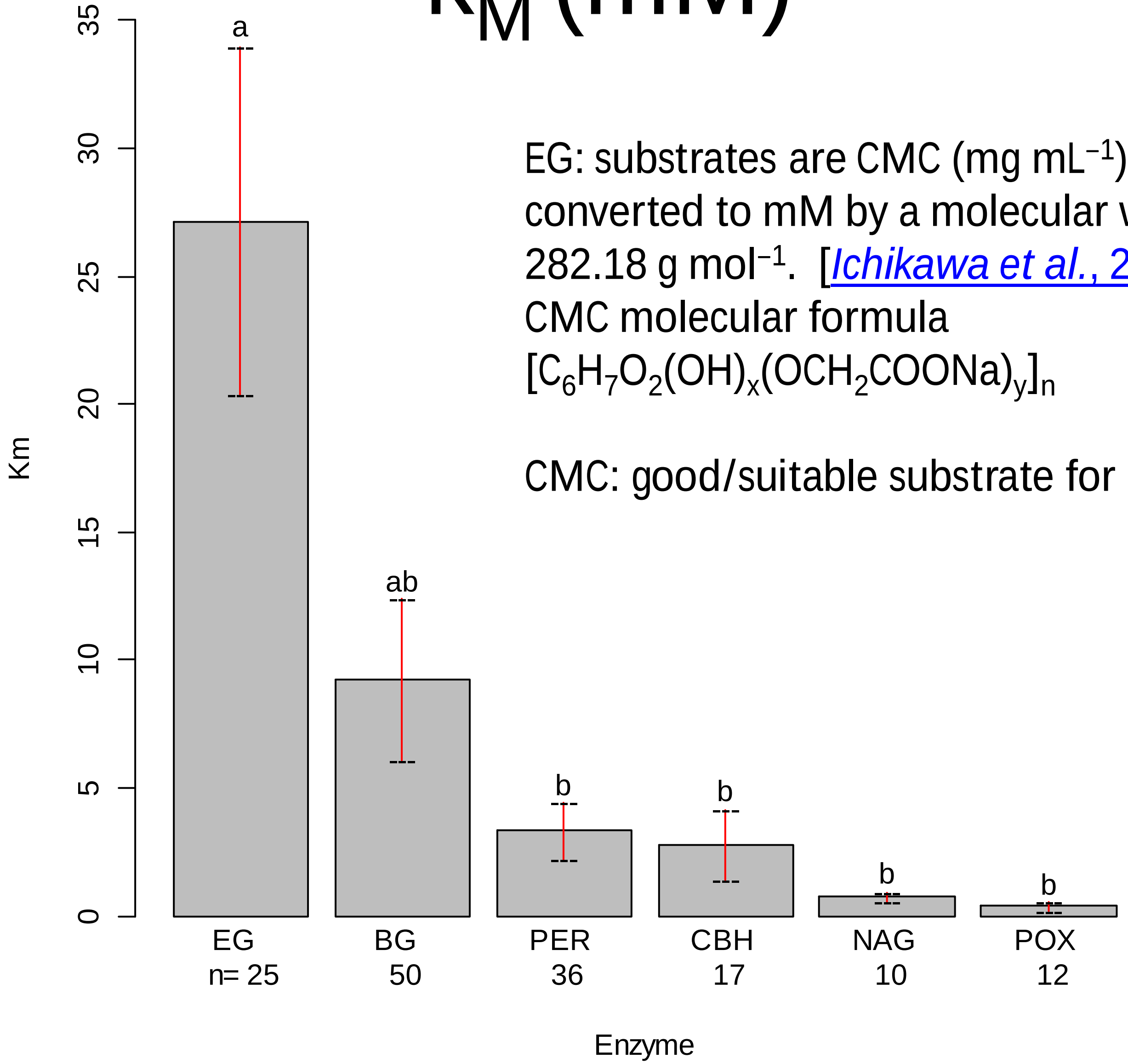


Soil Enzymes

Process	Enzyme	Abbr.	EC	Substrate
Degradation of Lignin	**Laccase (phenol oxidase)**	**POX**	1.10.3.2	L-3,4-dihydroxyphenylalanine (DOPA)
	Peroxidase	**PER**	1.11.1.7	DOPA + H_2O_2
Degradation of Cellulose	**β-1,4-glucosidase; Cellobiase**	**BG**	3.2.1.21	4-methylumbelliferone (MUB)-β-D-glucoside; p-nitrophenyl (pNP)-glucopyranoside
	Cellobiohydrolase ; Exoglucanase; Cellulose 1,4-β-cellobiosidase	**CBH**	3.2.1.91	4-MUB-β-D-cellobioside; pNP-β-D-cellobioside
	Endo-glucanase Cellulase Carboxymethylcellulase	**EG**	3.2.1.4	Carboxymethyl cellulose (CMC)
N acquisition	**N-acetyl-β-D-glucosaminidase; β-1,4-N-acetylglucosaminidase**	**NAG**	3.2.1.14 3.2.1.52	4-MUB-N-acetyl-β-D-glucosaminide; pNP-β-N-acetylglucosaminide

72 papers
181 observations

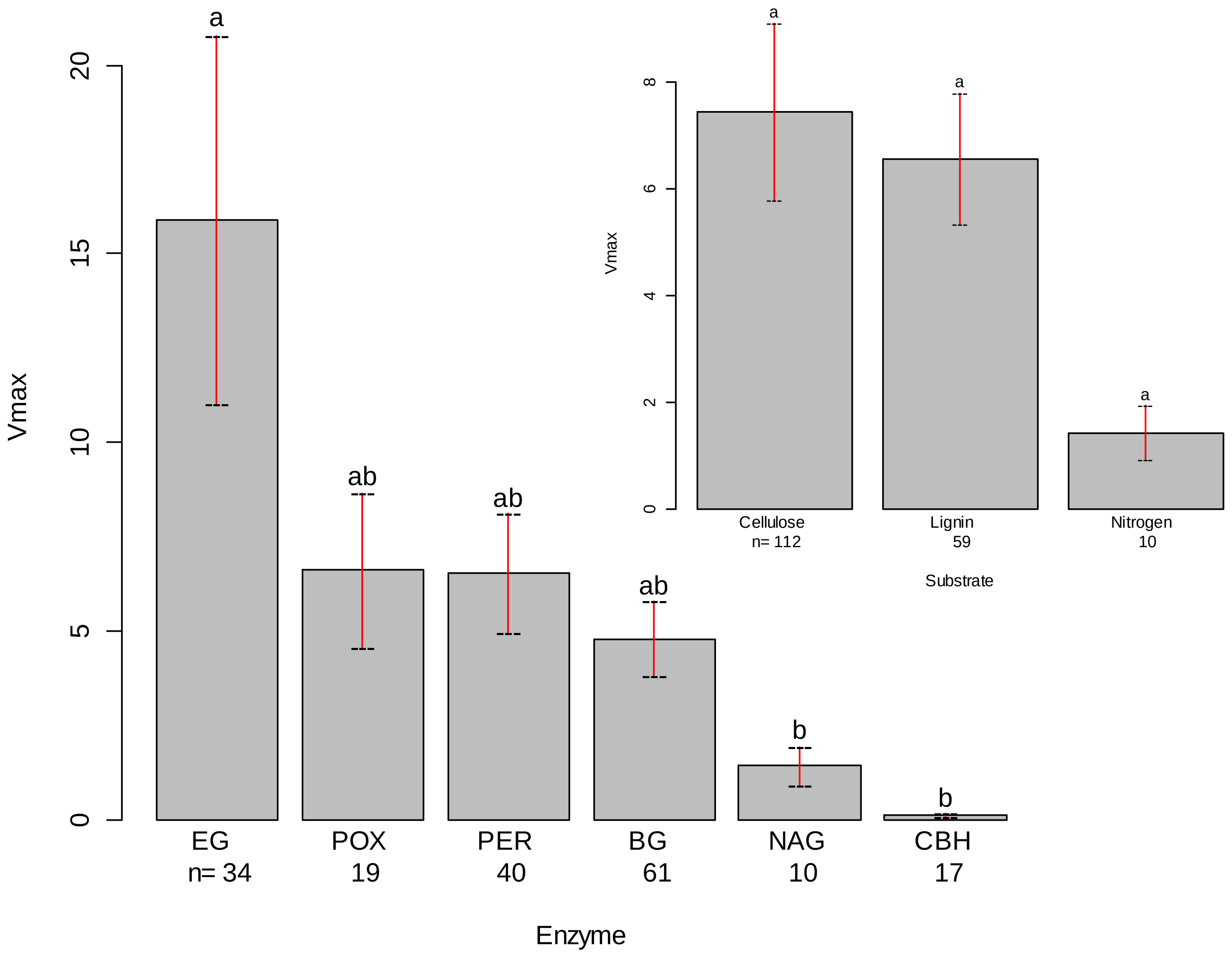
k_M (mM)



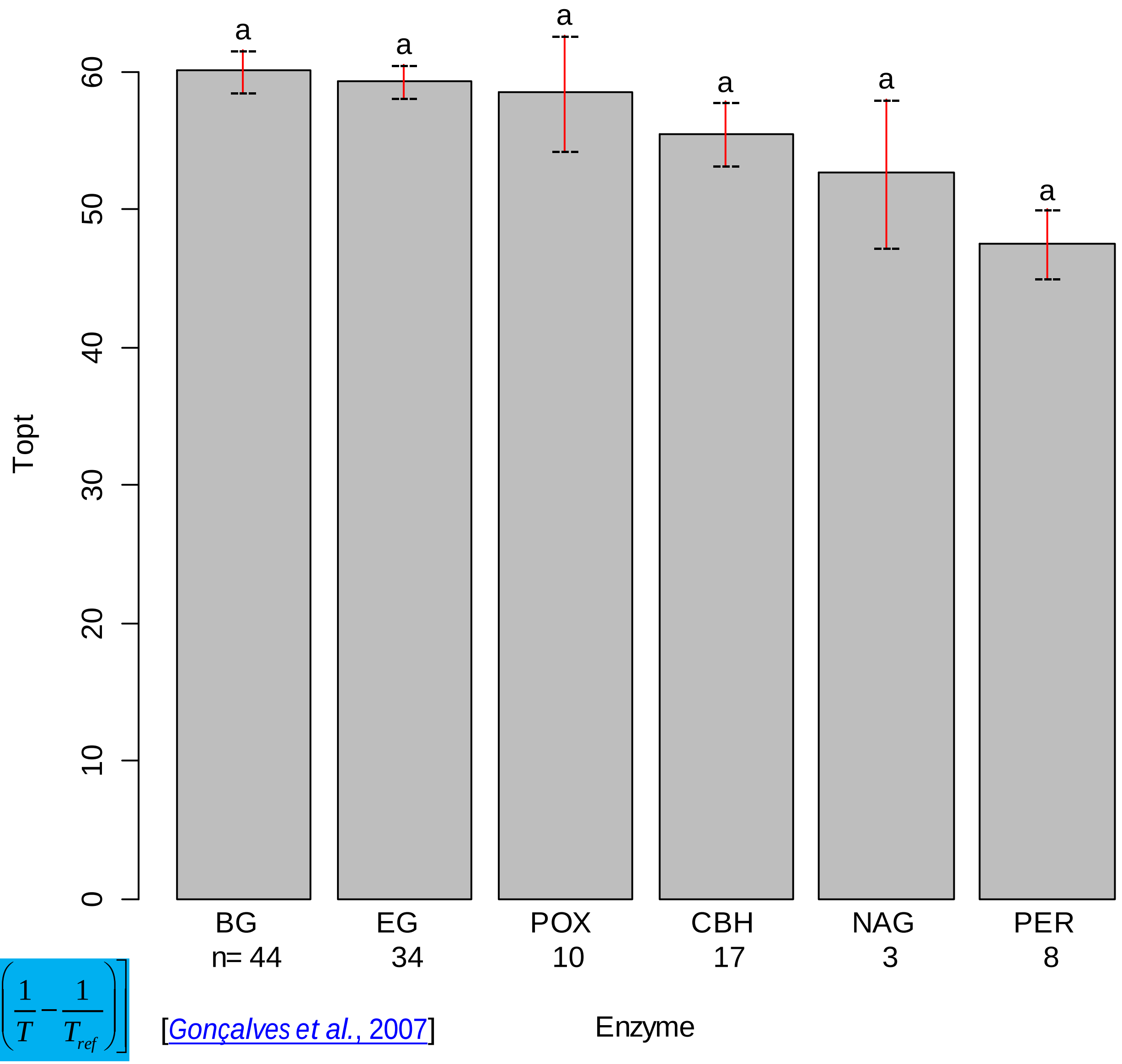
EG: substrates are CMC (mg mL^{-1}), which is converted to mM by a molecular weight of 282.18 g mol^{-1}. [*Ichikawa et al.*, 2005]
CMC molecular formula
$[C_6H_7O_2(OH)_x(OCH_2COONa)_y]_n$

CMC: good/suitable substrate for EG

v_m (mmol Enzyme mg^{-1} soil h^{-1}) at 20 °C & pH_{opt}



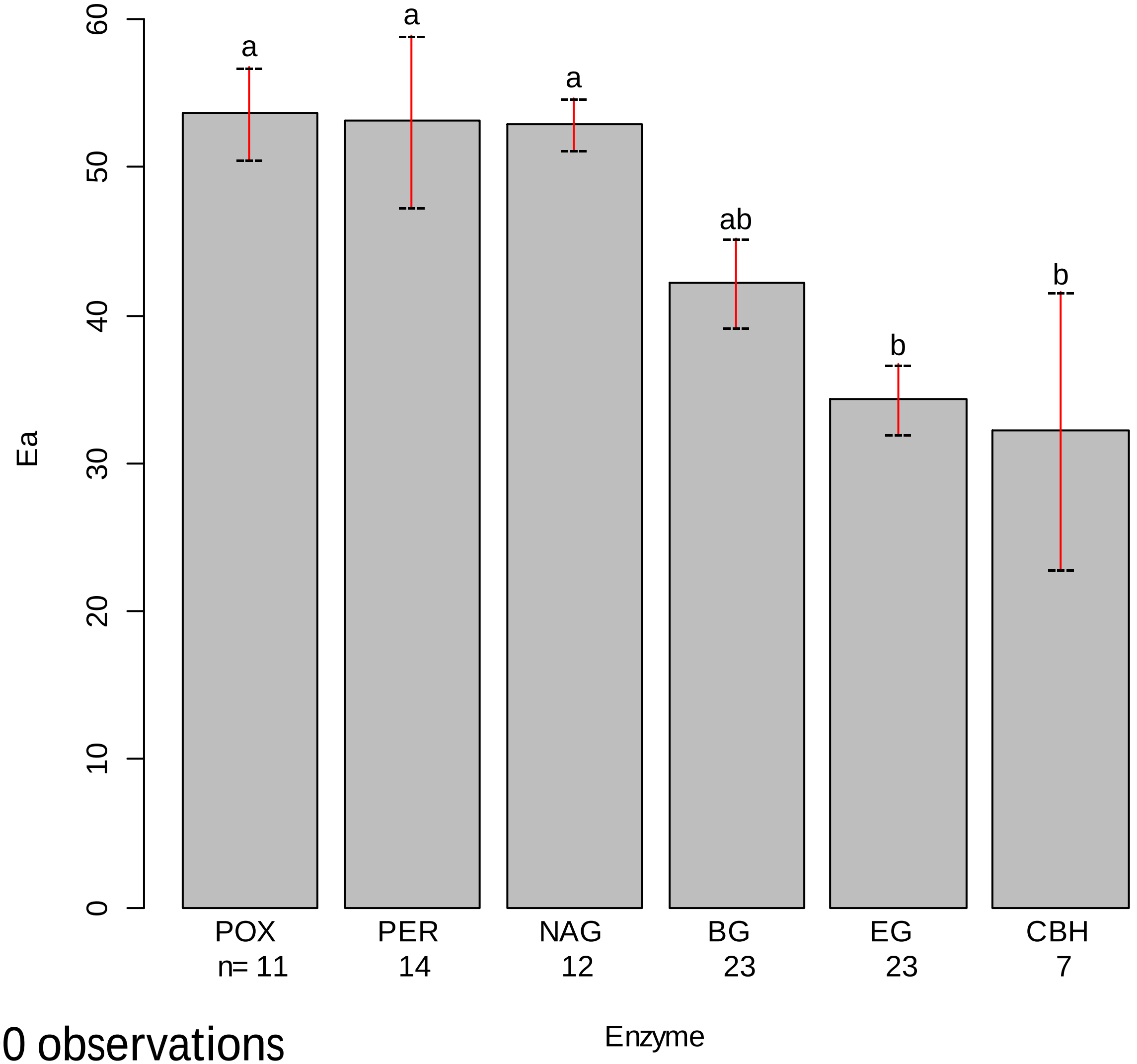
Optimum Temperature (°C)



$$V = V_{ref} \cdot \exp\left[-\frac{E_a}{R}\left(\frac{1}{T}-\frac{1}{T_{ref}}\right)\right]$$

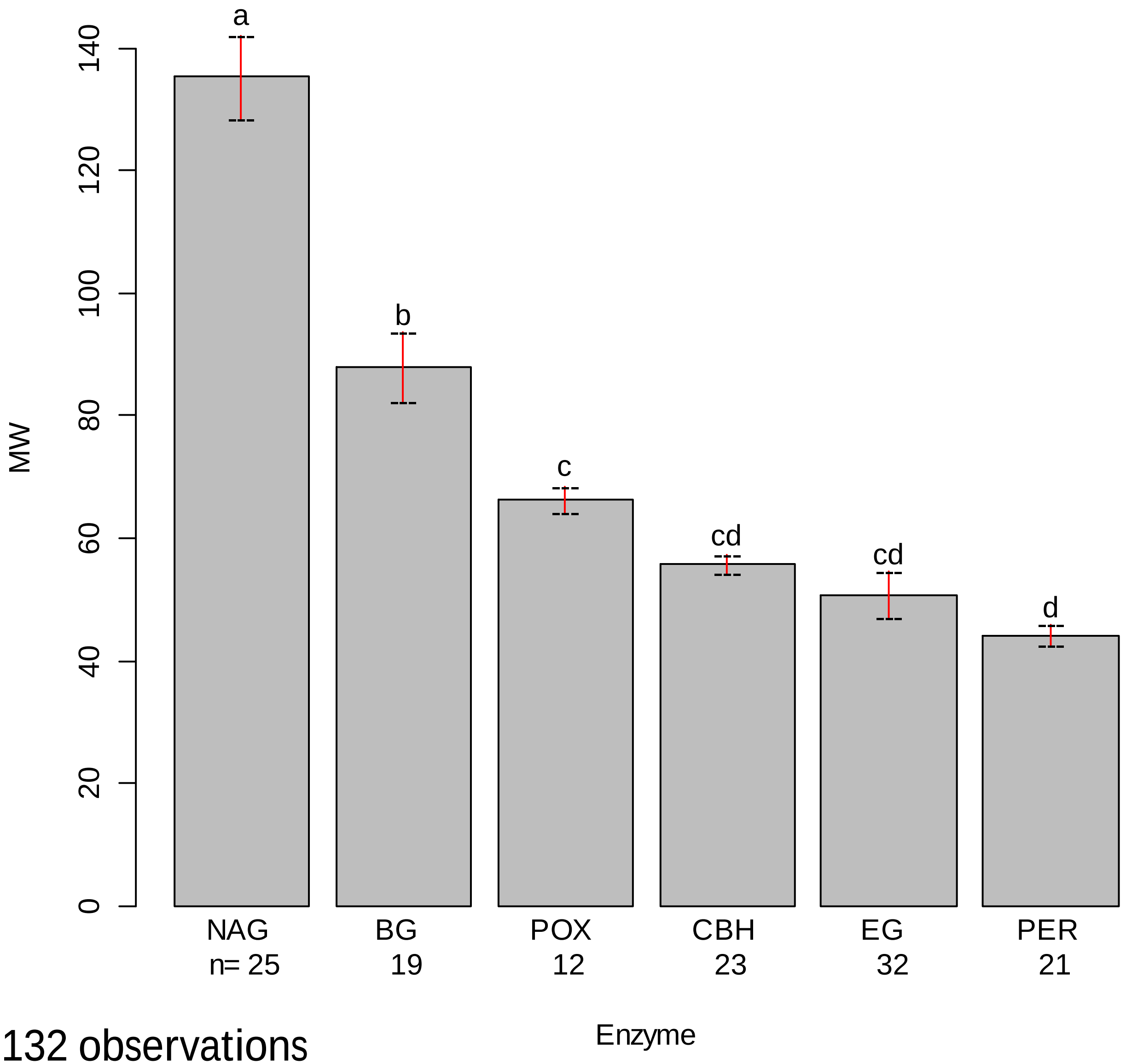
[*Gonçalves et al.*, 2007]

Activation Energy (kJ mol^{-1})



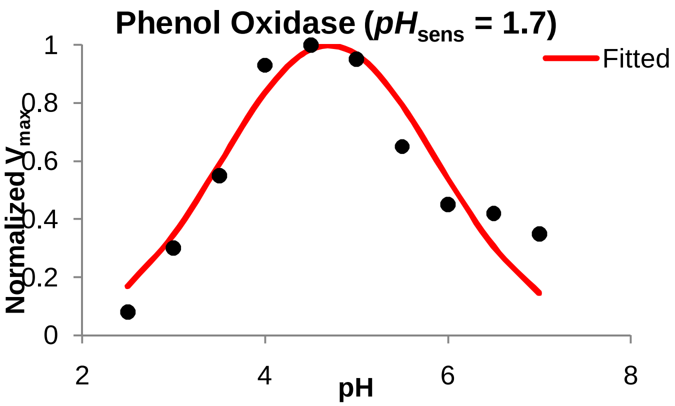
42 papers, 90 observations

Molecular Weight (kDa)

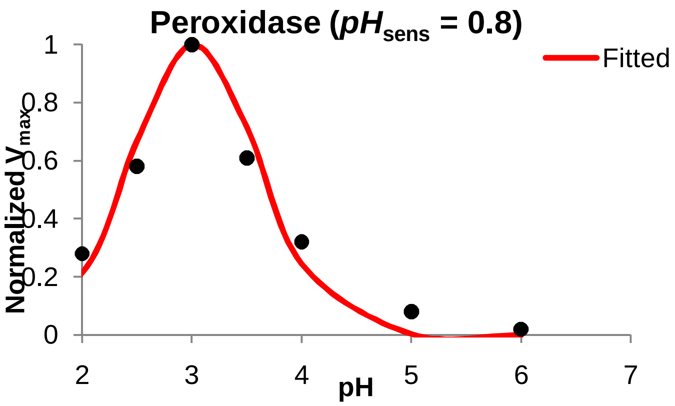


83 papers, 132 observations

pH response
(exponential-quadratic)



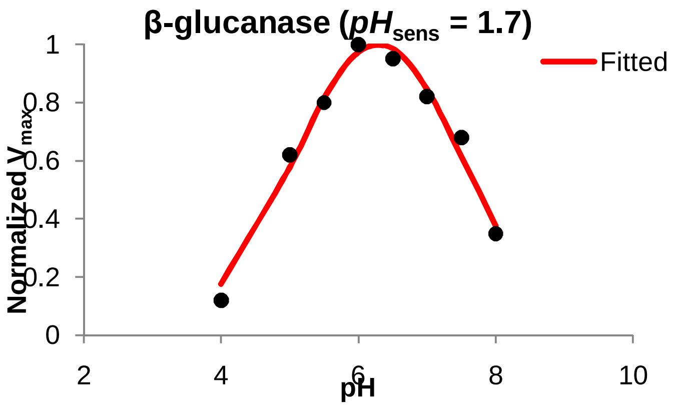
Phenol Oxidase (pH_{sens} = 1.7)



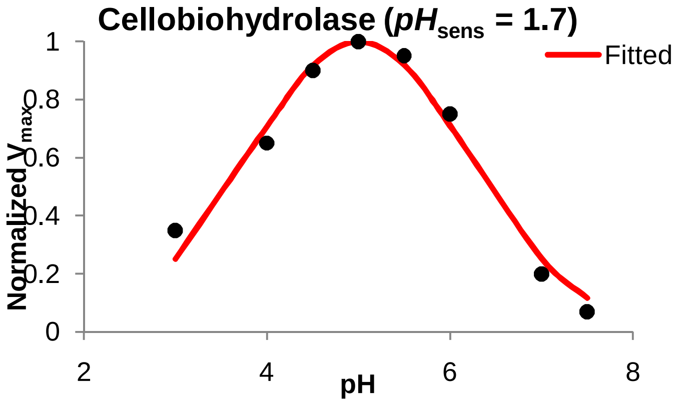
Peroxidase (pH_{sens} = 0.8)

$$m_{pH} = \exp\left[-\left(\frac{pH - pH_{opt}}{pH_{sen}}\right)^2\right]$$

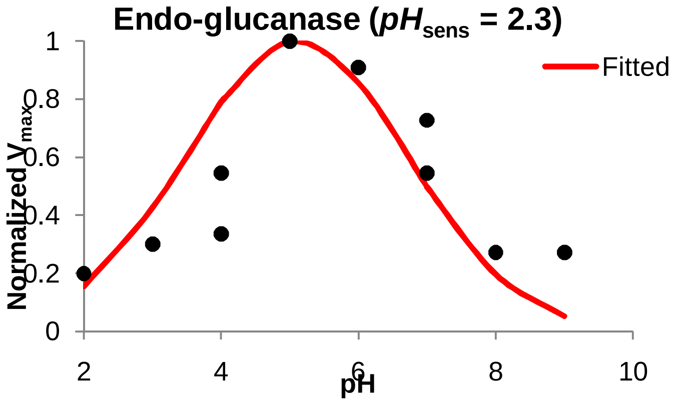
(data complied from Patchett et al., 1987; Gusakov et al., 2005; Lee and Jeya, 2010; Guida et al., 2011; Liers et al., 2007)



β-glucanase (pH_{sens} = 1.7)



Cellobiohydrolase (pH_{sens} = 1.7)



Endo-glucanase (pH_{sens} = 2.3)

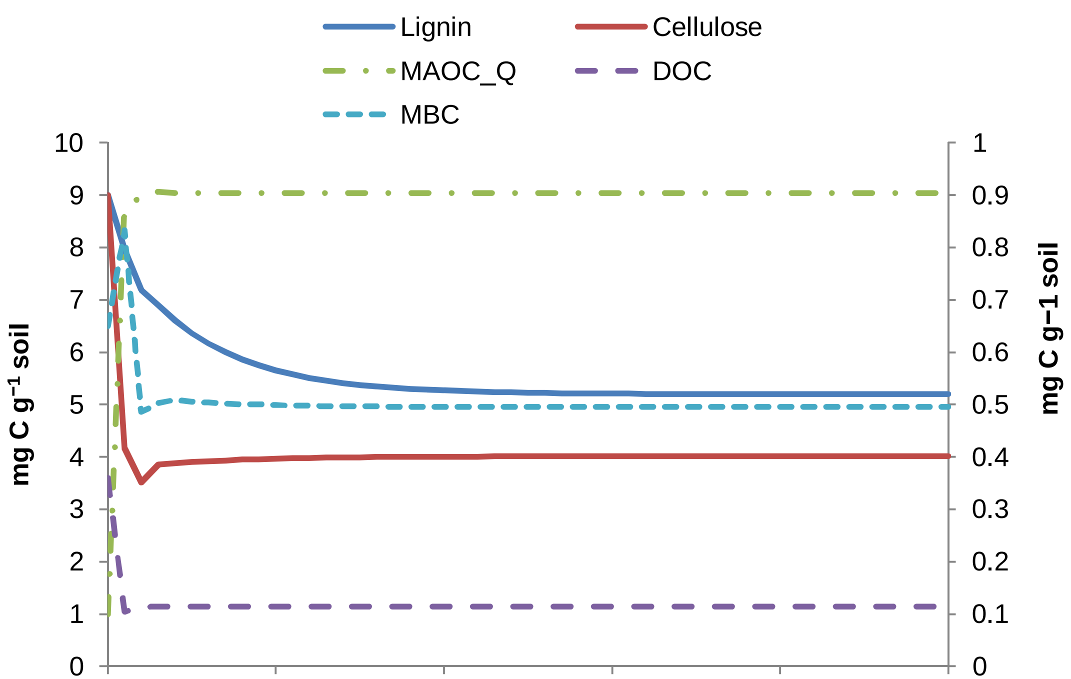
Example Simulation

Spin-up model (50 years)

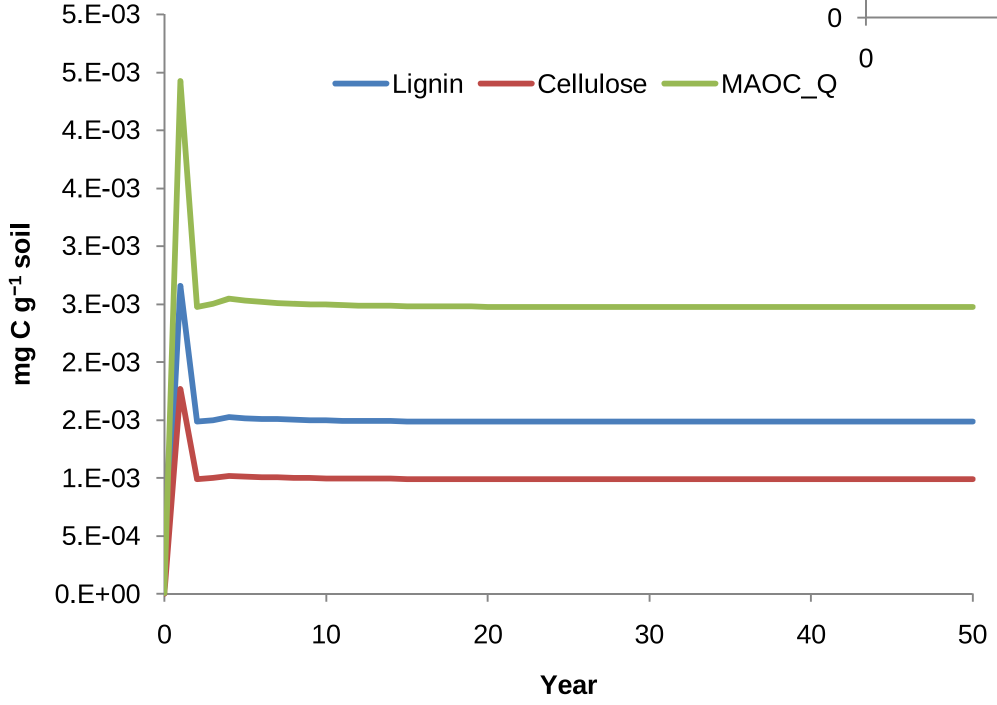
- Soil: Alfisols (SOC=28, DOC=0.36, MBC=0.65 mg C g^{-1})
- T = 20°C
- pH = 6

	Lignin	Cellulose	DOC
External input (×10^{-4} mg C g^{-1} h^{-1})	1	5	5
V_{max} (mg C mg^{-1} ENZ h^{-1})	1.54	39.02	
Km (mg C g^{-1})	100	300	

Carbon Pools



Enzyme Pools



Next Steps

- Include N equations
- Reality using long-term experimental datasets
- Currently parameters are estimated using data largely from chemostat experiments
- Estimation of soil enzyme kinetic equation parameters
  - need to be estimated from a combination of field and laboratory experiments
  - using soils and soil carbon substrates

Summary

- C-N interaction effects on decomposition dynamics is currently imposed in models.
- New microbial enzyme kinetics approach shows promise of addressing various observed phenomena from first principles.
- Compromises are required to limit models to manageable complesity.
- New measurement approaches are needed to estimate suitable model parameters.
- Approach offers an opportunity utilize the new information becoming available from microbial genomics.