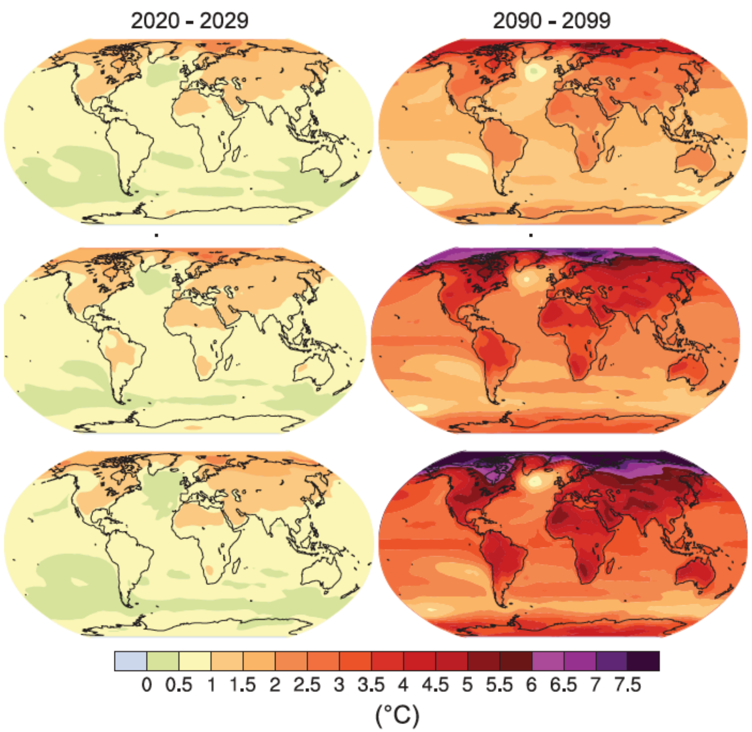
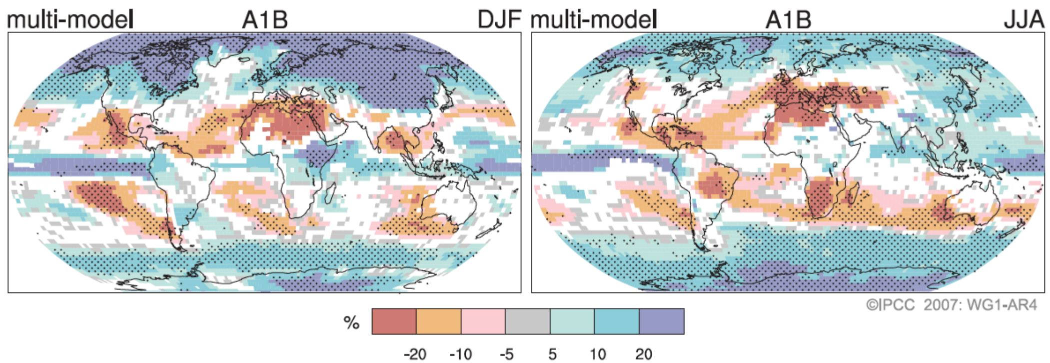
Effects of temperature and moisture on the decomposition of soil organic matter

Instructor: Carlos A. Sierra via Shane Stoner
Max Planck Institute for Biogeochemistry

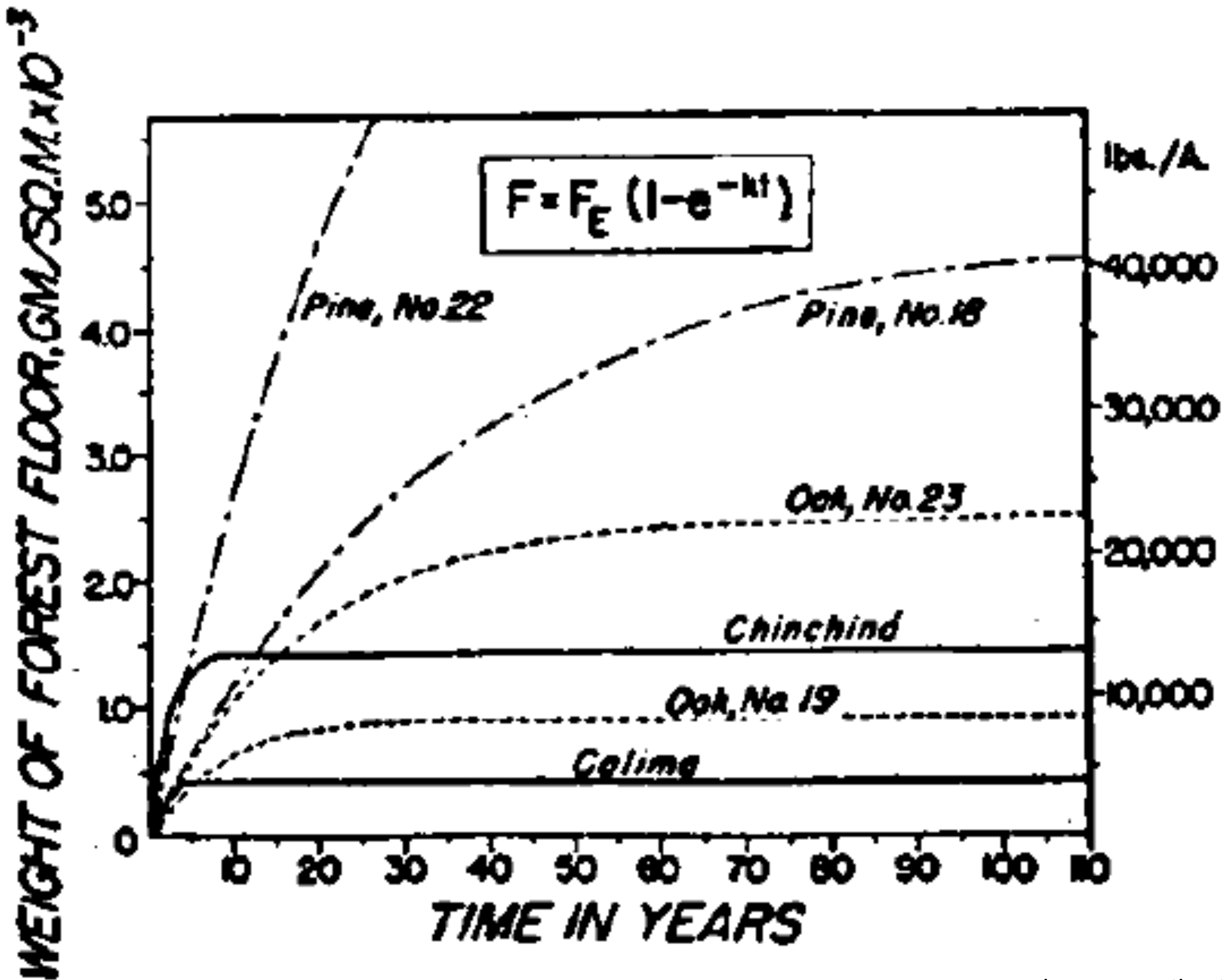
Main research question:

- How do soil processes respond to changes in climate (BOTH temperature and precipitation)?



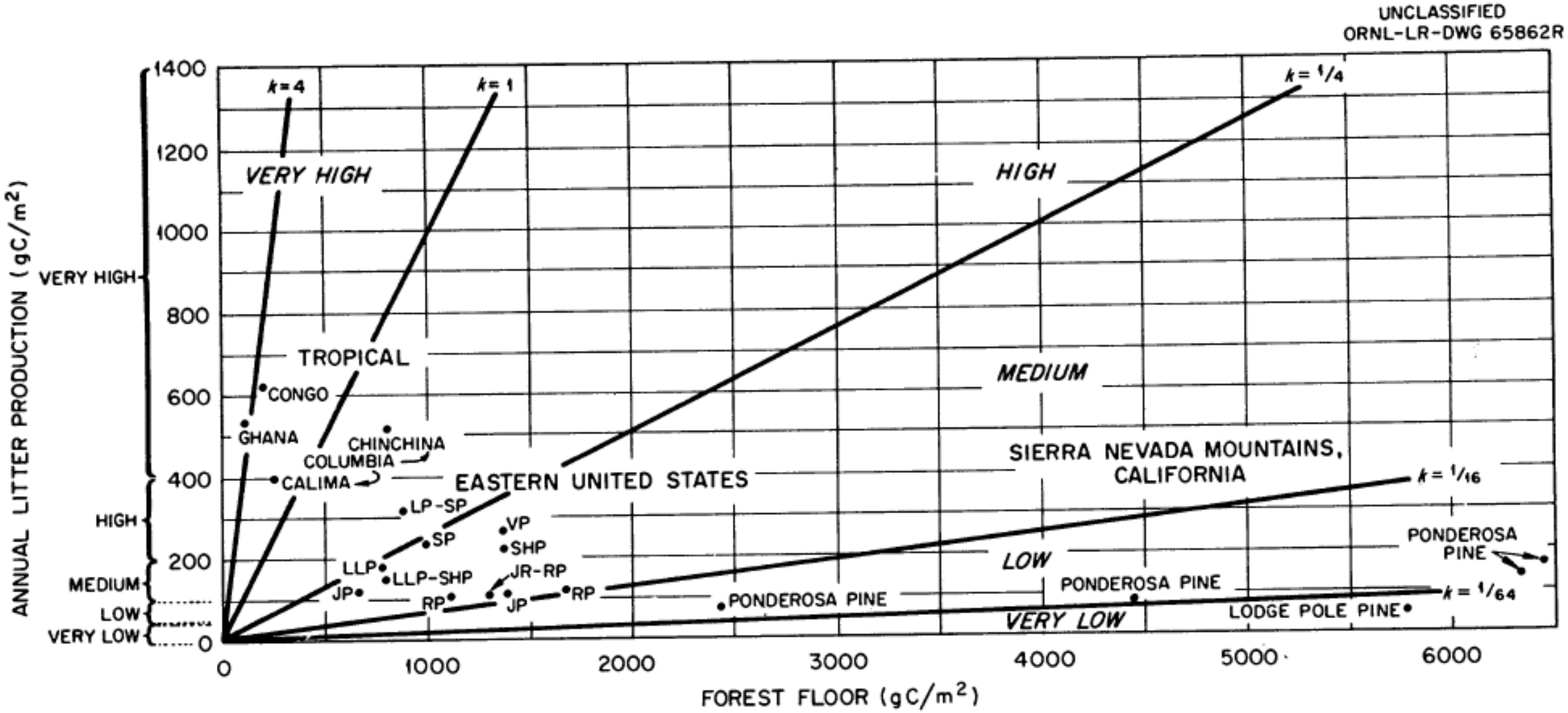


Climate control on soil carbon stocks



Jenny et al. 1949. Soil Science 68: 419.

Climate control on soil carbon stocks



Olson 1963. Ecology 44: 322.

First simulations of projected climate change on soil C release

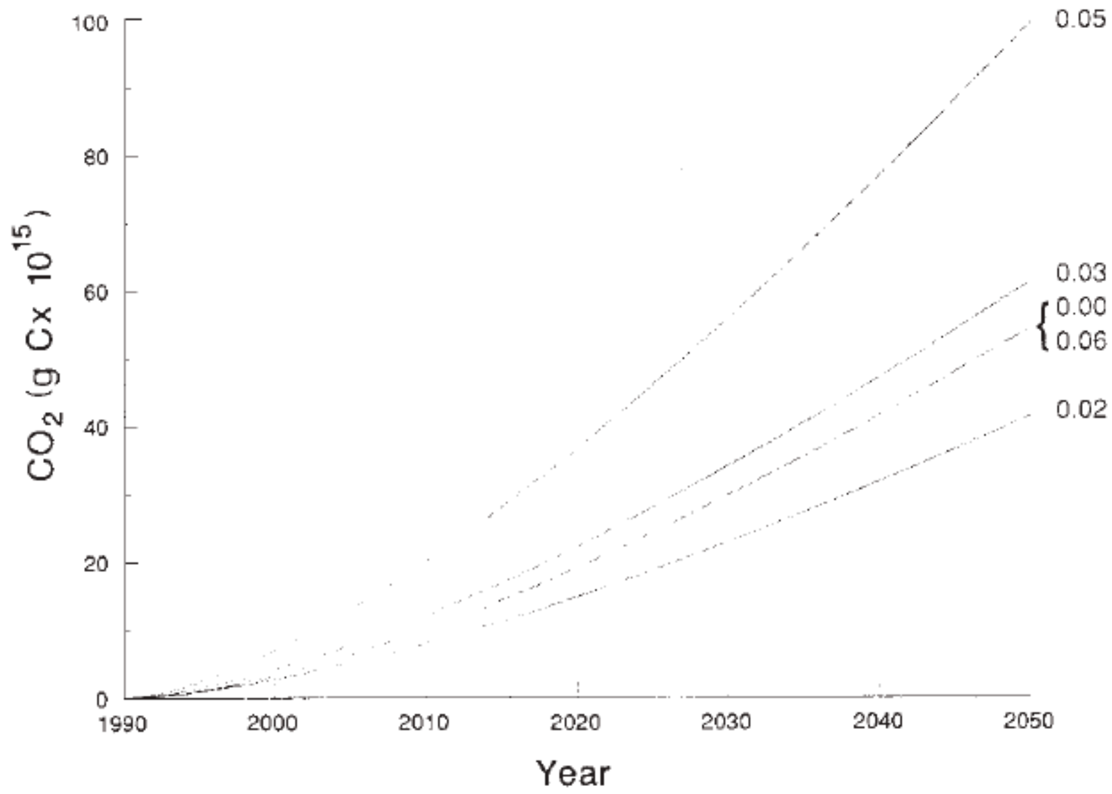
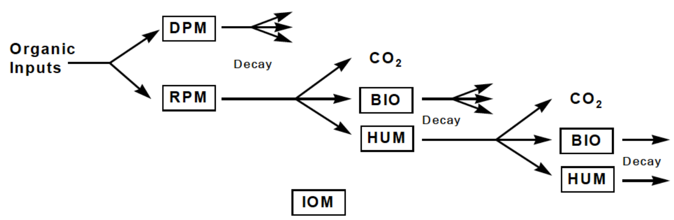


Figure 1 - Structure of the Rothamsted Carbon Model



RPM : Resistant Plant Material
DPM : Decomposable Plant Material
BIO : Microbial Biomass
HUM : Humified OM
IOM : Inert Organic Matter

Jenkinson et al. 1991. Nature 351: 304.

Temperature, moisture and clay content the main factors controlling decomposition in Roth-C

Figure 2 - The rate modifying factor for temperature

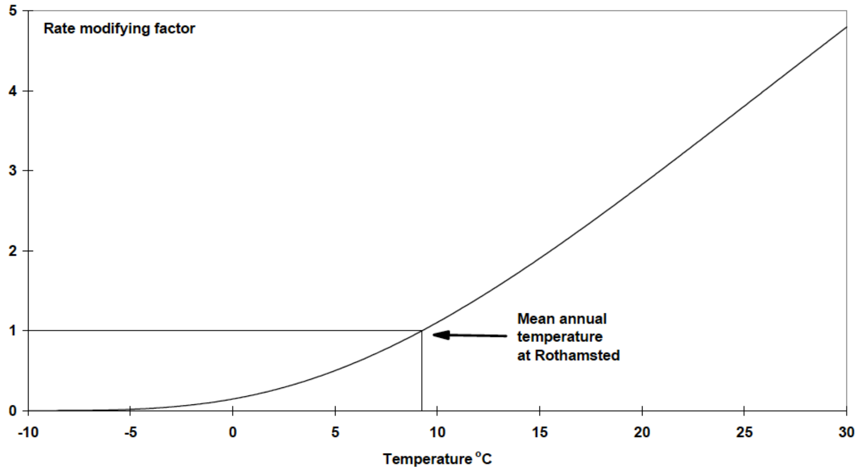


Figure 3 - The rate modifying factor for moisture

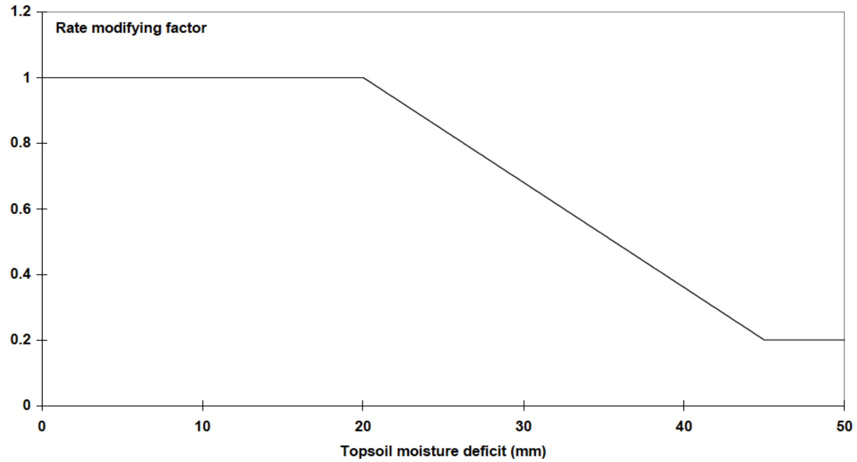
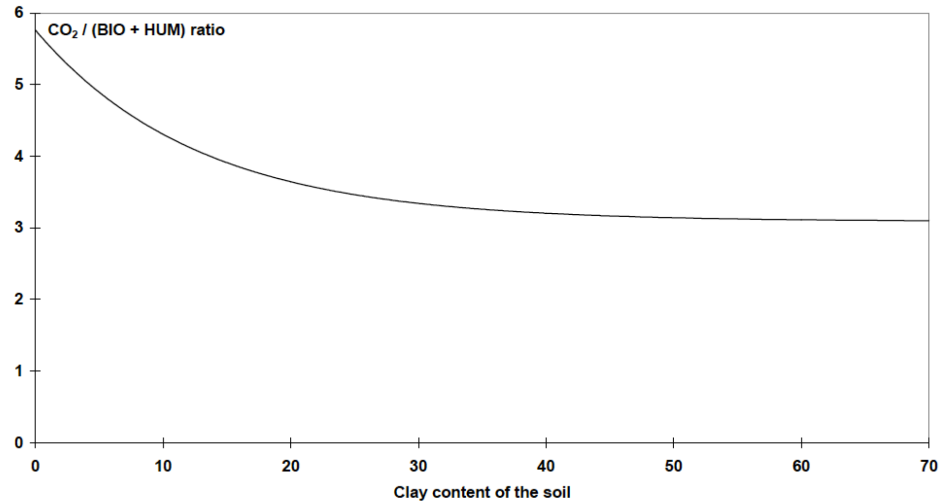
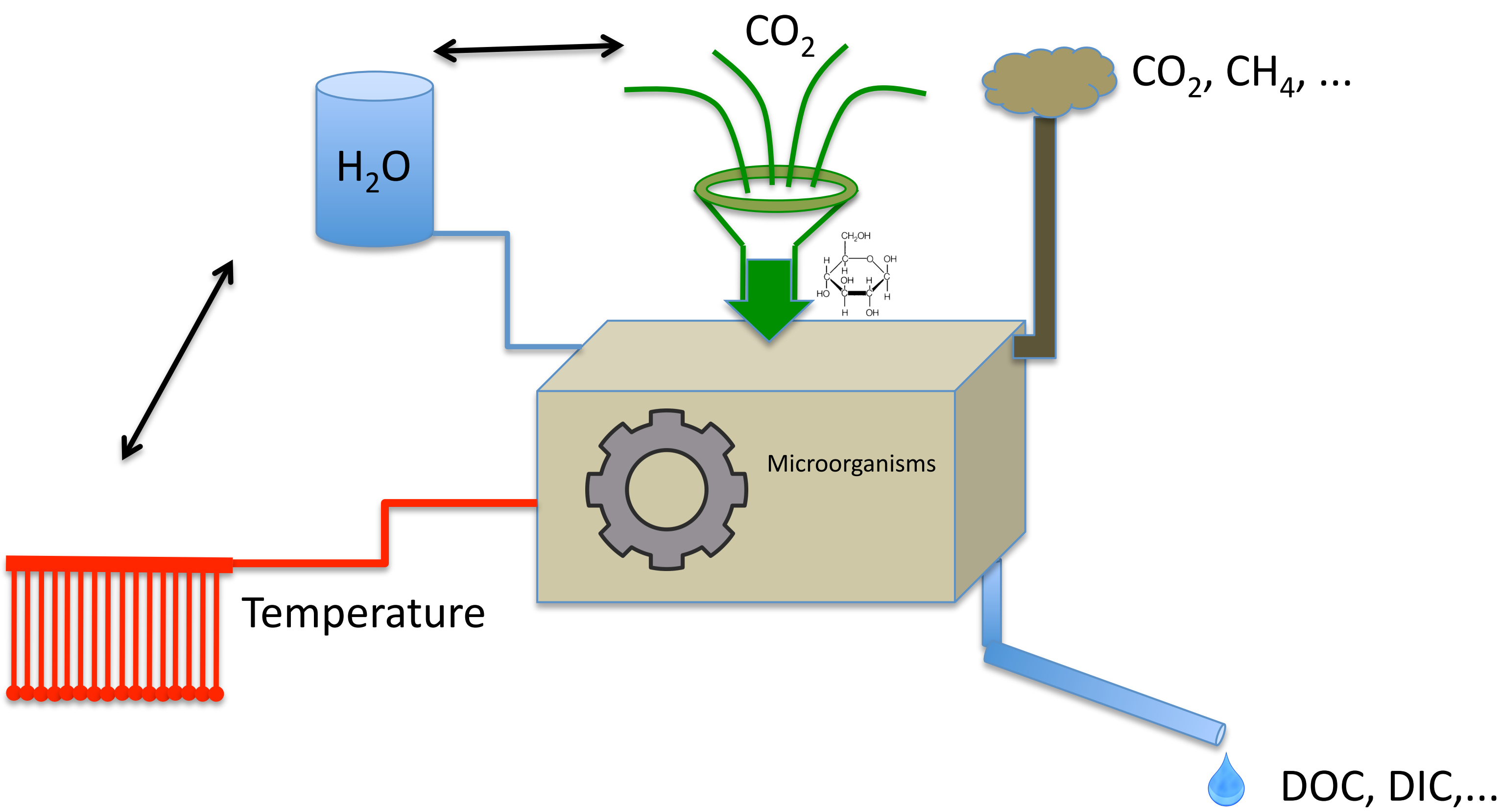


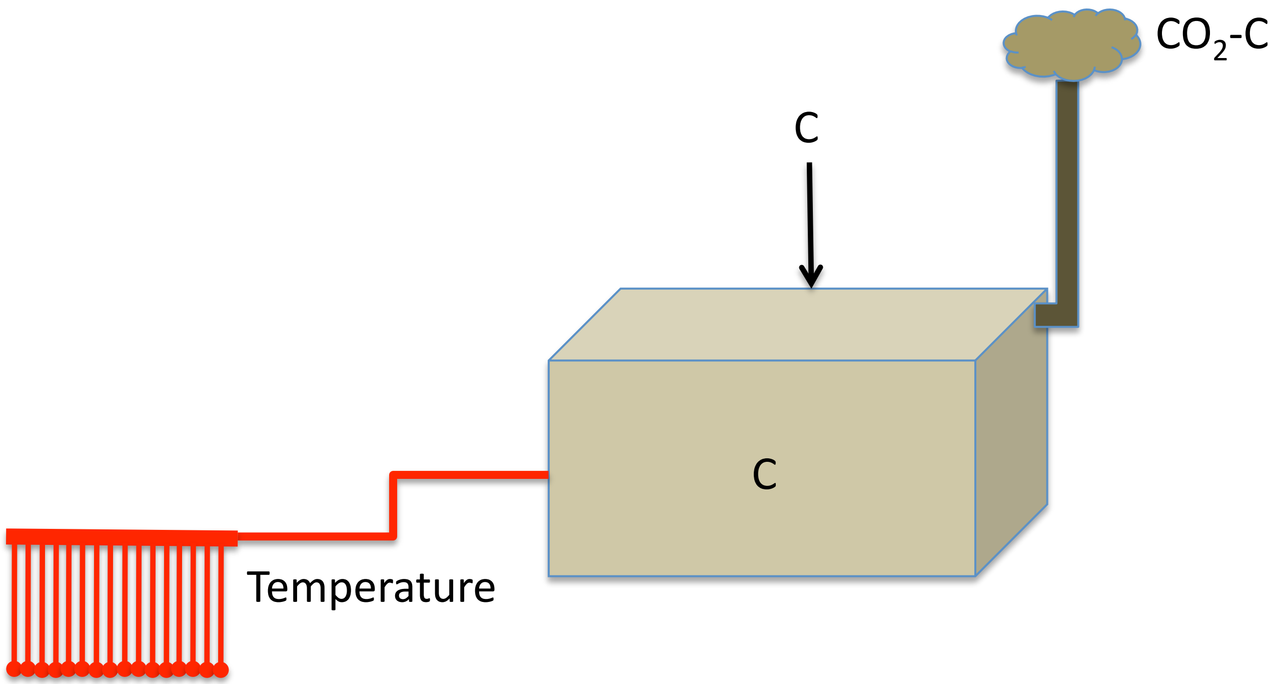
Figure 4 - The effect of clay on the ratio of CO_2 released to (BIO + HUM) formed



Die Bodenmaschine

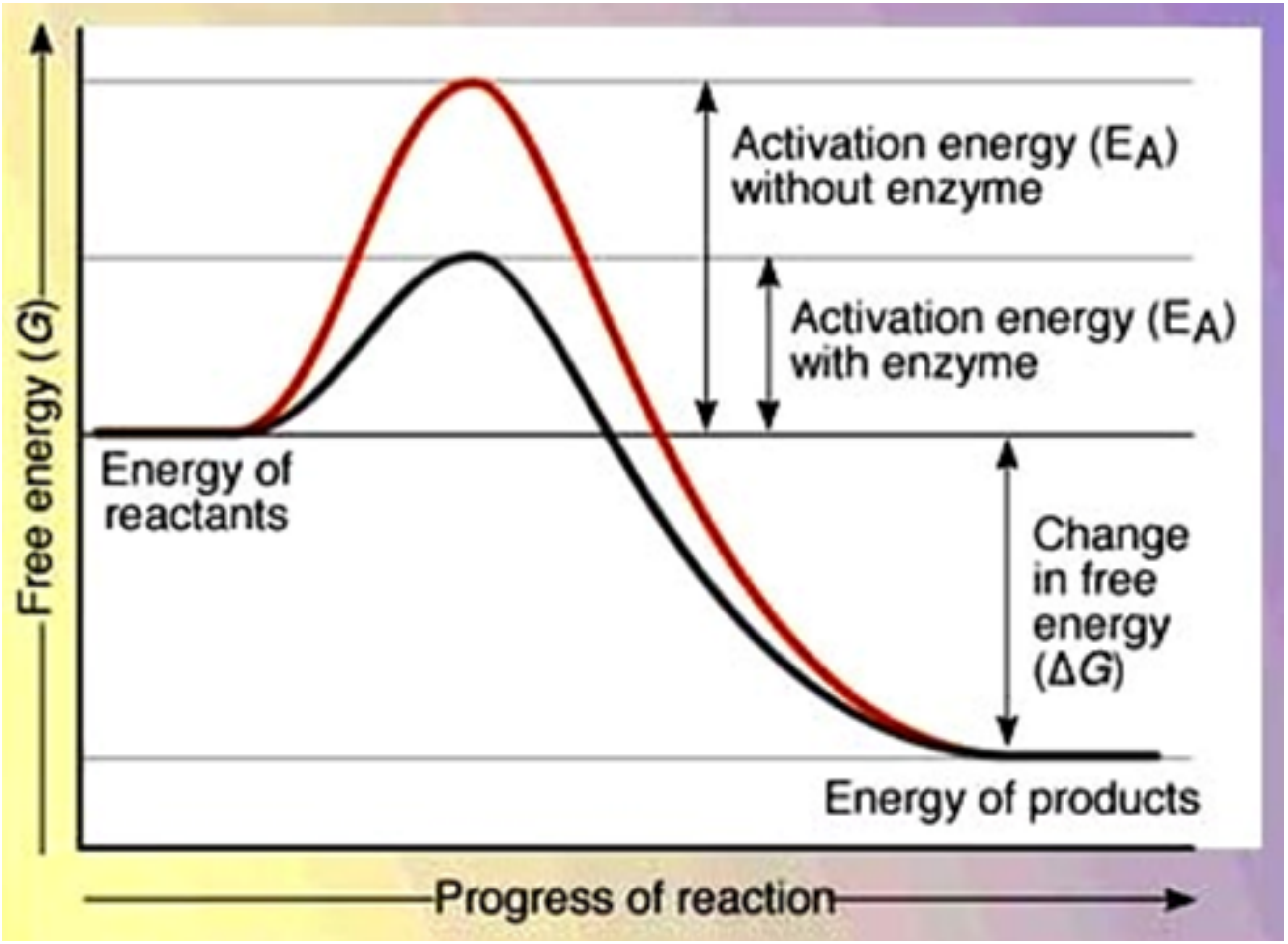


Die Bodenmaschine



Temperature dependence of decomposition

Activation Energy of chemical reactions



Microbial growth depends on activation energy of the substrate

$$E + S_0 \overset{K_0^*}{\leftrightarrow} ES_0^* \overset{K_0}{\leftrightarrow} E + S_1 \overset{K_1^*}{\leftrightarrow} ES_1^* \xrightarrow{k} E + S_2$$

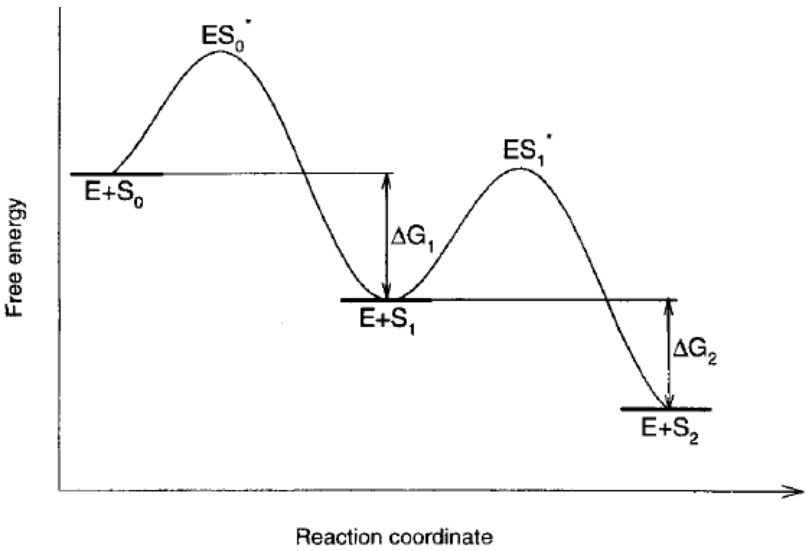
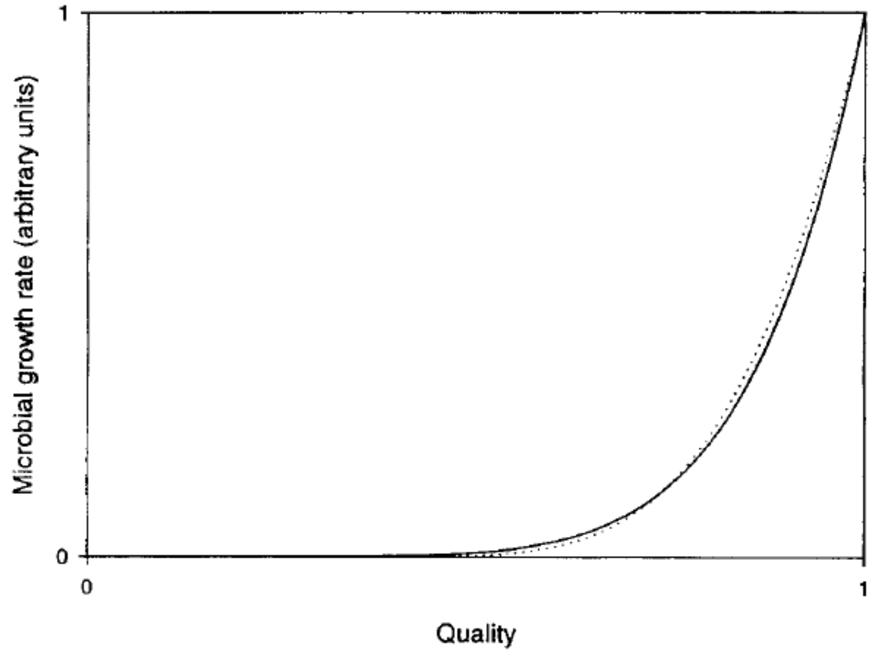


Fig. 1. Free energy profile for the enzymatic reaction (2).



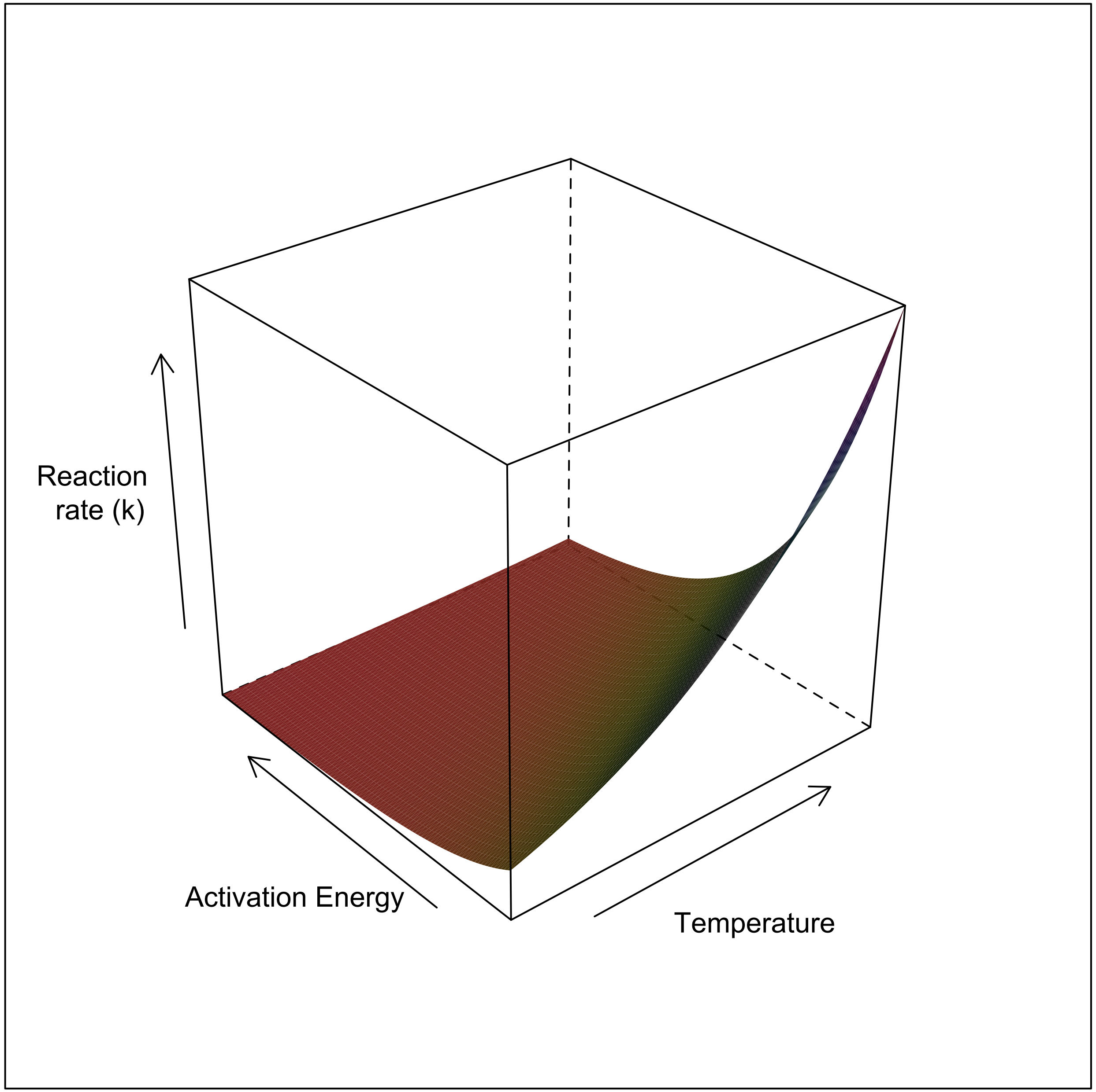
$q = 1/n$

Bosatta & Agren 1991. Soil Biol. Biochem. 31: 1889.

The Arrhenius equation

$$k = A \exp\left(\frac{-E}{\Re T}\right)$$

k = reaction or decomposition rate
E = Activation energy
T = Temperature in Kelvin
A = pre-exponential factor
R = Universal gas constant


Reaction
rate (k)
Activation Energy
Temperature

PERGAMON

Soil Biology and Biochemistry 31 (1999) 1889–1891

Soil Biology & Biochemistry

www.elsevier.com/locate/soilbio

Soil organic matter quality interpreted thermodynamically

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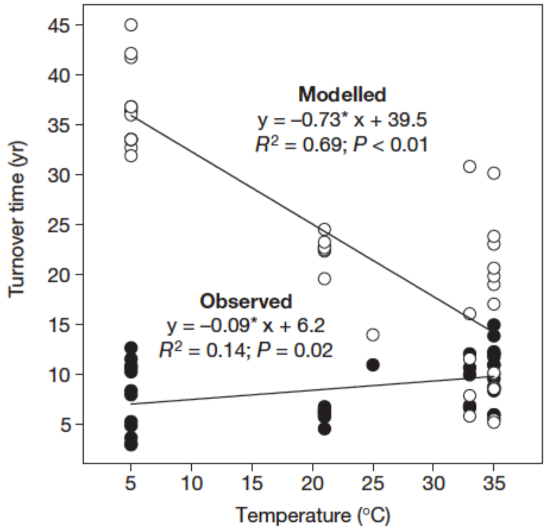
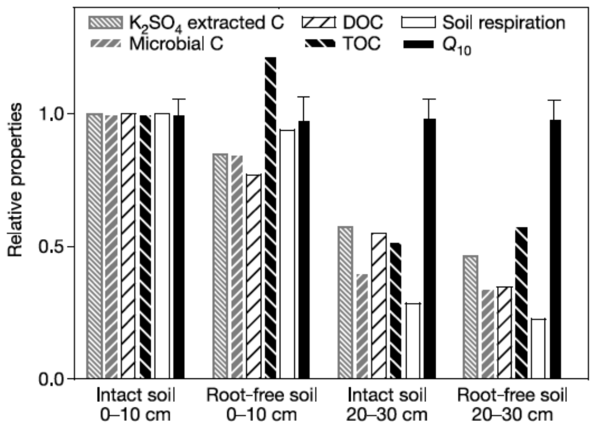
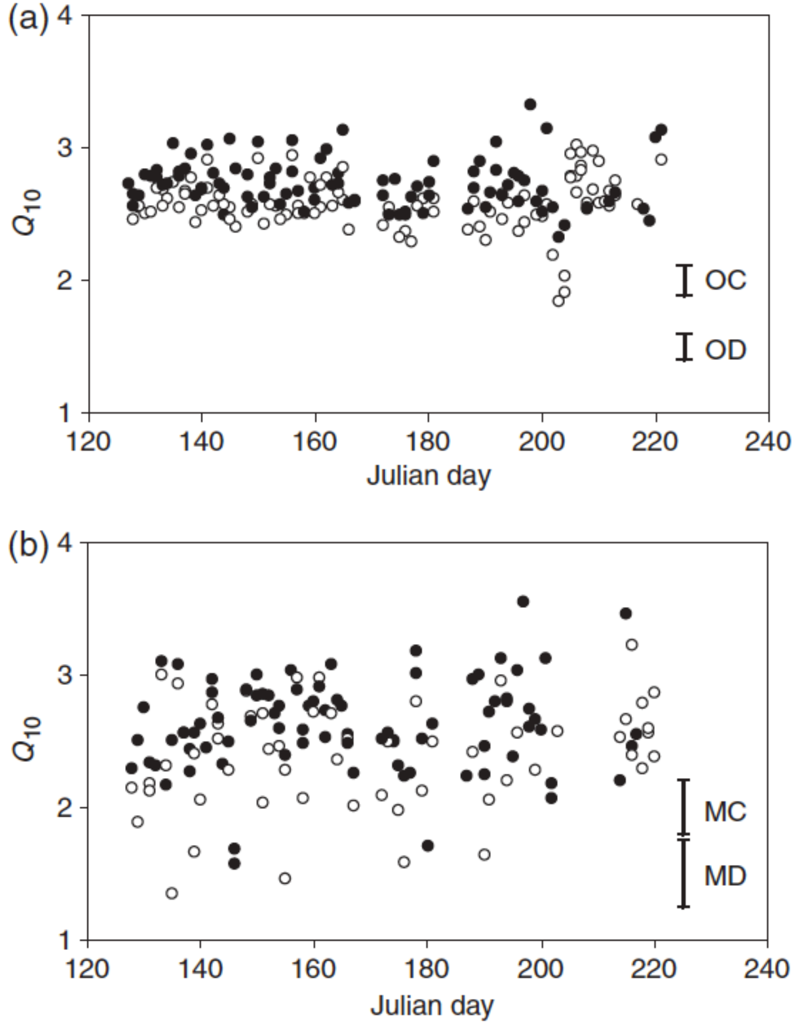
$$u(q) = u_0 e^{\Delta G^0 / RTq}$$

The relative sensitivity to temperature of the microbial assimilation rate is $\partial \ln u / \partial T = -|\Delta G^0|/(RT^2 q)$. A consequence is that the decomposition rate of low quality substrates will have a stronger temperature dependency than high quality substrates. Such behaviour has been observed with lit-

Experimental data have shown contradictory results



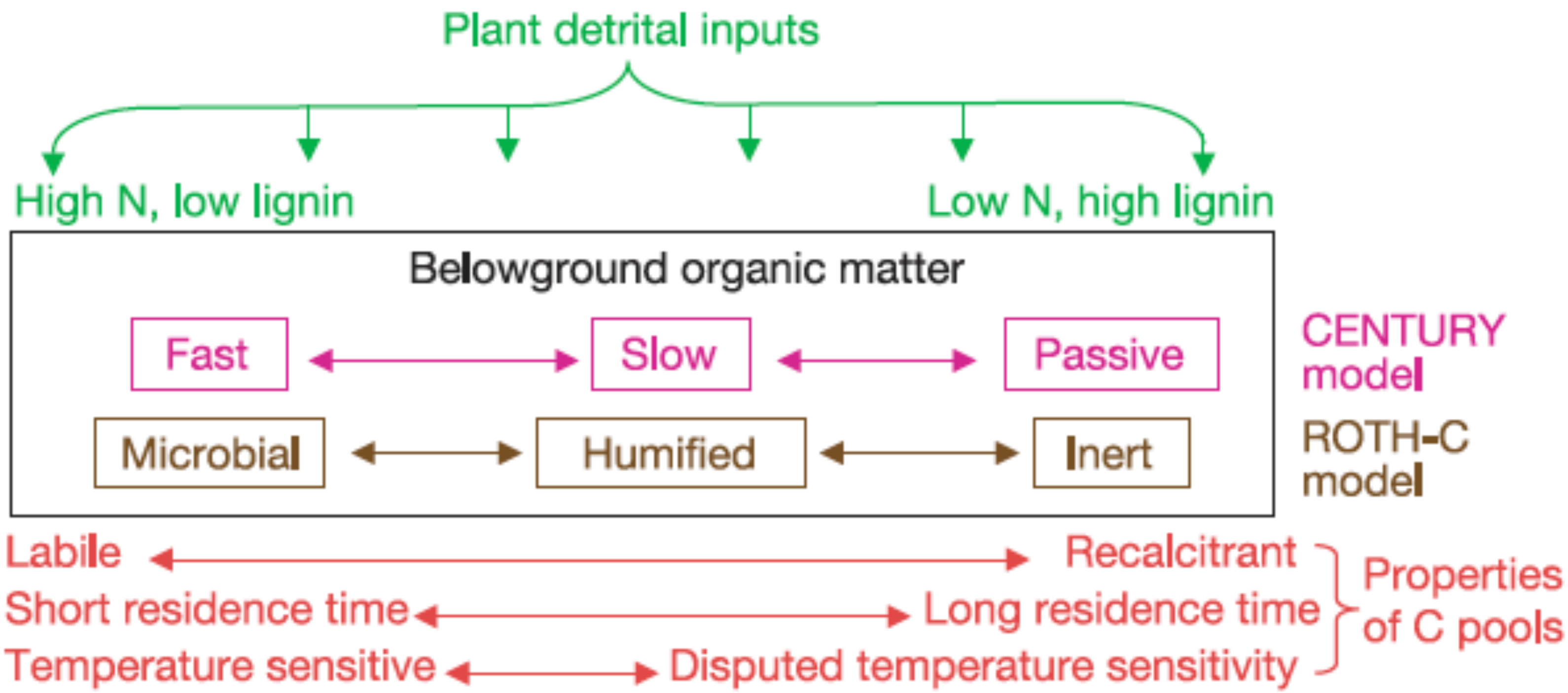




Giardina & Ryan 2000. Nature 404: 858.
Fang et al. 2005. Nature 433: 57.

Reichstein et al. 2005. Glob Chang Biol 11: 1754.

SOM quality and temperature sensitivity



Davidson & Janssens 2006. Nature 440: 165.

Opposing views

- Decomposition of stable SOM is not temperature sensitive
- Decomposition of stable SOM have higher temperature sensitivity
- Labile and resistant SOM respond similarly to changes in temperature
- Labile SOM is more temperature-sensitive

von Lützow & Kögel-Knabner 2009. Biol Fert Soils 46: 1.

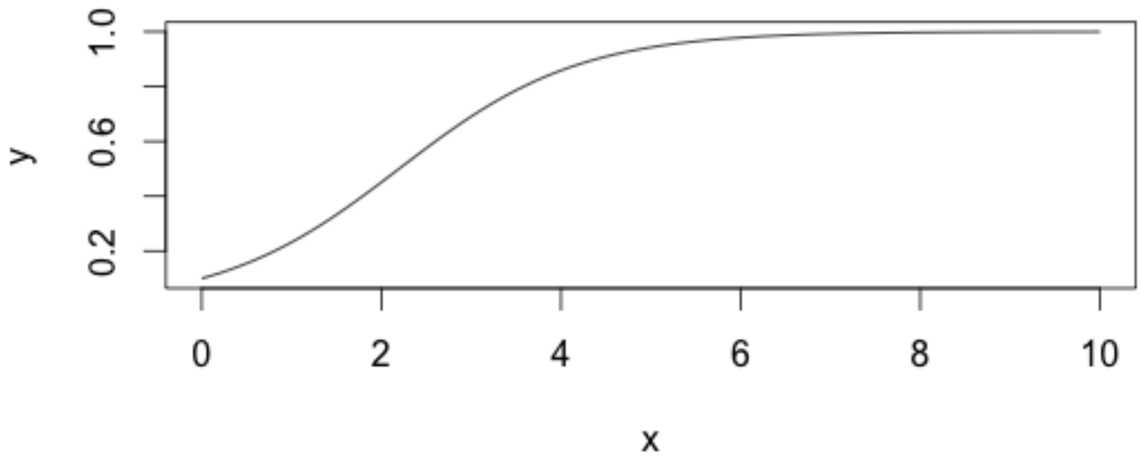
How to resolve these apparent contradictions?

- Define terms clearly
  - Dependence: A process is temperature dependent if temperature is an explanatory or independent variable in the mathematical representation of this process. $R=f(T)$
  - Sensitivity: the rate of change of some measure *X* *(respiration flux, decomposition rate, or turnover time) with respect to temperature while all other variables are held constant. dX/dT.*
- Look at theoretical predictions and compare with observations

Definitions

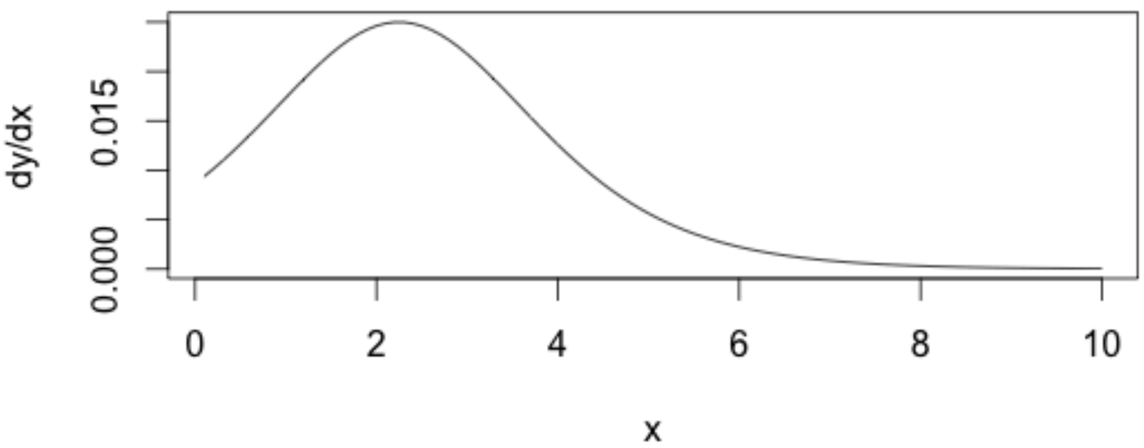
Dependence

$$y = f(x)$$



Sensitivity

$$\frac{dy}{dx} = f'(x)$$



Some measures of sensitivity

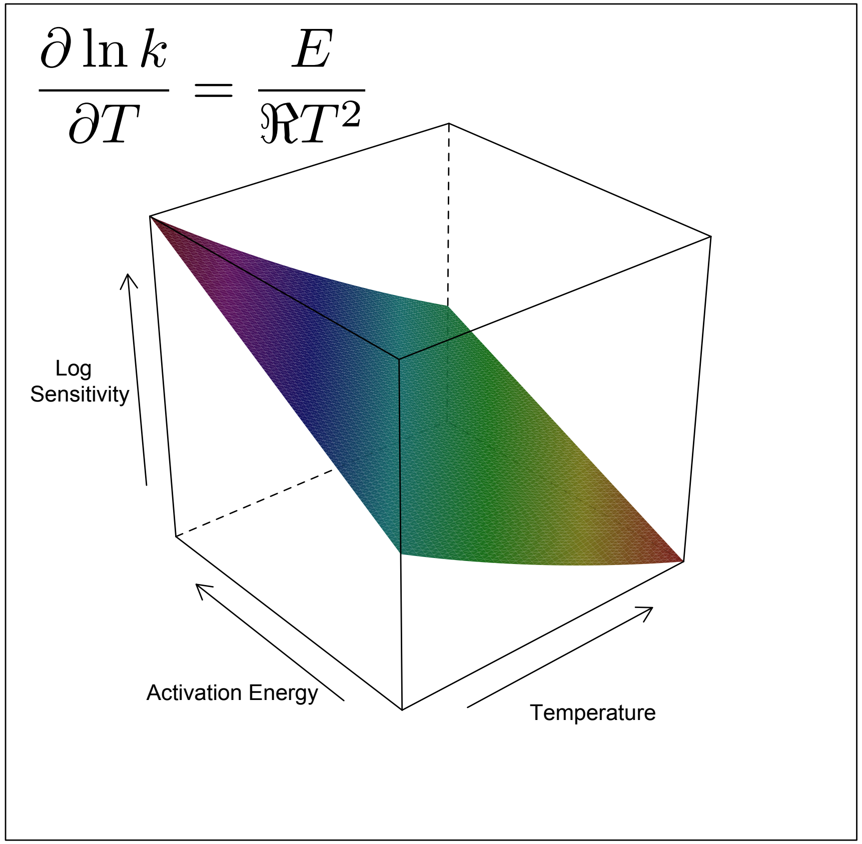
$$k = A \exp\left(\frac{-E}{\Re T}\right)$$

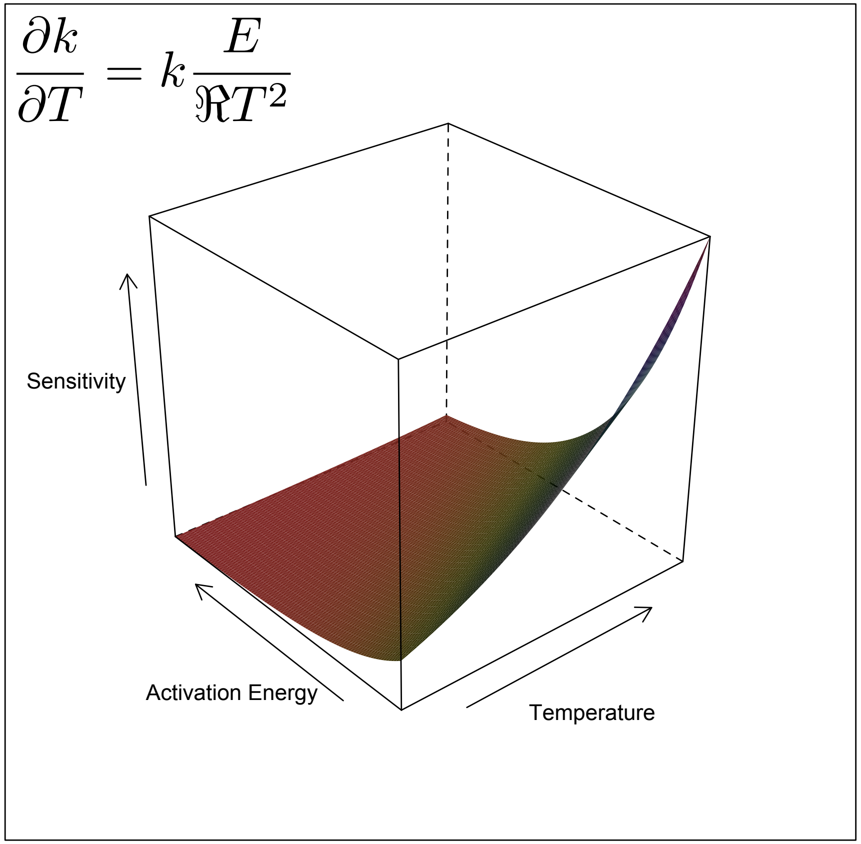
$$\frac{\partial k}{\partial T} = \frac{EA}{\Re T^2} \exp\left(\frac{-E}{\Re T}\right)$$

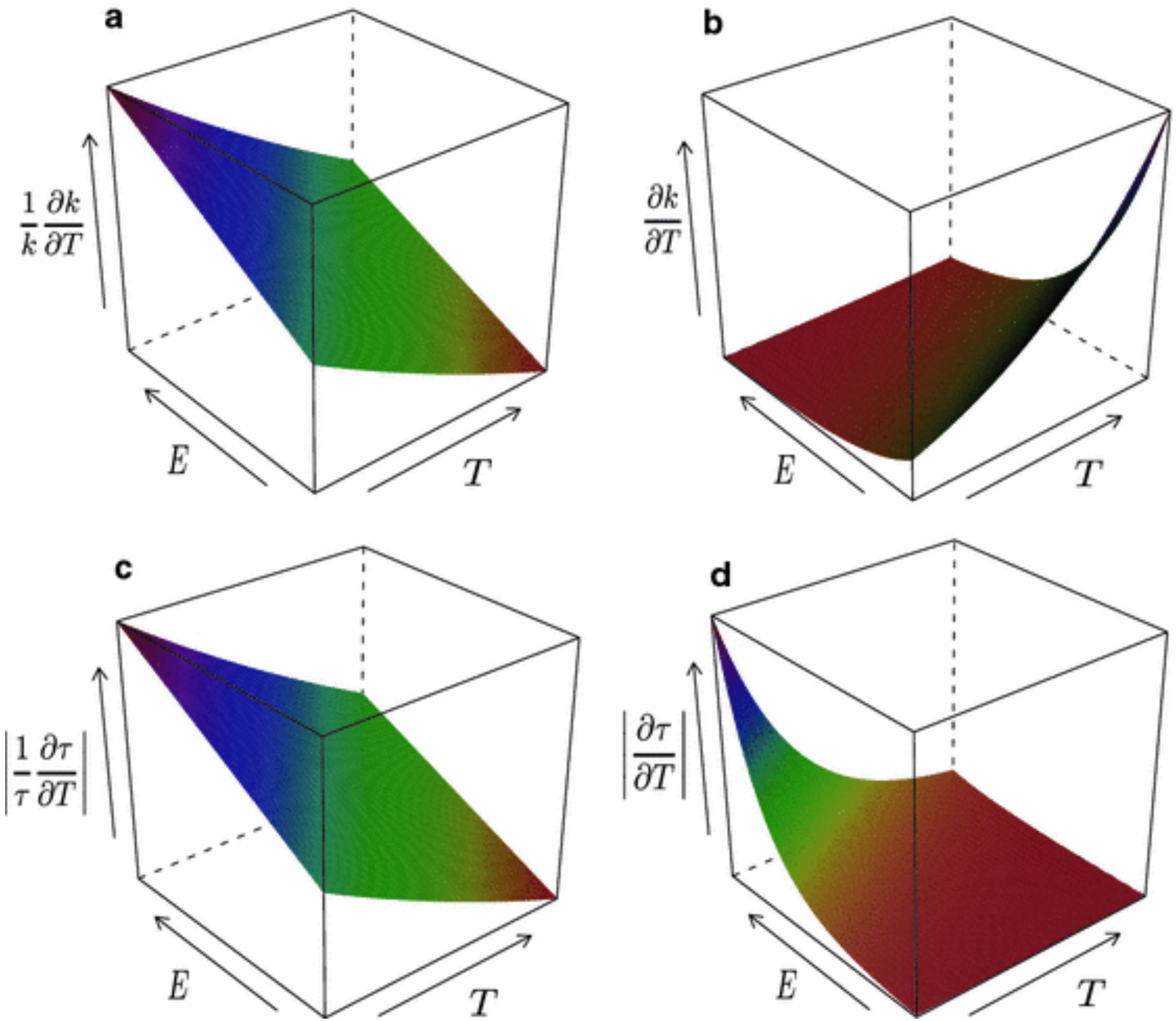
$$\frac{\partial k}{\partial T} = k \frac{E}{\Re T^2}$$

$$\ln k = \ln A - \frac{E}{\Re T}$$

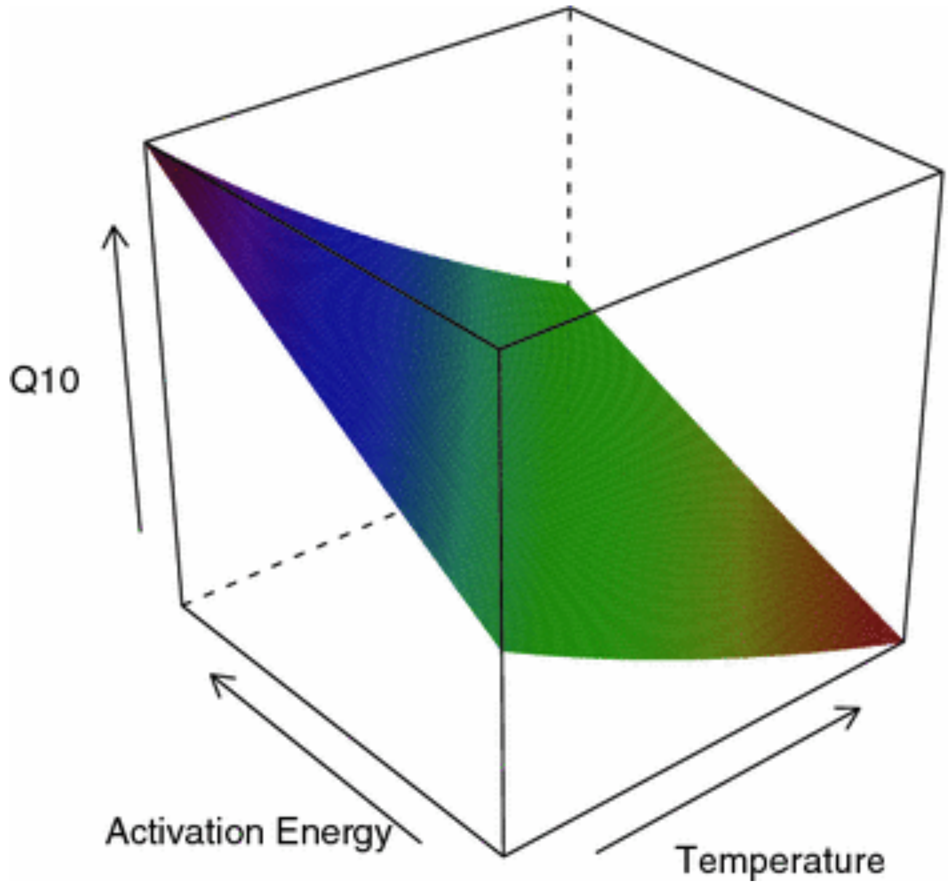
$$\frac{\partial \ln k}{\partial T} = \frac{E}{\Re T^2}$$


$\frac{\partial \ln k}{\partial T} = \frac{E}{\Re T^2}$
Log Sensitivity
Activation Energy
Temperature


$\frac{\partial k}{\partial T} = k\frac{E}{\Re T^2}$
Sensitivity
Activation Energy
Temperature



a
$\frac{1}{k}\frac{\partial k}{\partial T}$
E
T
b
$\frac{\partial k}{\partial T}$
E
T
c
$\left|\frac{1}{\tau}\frac{\partial \tau}{\partial T}\right|$
E
T
d
$\left|\frac{\partial \tau}{\partial T}\right|$
E
T

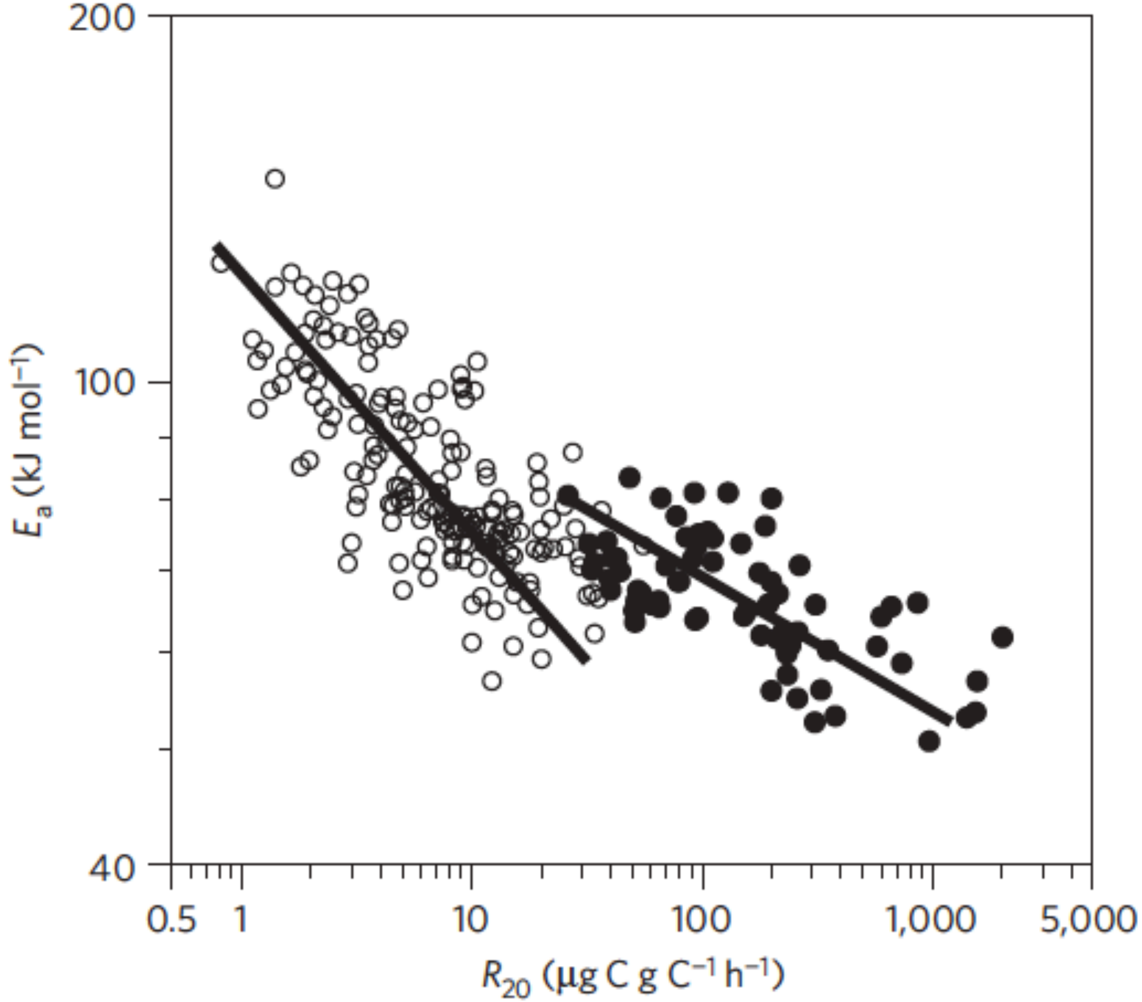


Q10
Activation Energy
Temperature

The majority of studies actually agree with Arrhenius theory!

Study	Measure of sensitivity	Agrees with Arrhenius theory?
1. Decomposition rates of stable SOM pools are not temperature sensitive within a temperature range 5–35°C		
Fang et al. (2005)	Q_{10}	No
Giardina and Ryan (2000)	τ	No
2. Decomposition of stable SOM pools have a higher temperature sensitivity than that of labile SOM pools		
Boddy et al. (2008)	k	No
Bol et al. (2003)	τ	Yes
Conant et al. (2008a)	Q_{10}	Yes
Conant et al. (2008b)	Q_{10}	Yes
Craine et al. (2010)	E	Yes
Curiel-Yuste et al. (2007)	Q_{10}	Yes/no
Hakkenberg et al. (2008)	τ	Yes
Hartley and Ineson (2008)	Q_{10}	Yes
Knorr et al. (2005)	$\ln \tau$	Yes
Koch et al. (2007)	Q_{10}	Yes
Koch et al. (2007)	$\left(\frac{1}{f}\frac{df}{dT}\right)^{a}$	Yes
Larionova et al. (2007)	Q_{10}	Yes
Leifeld and Fuhrer (2005)	Q_{10}	Yes
Rey et al. (2008)	Q_{10}	Yes
Vanhala et al. (2007)	Q_{10}	Yes
3. Labile and resistant SOM pools respond similarly to changes in temperature		
Fang et al. (2005)	Q_{10}	Partially
Reichstein et al. (2005)	Q_{10}	Partially
Townsend et al. (1995)	τ, $\ln 2/k$	Partially
4. The decay rate of the labile SOM is very temperature-sensitive, but not the decay rate of stable SOM		
Bradford et al. (2008)	C, R	Yes
Eliasson et al. (2005)	R	Yes
Liski et al. (1999)	k, C, soil age	Yes
Luo et al. (2001)	Q_{10}	No
Melillo et al. (2002)	k	Yes
Trumbore et al. (1996)	τ	No

Soil incubations from North and Central America confirm Arrhenius theory



Craine et al. 2010. Nat Geosc 3: 854.

Confirmation from the molecular level

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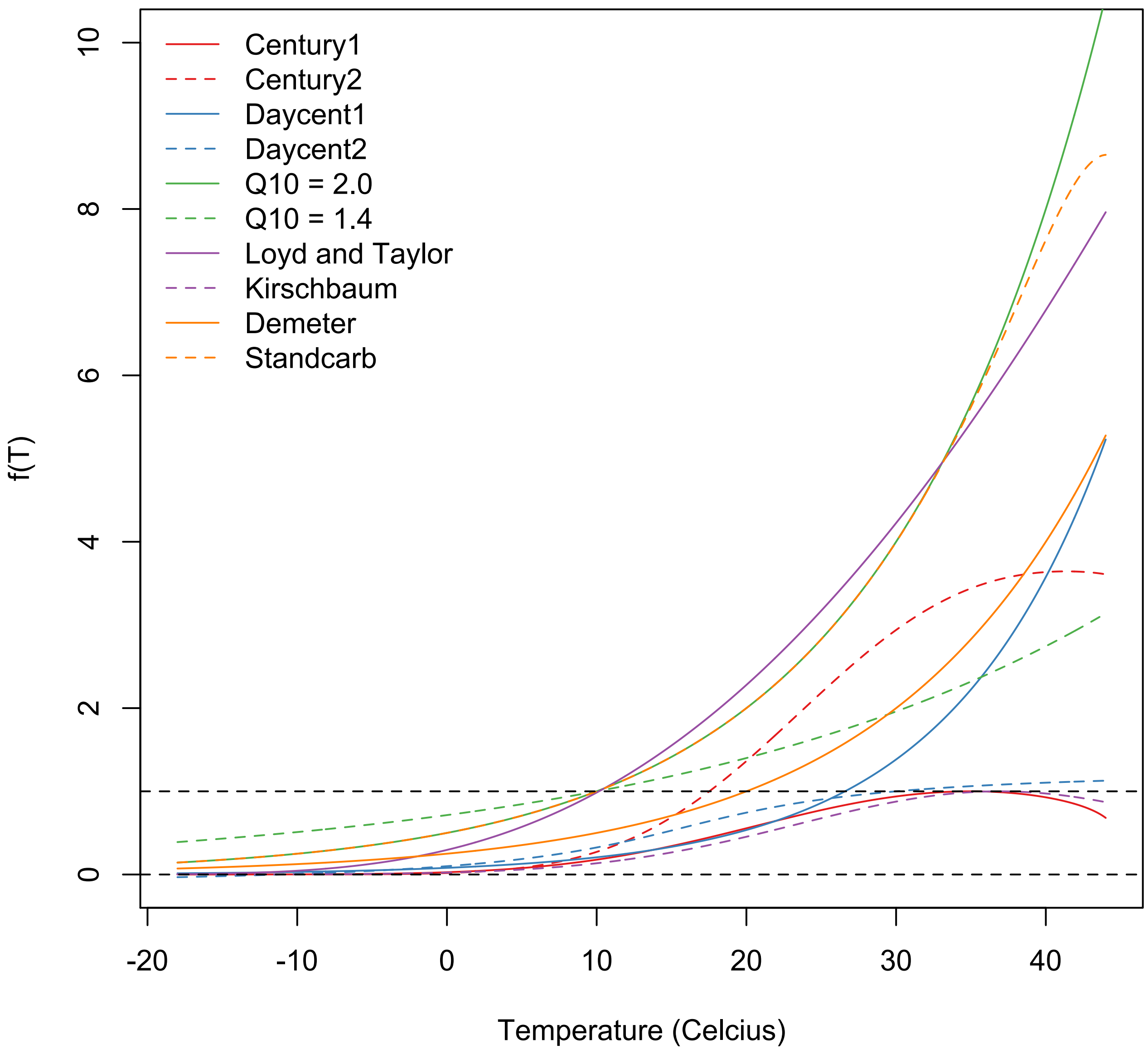
Temperature-mediated changes of exoenzyme-substrate reaction rates and their consequences for the carbon to nitrogen flow ratio of liberated resources

Christoph A. Lehmeier, Kyungjin Min, Nicole D. Niehues, Ford Ballantyne IV [1], Sharon A. Billings*

Department of Ecology and Evolutionary Biology, Kansas Biological Survey, The University of Kansas, 2101 Constant Ave., Lawrence, KS 66047, USA

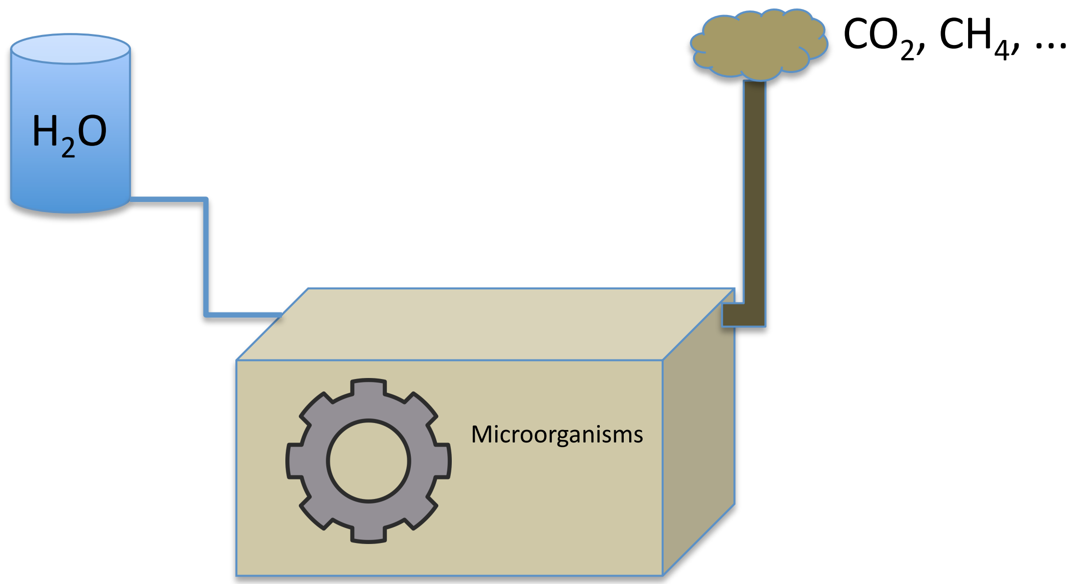
Temperature-decomposition functions



Take home message

- Rates of decomposition of SOM obey Arrhenius kinetics. This implies:
  - Decomposition is an energy limited process and temperature helps to remove this energy barrier.
  - Recalcitrant SOM is less sensitive to changes in temperatures than labile SOM. In relative terms the trend is opposite.
- Despite progress in mechanistic understanding, models still include a variety of functions.

Die Bodenmaschine



Microbial activity and soil water content

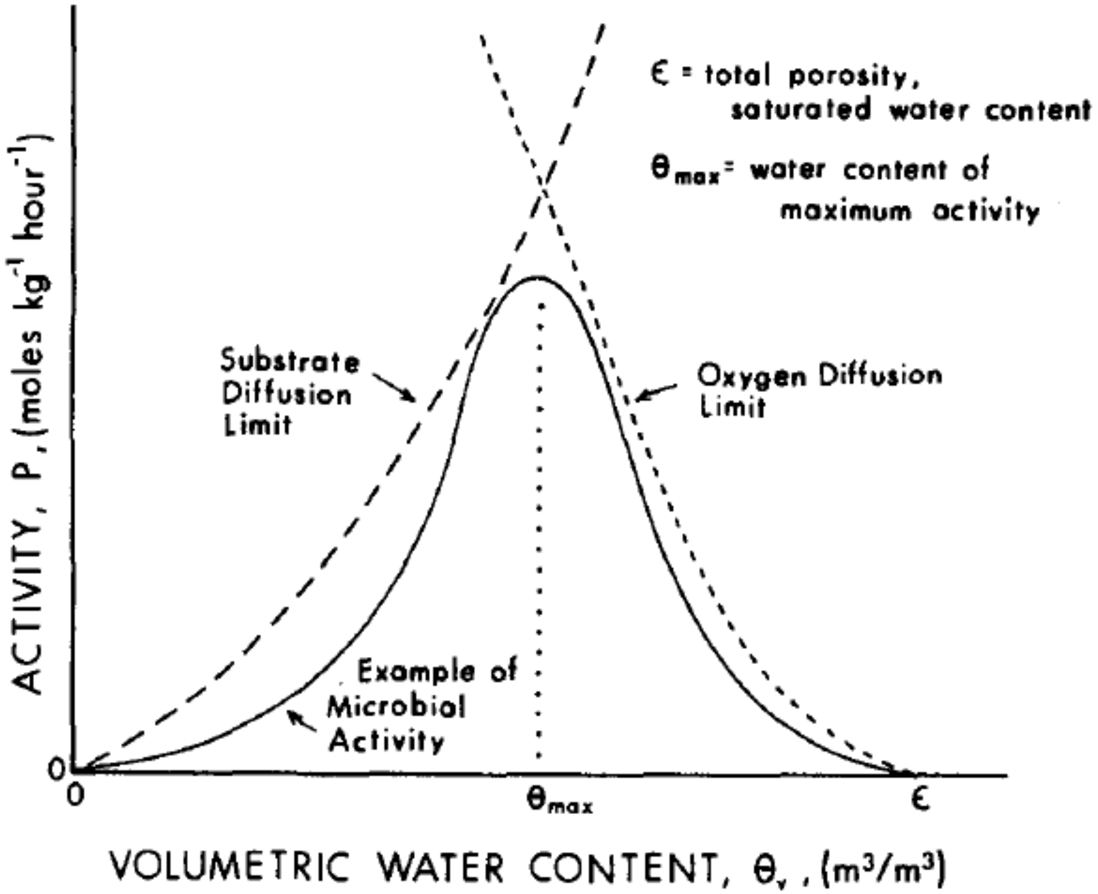
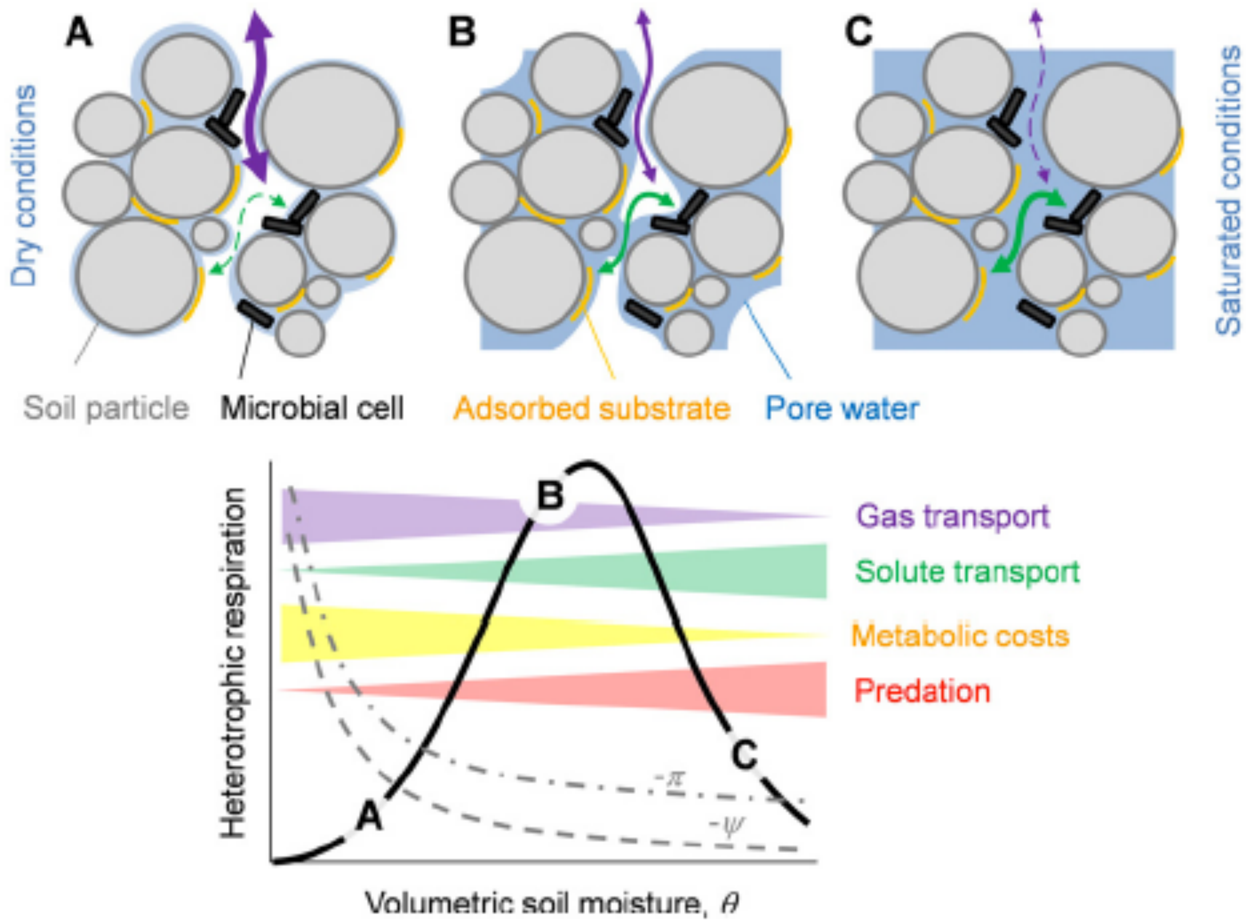


Fig. 1. Conceptual plot of microbial activity as a function of soil water content. Also, indicated by straight lines are the theoretical limits to activity posed by either the flux or total substrate.

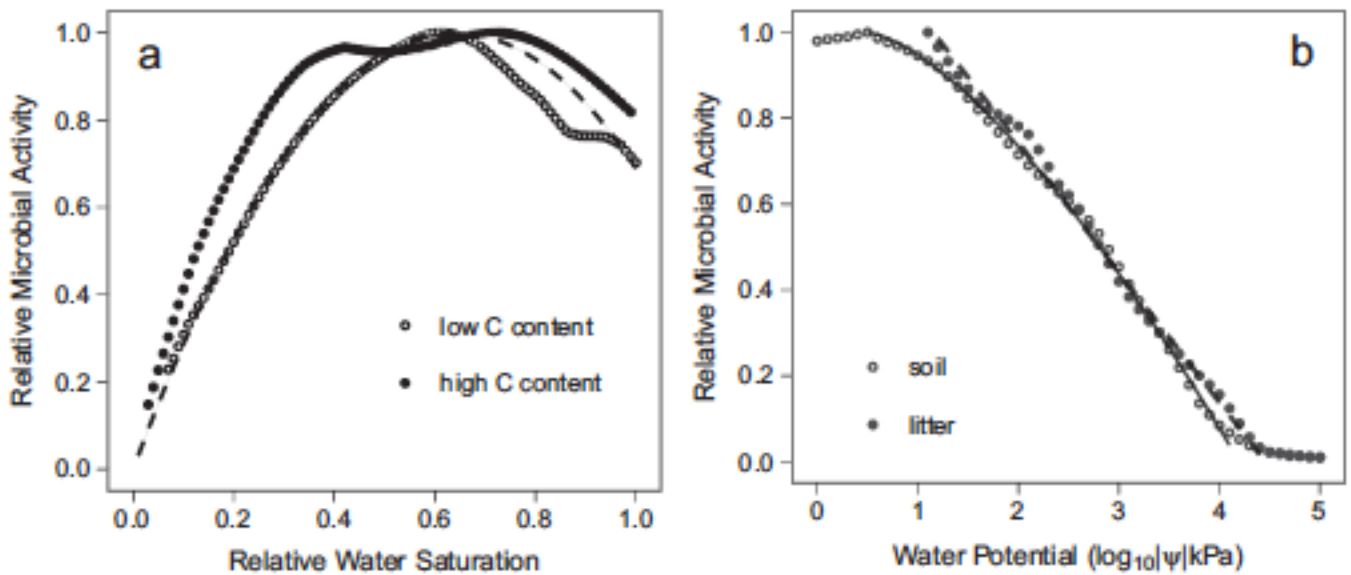
Skopp et al. 1990. Soil Sci Soc Am J 54: 1619.

Our current view



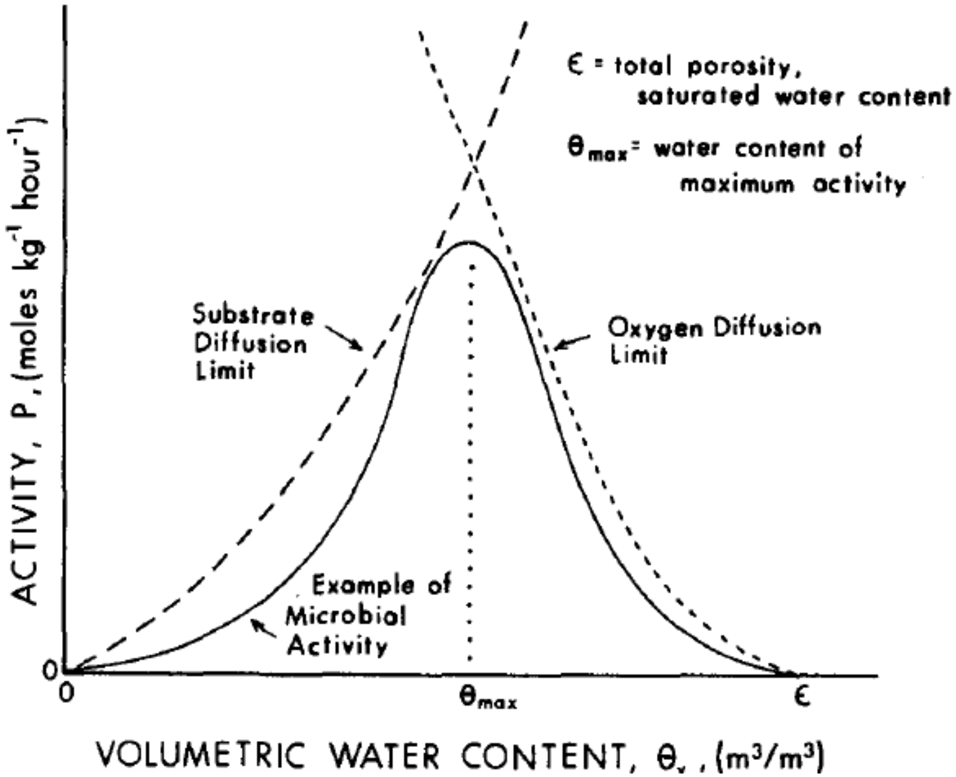
Moyano et al. 2013. Soil Biol Biochem 59: 72.

Measures of soil moisture and microbial activity



Moyano et al. 2013. Soil Biol Biochem 59: 72.

How to model the effects of moisture on decomposition?

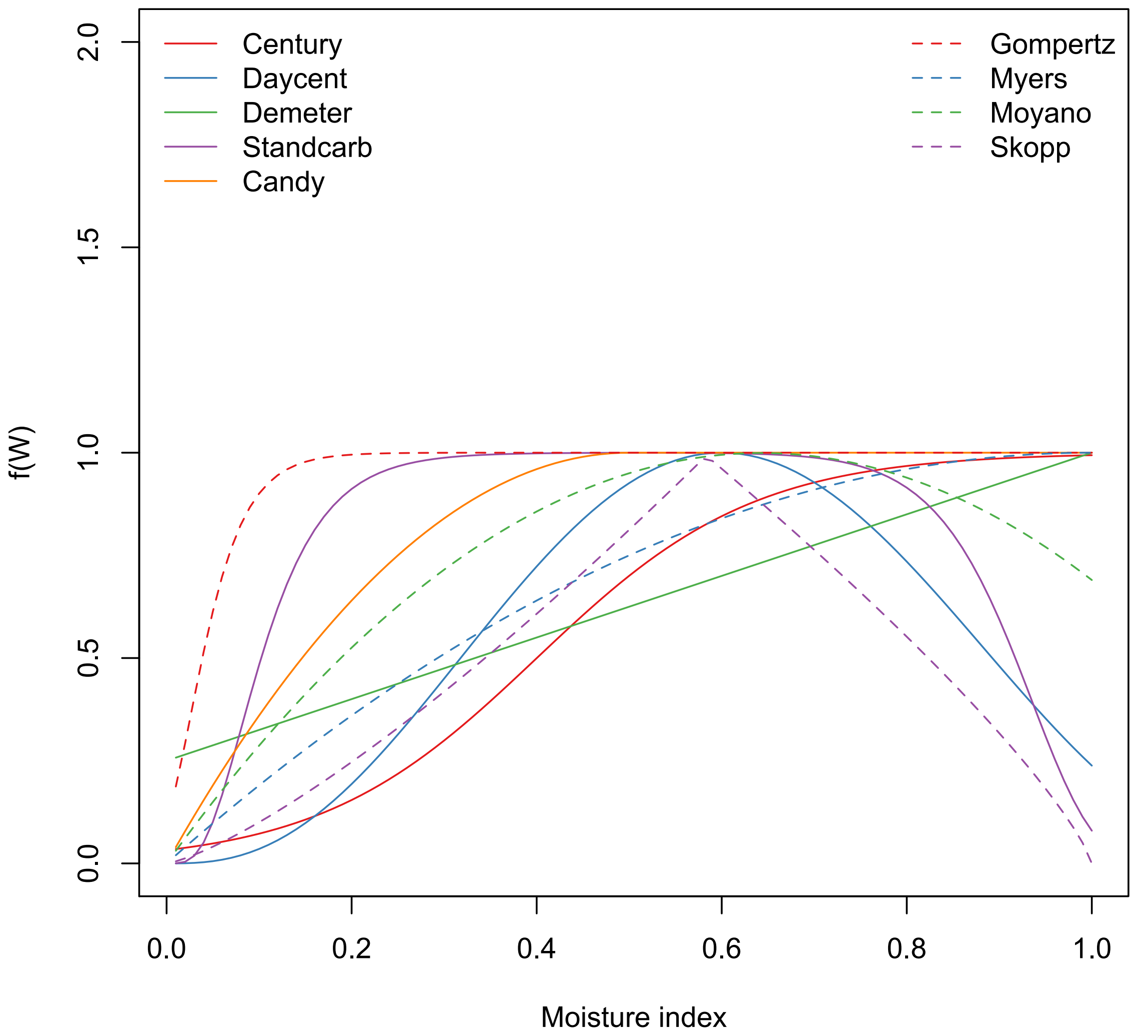


$$\frac{M}{a_1 + M}$$

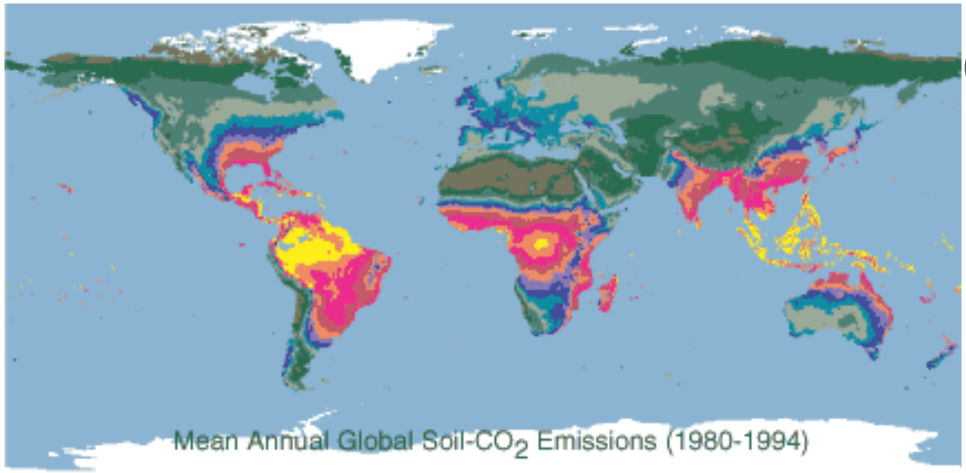
$$1 - \frac{M}{a_2 + M} = \frac{a_2}{a_2 + M}$$

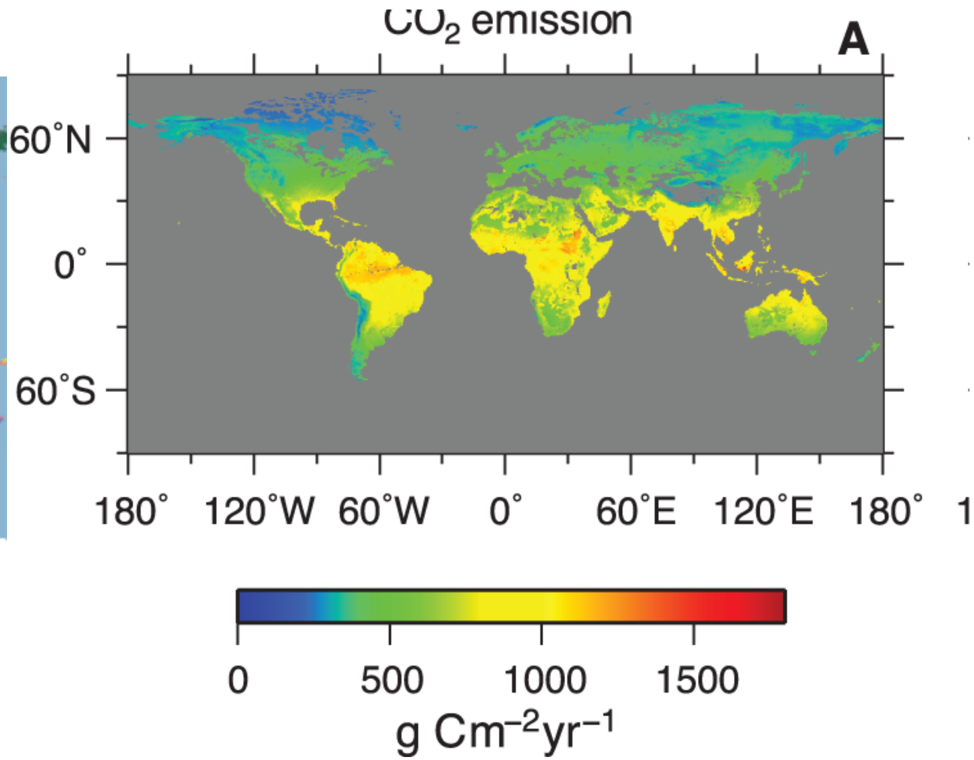
Bunnell et al. 1977. Soil Biol Biochem 9: 33.

Moisture decomposition functions



Global predictions based on temperature and moisture functions





Raich et al. 2002. Glob Change Biol 8: 800.

Hashimoto 2012. Plos One 7(8): e41962.

Temperature and moisture in combination

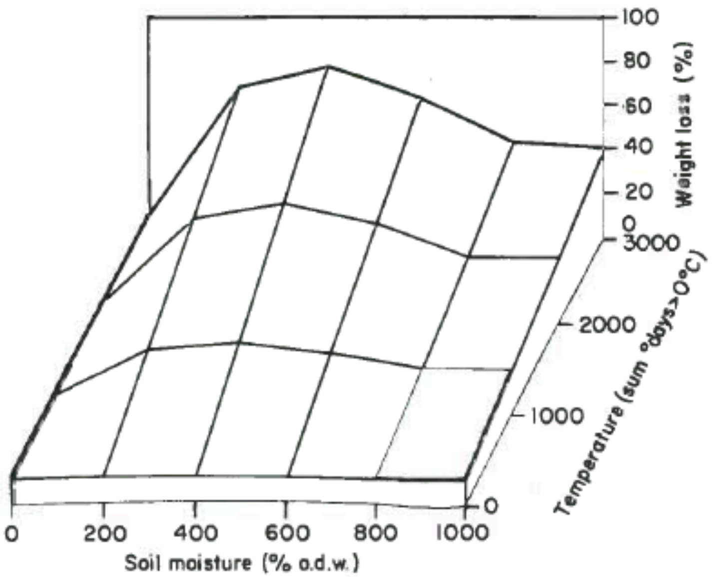
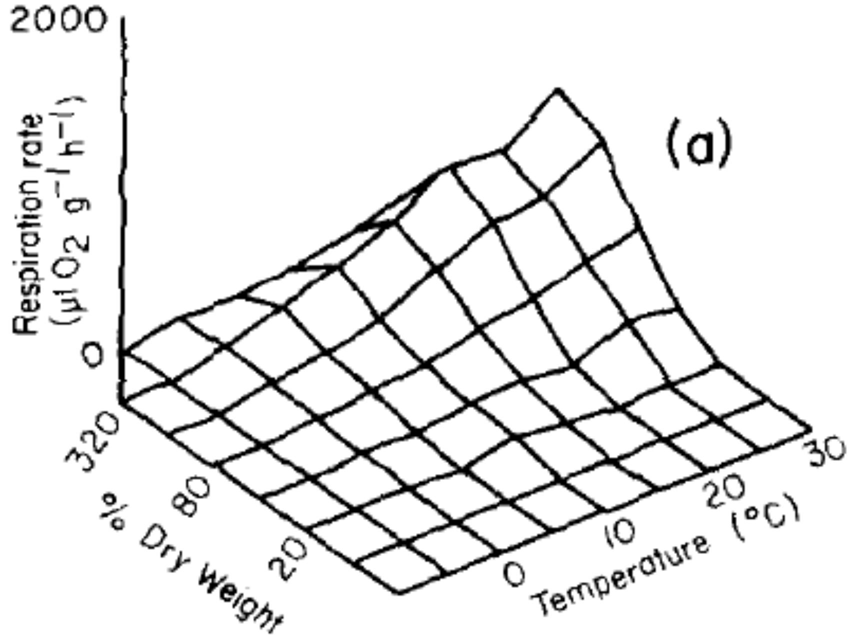


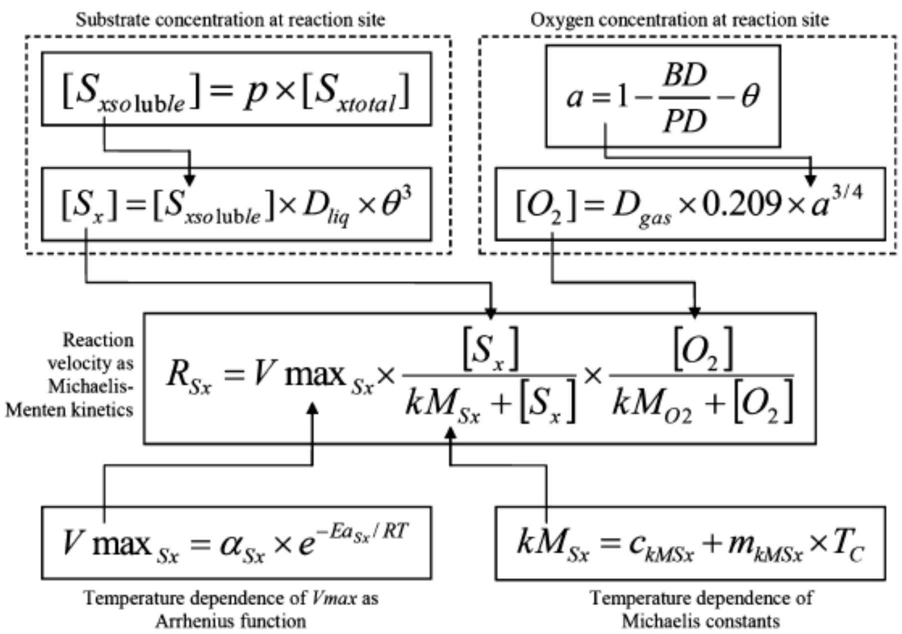
FIG. 6.17. A regression surface showing the interactive effects of soil moisture (% o.d.w.) and thermal environment (temperature sum = $\sum$ degree days at temperatures > 0°C). The regression equation for the relationship of the three factors was $Y = 11{\cdot}62 + 0{\cdot}0147.T.W - 0{\cdot}00289.T.W^2 + 0{\cdot}000152.T.W^3$ ($r = 0{\cdot}769$), where Y = per cent weight loss, T = temperature sum and W = soil moisture (from Heal & French 1974).

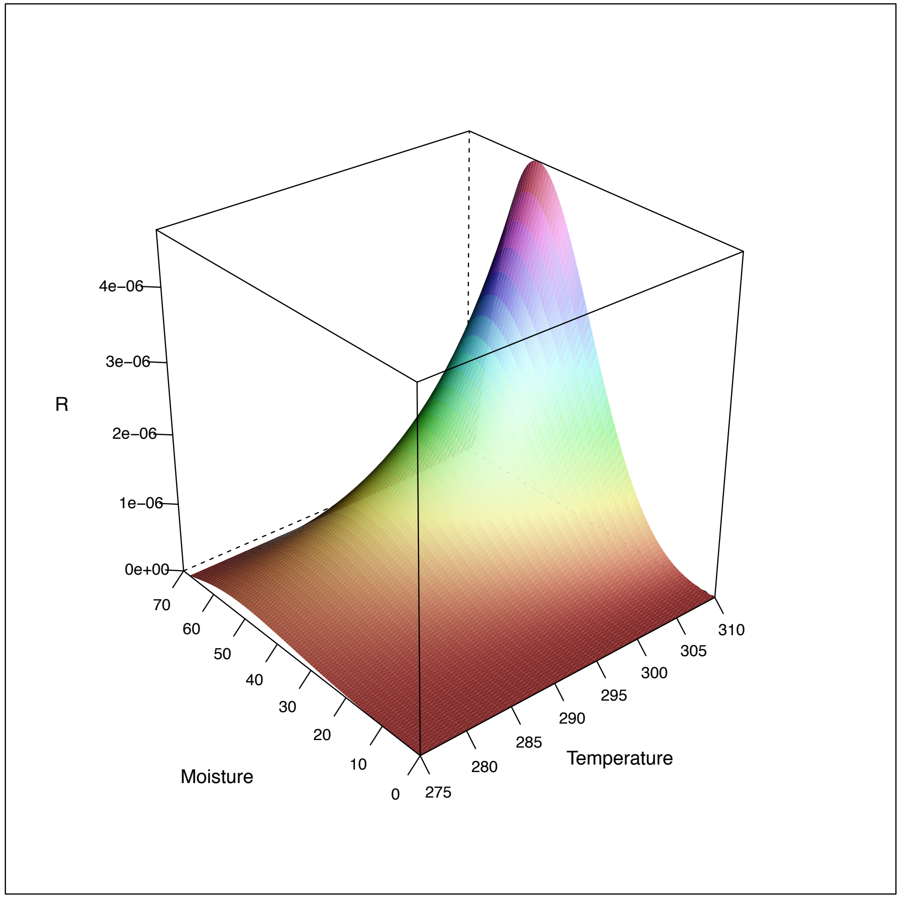


$$R(T,M) = \frac{M}{a_1 + M} \times \frac{a_2}{a_2 + M} \times a_3 \times a_4^{[(T-10)/10]}.$$

Bunnell et al. 1977. Soil Biol Biochem 9: 33.

The DAMM model

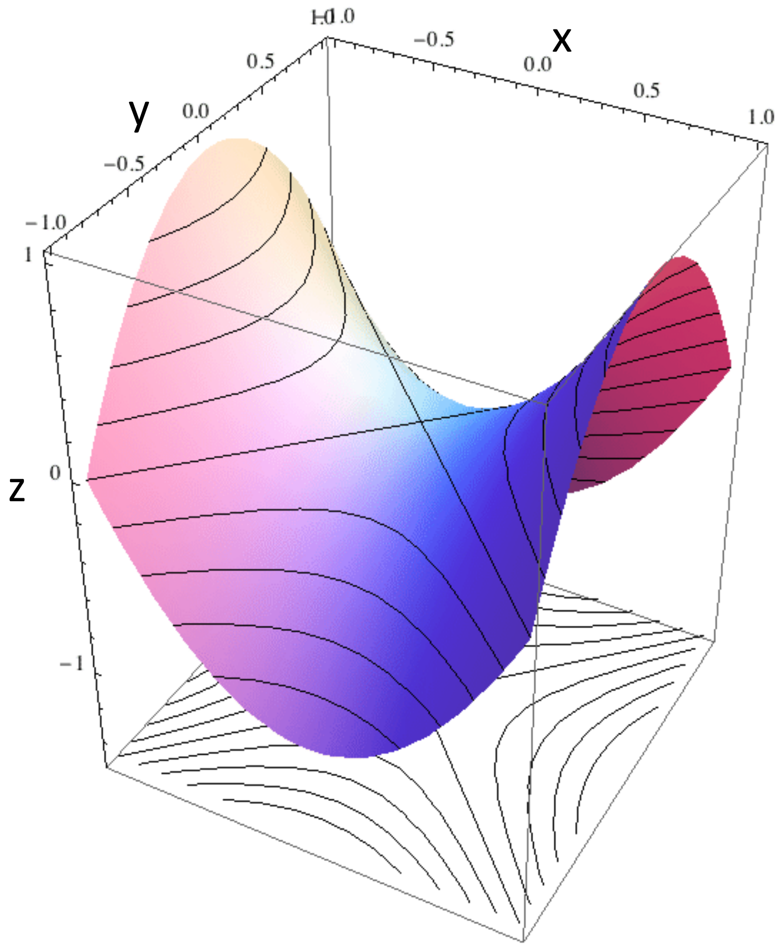




Davidson et al. 2011. Glob Change Biol 18: 371.

How do we calculate the sensitivity when both temperature and moisture change simultaneously?

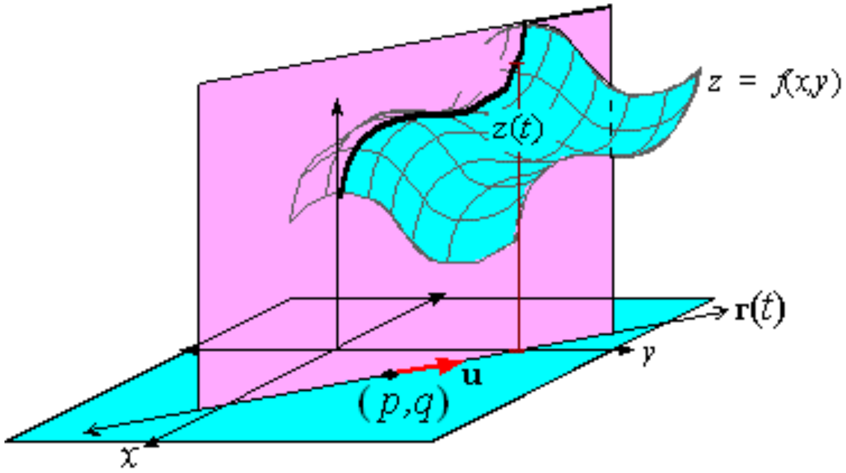
When the response depends on two variables



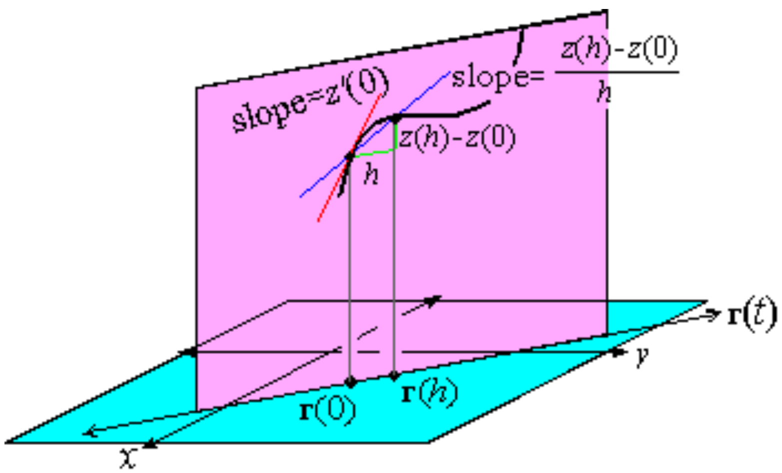
$$\nabla z = \left\langle \frac{\partial z}{\partial x}, \frac{\partial z}{\partial y} \right\rangle$$

This is the gradient, a set of partial derivatives

Directional derivatives

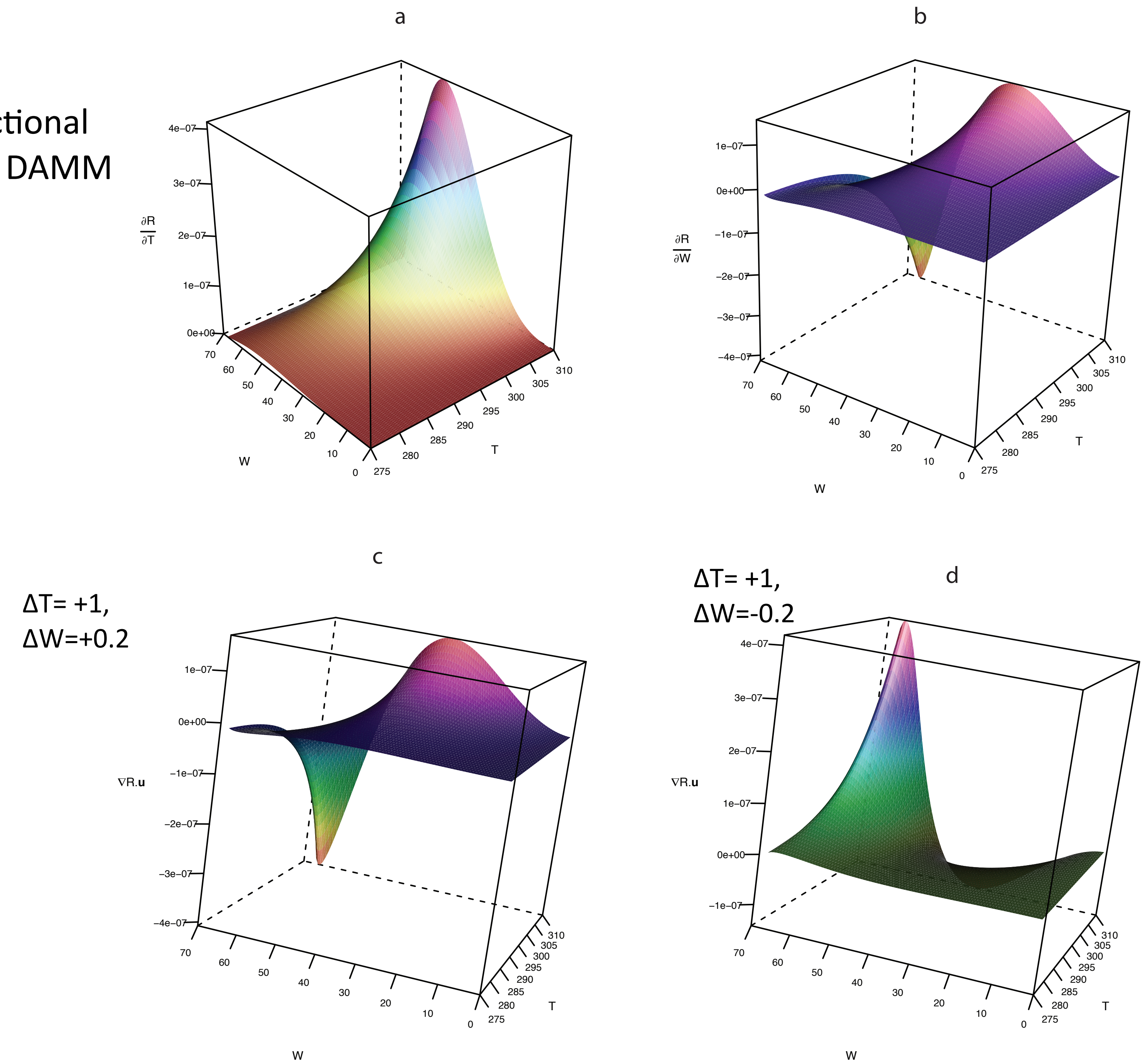


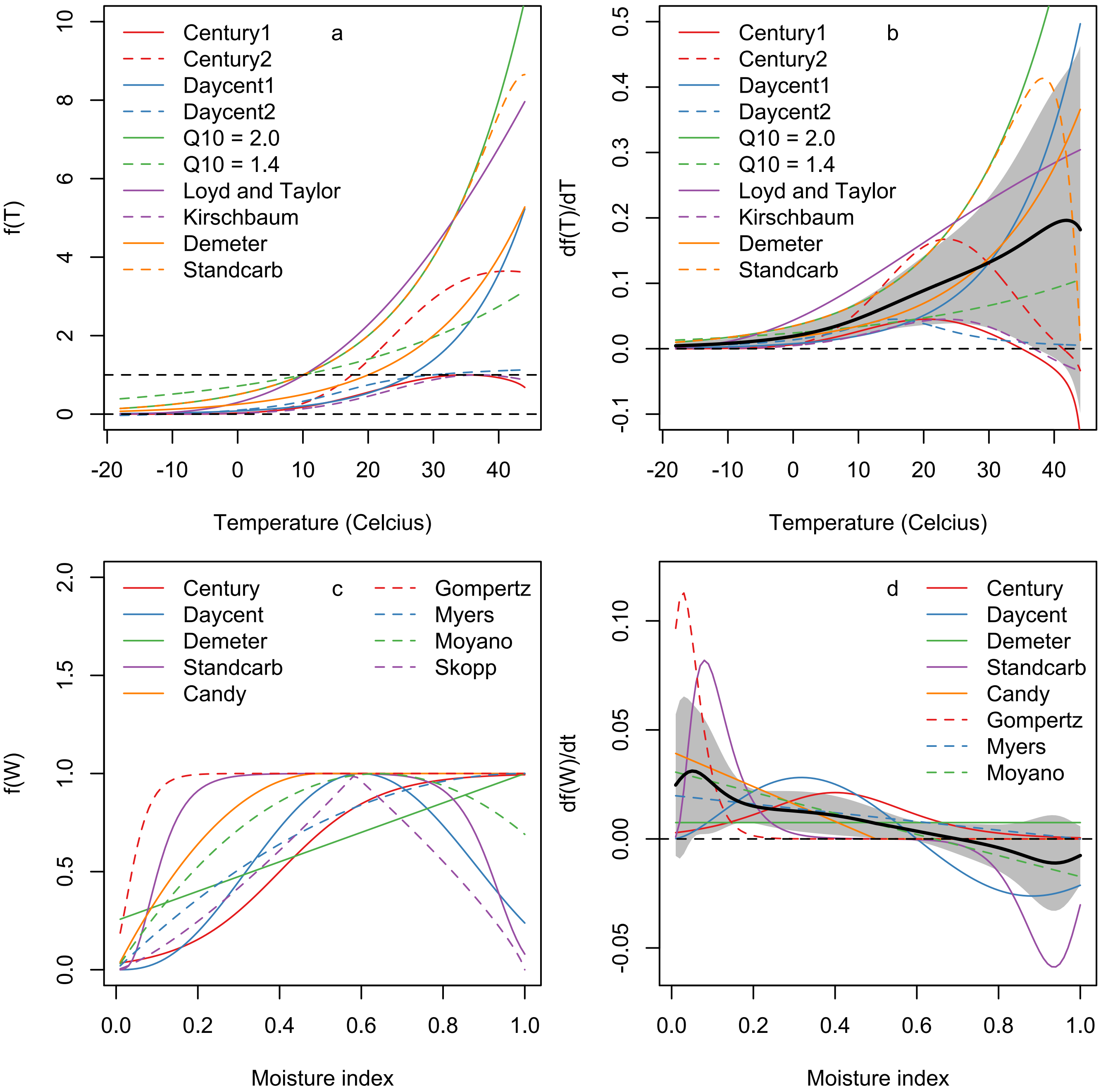
$$\nabla z \cdot \mathbf{u} = \frac{\partial z}{\partial x} u_1 + \frac{\partial z}{\partial y} u_2$$



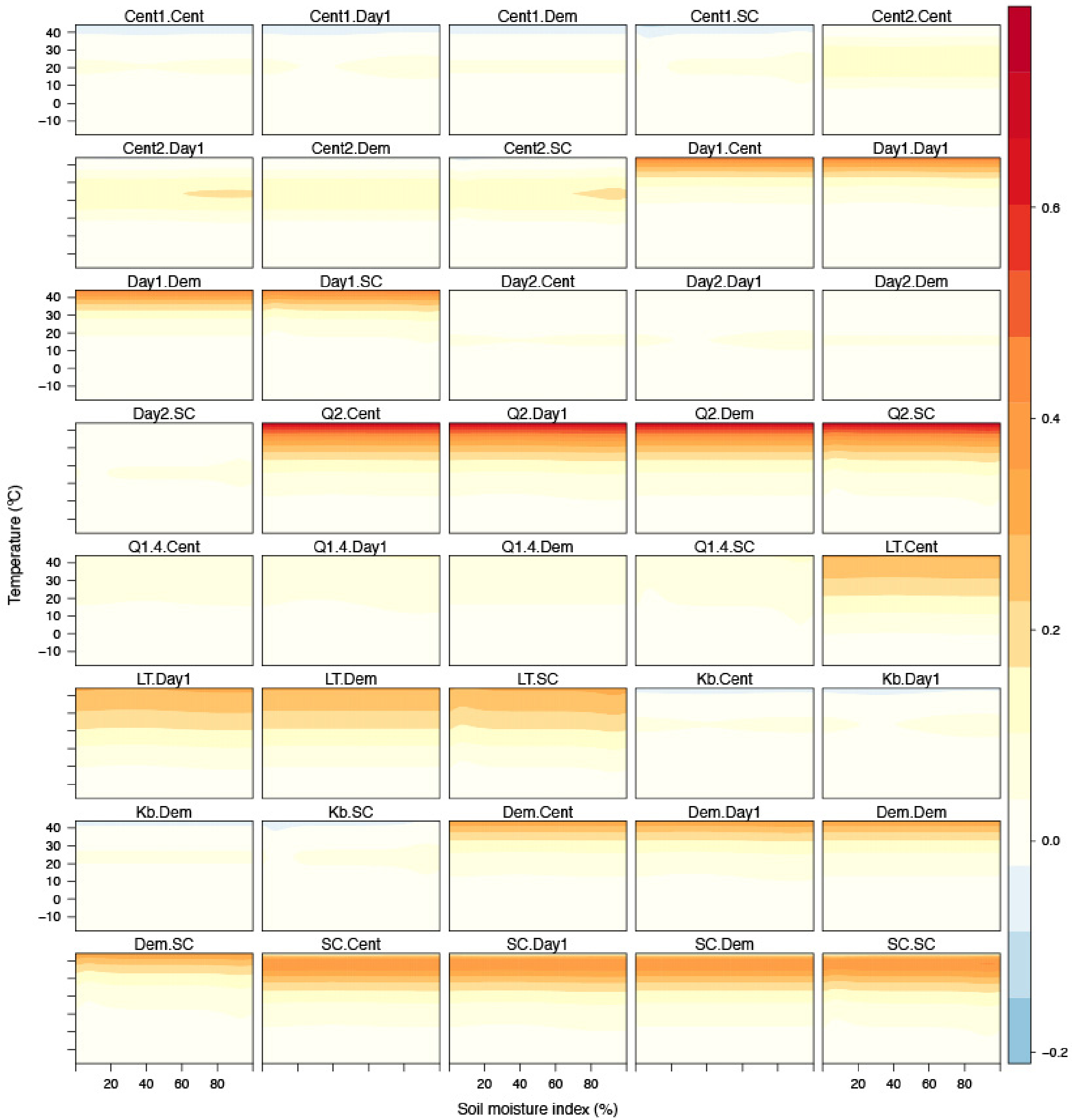
Gives the change of the response variable caused by a simultaneous change in the driving variables in the direction **u**.

Gradient and directional derivatives for the DAMM model.

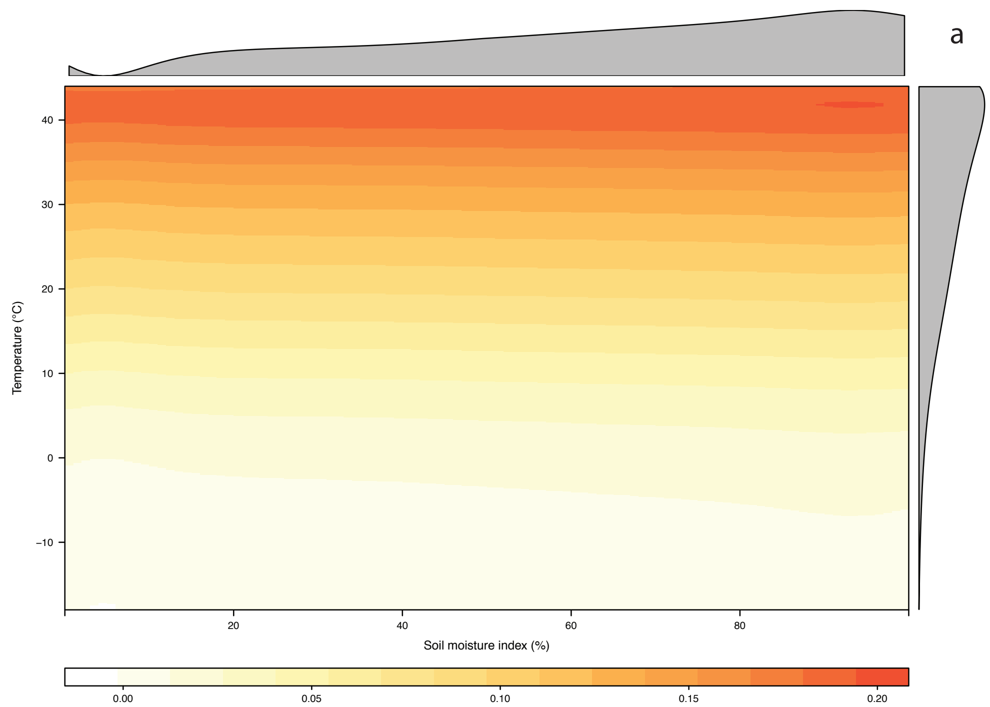


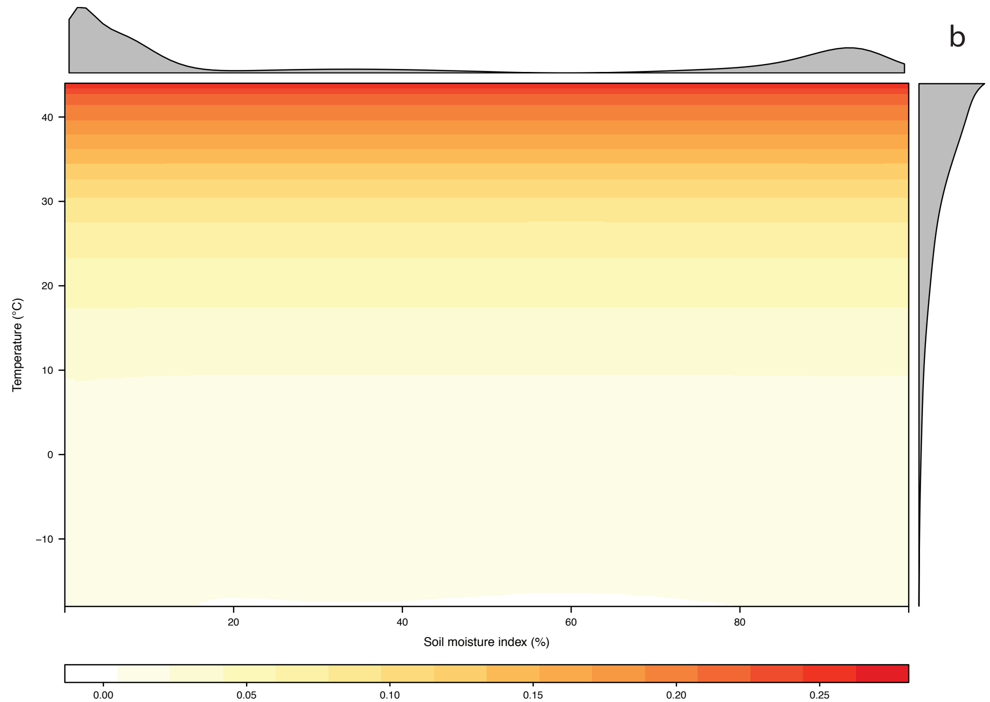


Century1
Century2
Daycent1
Daycent2
Q10 = 2.0
Q10 = 1.4
Loyd and Taylor
Kirschbaum
Demeter
Standcarb
a
f(T)
Temperature (Celcius)
b
df(T)/dT
Temperature (Celcius)
Century
Daycent
Demeter
Standcarb
Candy
Gompertz
Myers
Moyano
Skopp
c
f(W)
Moisture index
d
df(W)/dt
Moisture index



$\Delta T = +1$,
$\Delta W = +0.2$

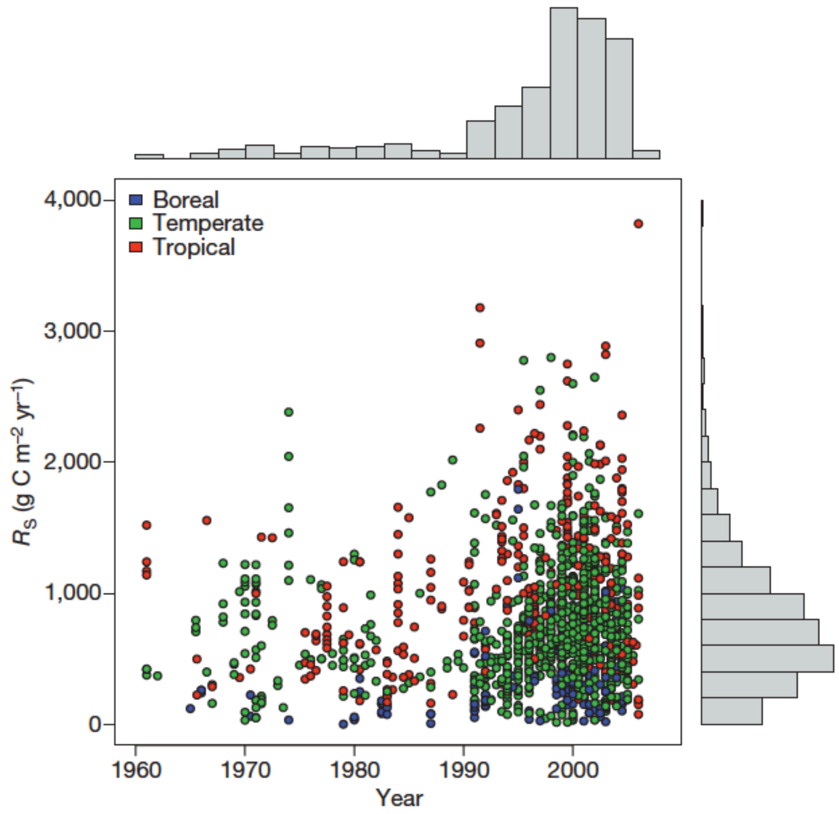

a
Temperature (°C)
40
30
20
10
0
−10
20
40
60
80
Soil moisture index (%)
0.00
0.05
0.10
0.15
0.20

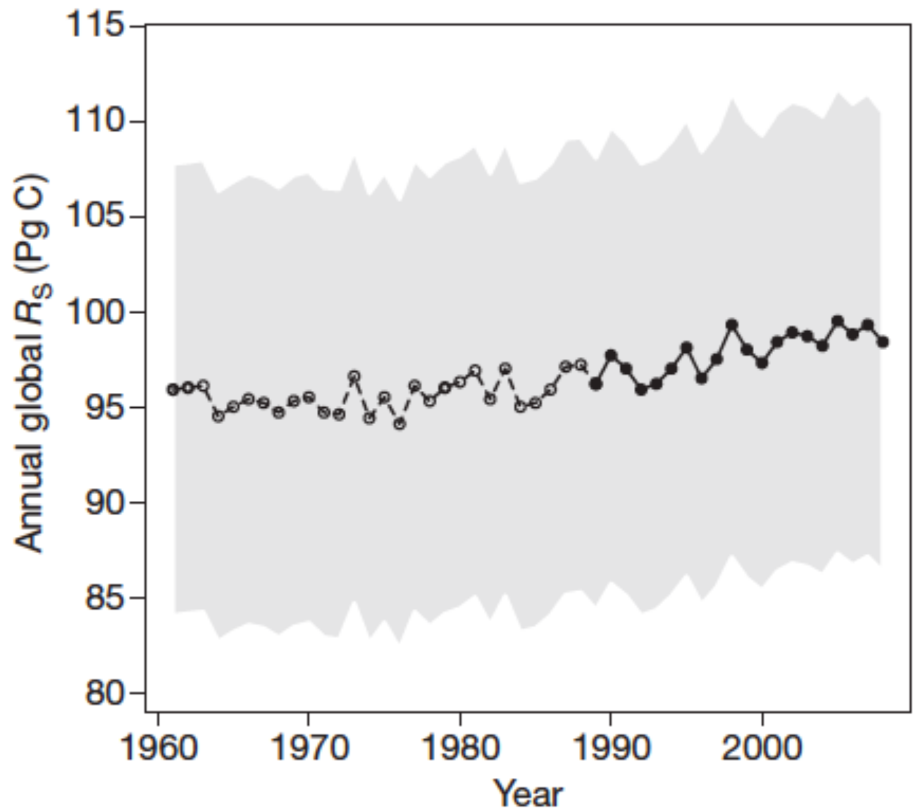

b
Temperature (°C)
40
30
20
10
0
−10
20
40
60
80
Soil moisture index (%)
0.00
0.05
0.10
0.15
0.20
0.25

Take home messages

- A theoretical model suggests higher sensitivities at high temperatures and moisture levels
- Empirical functions in models predict large sensitivities and uncertainties at the extreme of the moisture range. Temperature sensitivities dominate in these models.

Trends in global soil respiration





Bond-Lamberty & Thomson 2010. Nature 464: 579.

Die Bodenmaschine