Enzyme inactivation and microbial energy limitation explain negative temperature response of recalcitrant soil carbon decomposition

Tanvir Shahzad, Nazia Perveen, Vincent V. Maire, Claire Chenu, Sébastien Fontaine

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INRA Clermont Ferrand

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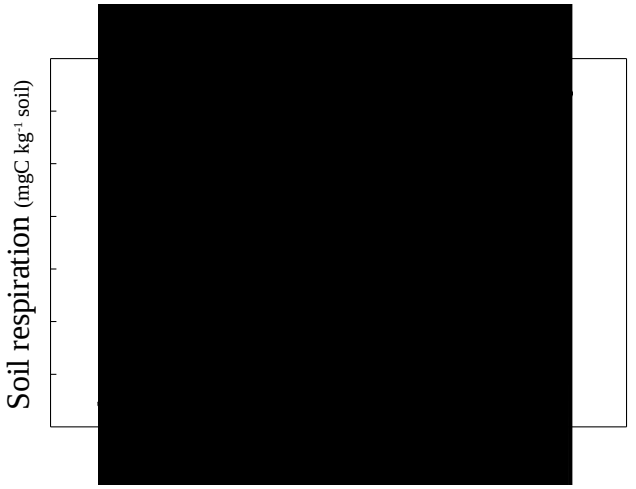
SOM decomposition & temperature: contradictory conclusions

- **Arrhenius theory:**

$$k = a \cdot exp(-Ea / RT)$$

Ea = activation energy

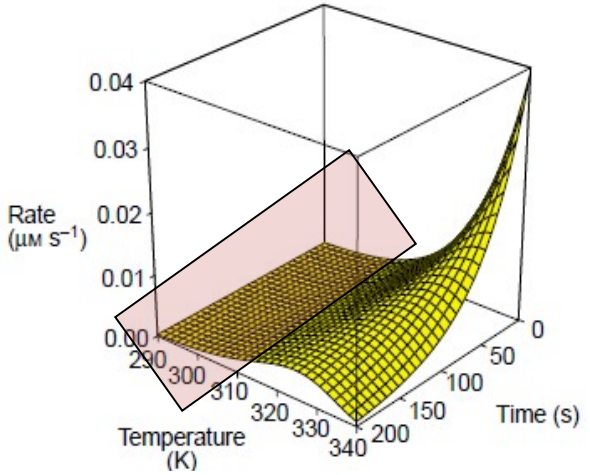
Increasing temperatrue response with increasing recalcitrance of OM (higher Ea)



- **Short-term lab incubations:**

-Support Arrhenius theory

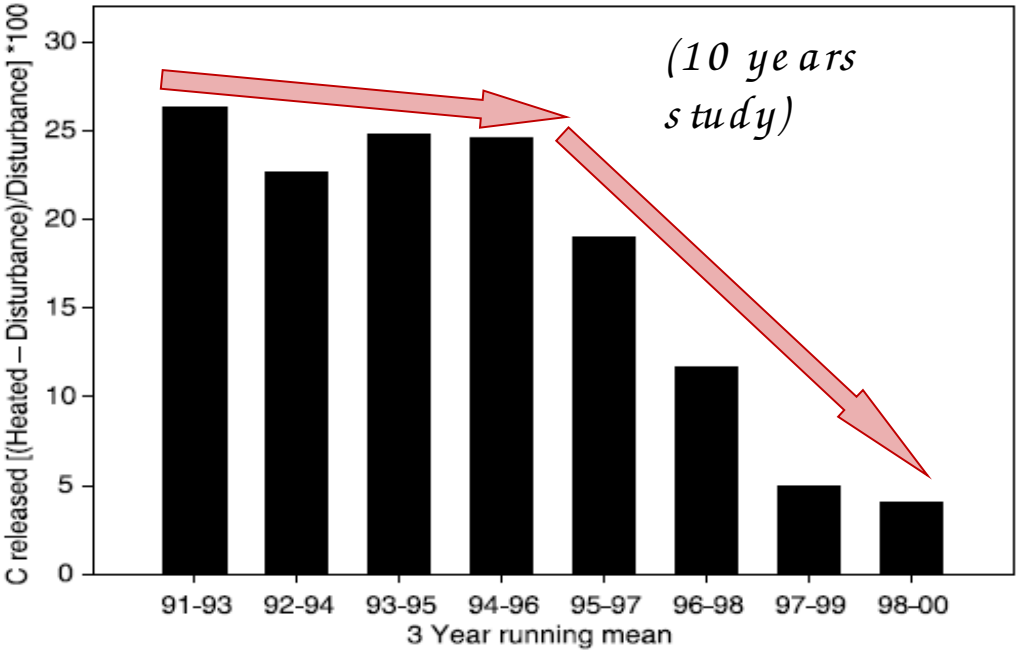
Increased SOM decomposition & enzyme activity with temperature un temperature'



(Kirschbaum 1995; Kätterer et al. 1998; Bol et al. 2003; Fierrer et al. 2003; Waldrop & Firestone 2004; Koch et al. 2007; Yuste et al. 2007; Conant et al. 2008).

SOM decomposition & temperature: contradictory conclusions

- **Long-term soil warming field experiments:**



(Melillo et al. 1998)

- Luo et al 2001 (1 yr) ;Eliasson et al 2005 (10 yrs); Bradford et al 2008 (15 yrs).

- **no effect of temperature in long run, no negative effect of temperature on C stocks;**

even positive effect! **(Phillips et al 1998; Sanderman et al 03)**

Objective of study:

- ***To reconcile these contradictory conclusions***

- ***Possible missing points in literature***

1) Energy limitation of microbes

2) Temperature dependent enzyme inactivation

Inactivation = *Enzyme is unable to catalyse a particular reaction, irreversible*

- *We developed a simple model and then tested it with an experiment.*

Model:

1) SOM decomposition:

$$\frac{dSOM}{dt} = -k_{act} \times E$$

Temperature-dependent specific enzyme activity

$$k_{act} = A_{act}.\exp^{-EA_{act} / RT}$$

2) Dynamics of enzymes :

$$\frac{dE}{dt} = -k_{inact} \times E + k_f \times C_f$$

Temperature-dependent enzyme inactivation

$$k_{inact} = A_{inact}.\exp^{-EA_{inact} / RT}$$

Production rate of enzymes

$$k_f = A_f.\exp^{-EA_f / RT}$$

Model:

3) Dynamics of energy-rich fresh C:

$$\frac{dC_f}{dt} = \Phi C_f(t) - k_f \times C_f$$

- **At steady state for FOM pool (Cf) and Enzymes (E):**

$$\frac{dC_f}{dt} = 0 \qquad \frac{dE}{dt} = 0$$

$$\Longrightarrow$$

$$C_f^* = \frac{\Phi C_f(t)}{k_f}$$

$$E^* = \frac{\Phi C_f(t)}{k_{inact}}$$

At equilibrium the rate of SOM decomposition can be written as:

$$\left(\frac{dSOM}{dt}\right)^{*} = -k_{act} \times E^{*}$$

$$E^{*} = \frac{\Phi C_f(t)}{k_{inact}}$$

$$k_{act} = A_{act}.\exp^{-EA_{act}\ /\ RT}$$

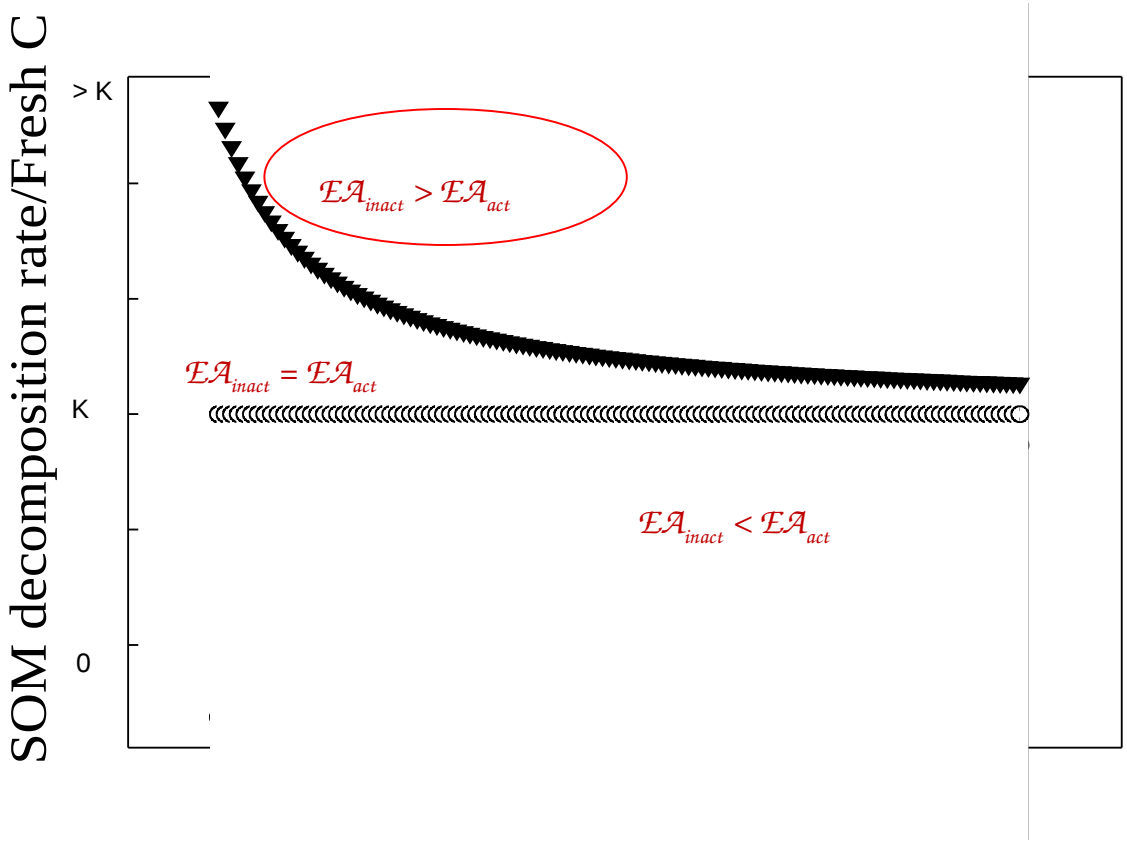
$$\left(\frac{dSOM}{dt}\right)^{*} = -\Phi C_f(t).K.\exp^{\frac{EA_{inact} - EA_{act}}{RT}}$$

$A_{act}/A_{inact} = \boldsymbol{K}$

- ***Thus temperature response of SOM decomposition depends on difference of activation energies of enzyme activity and inactivation.***

Model Results:

$$\left(\frac{dSOM}{dt}\right)^{*} / \Phi C_f(t) = -K.\exp^{\frac{EA_{inact} - EA_{act}}{RT}}$$



- *In enzymology, EAinact > EAact has been shown for large number of enzymes . See Daniel et al; 2010*

- ***Thus we assume negative relationship between SOM decomposition and temperature.***

Experimental test of theory

- ***The need to distinguish the plant derived (fresh energy) C from soil derived (SOM) C.***

$$\left(\frac{dSOM}{dt}\right)^{*} = -\Phi C_f(t).\frac{A_{act}}{A_{inact}}.\exp^{\frac{EA_{inact}-EA_{act}}{RT}}$$

- ***If soil derived C is lumped with fresh C, may confound the temperature response.***

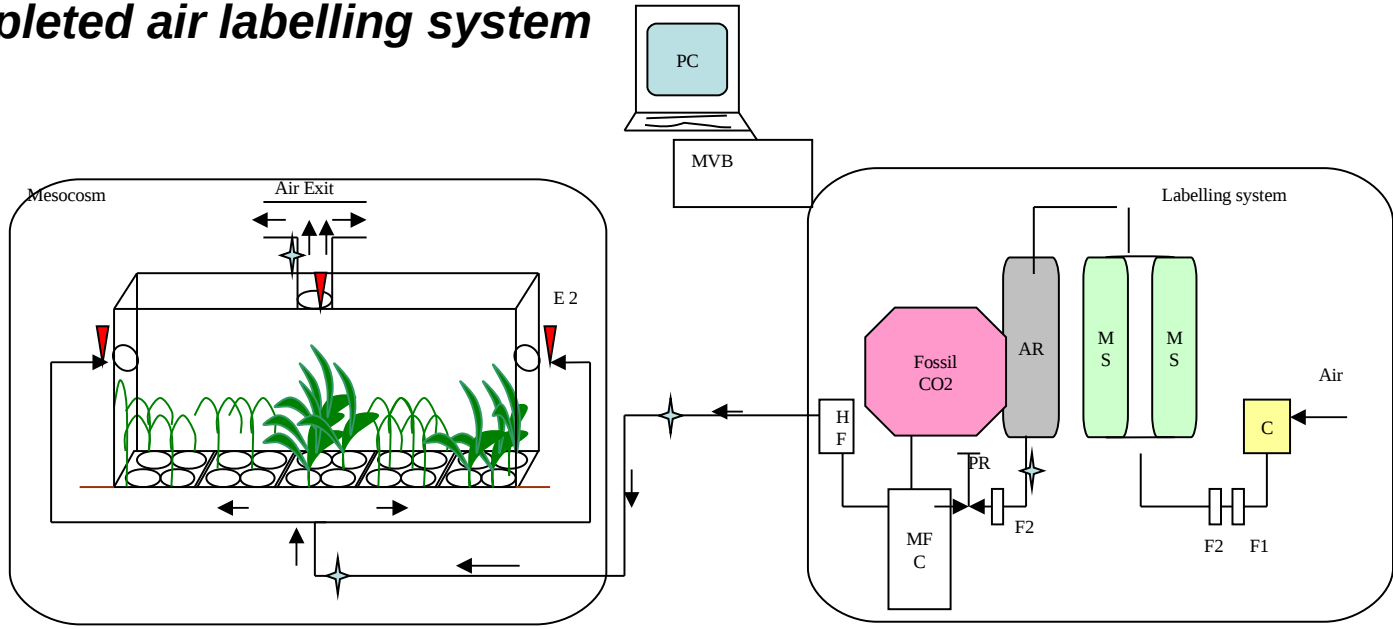
Labelling system & mesocosm

- ***Continuous ^{13}C depleted air labelling system***

Air δ ^{13}C = -38.55 ‰

Biomass δ ^{13}C = -57.68 ‰

Duration = 479 days

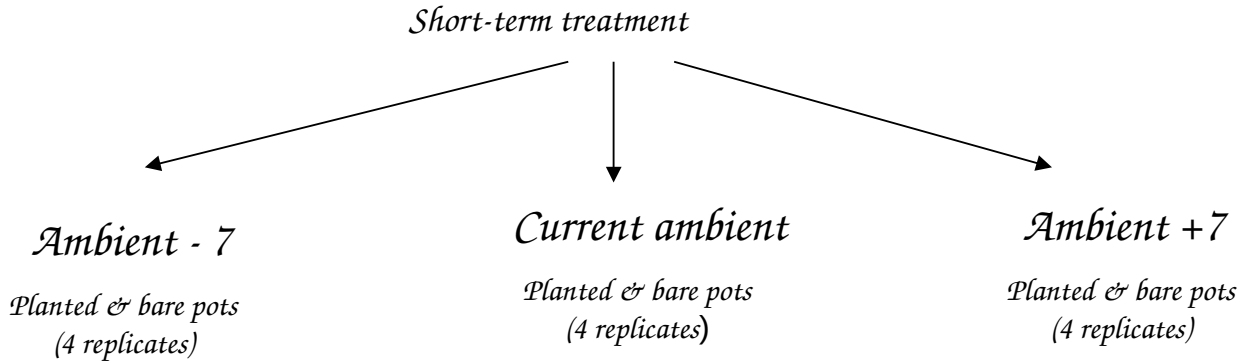


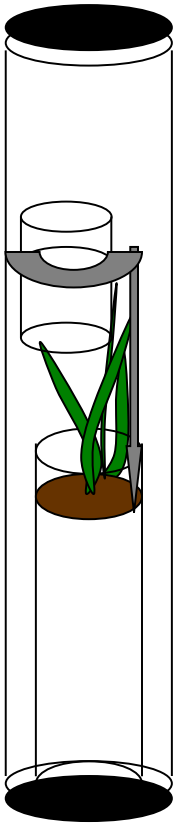
Soil, plant & temperature treatments

- A Cambisol from upland prairie
- 10-40 horizon sampled & sieved (5mm)
- Put into PVC pots
- 12 pots sown with Lolium perenne & 12 left bare

2 types of temperature treatments for respiration measures

1) Short-term (24 hrs) treatment under controlled chambers



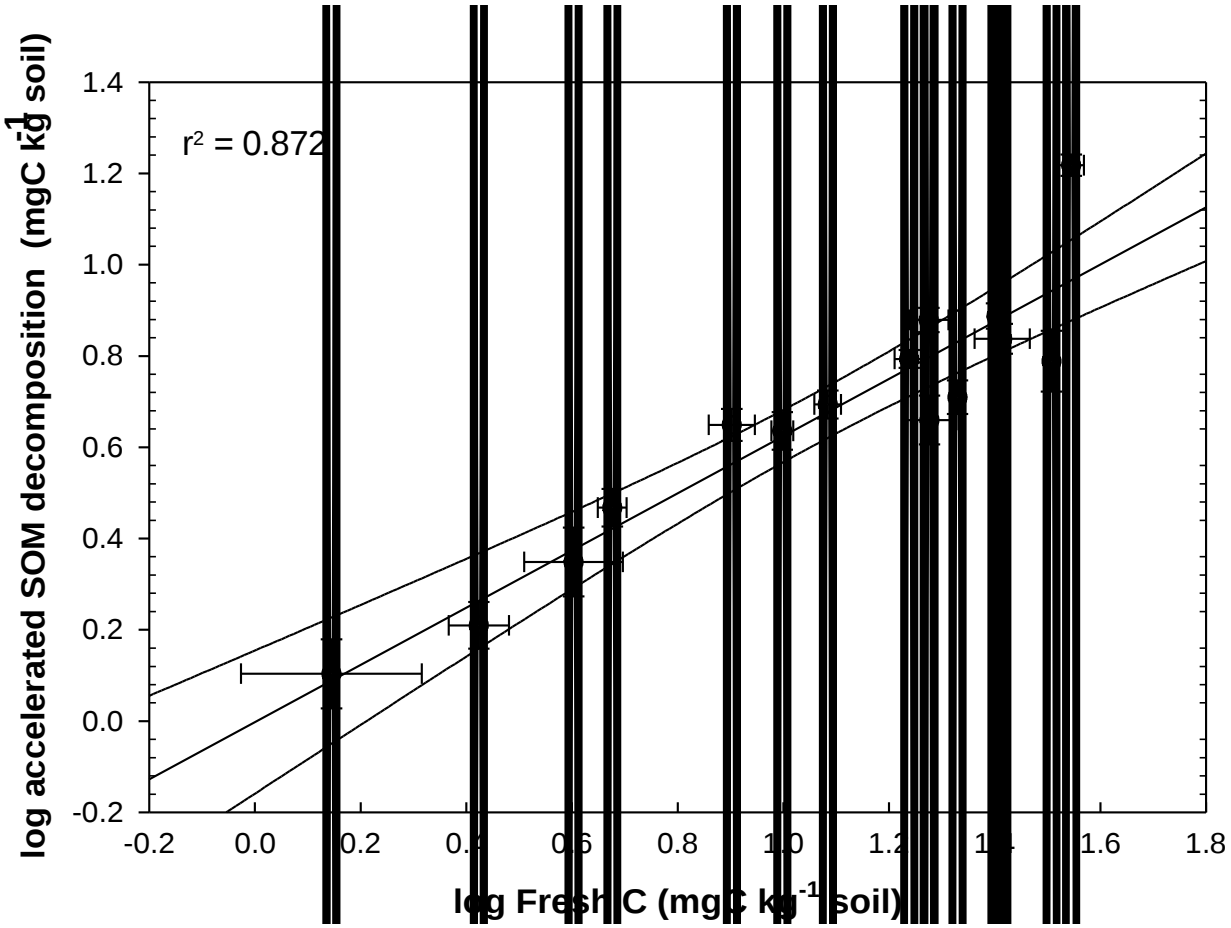


Placed for 24 hrs under controlled temperature

2) Seasonal temperature variation: Spring 2009 – Summer 2010

Results & Discussion:

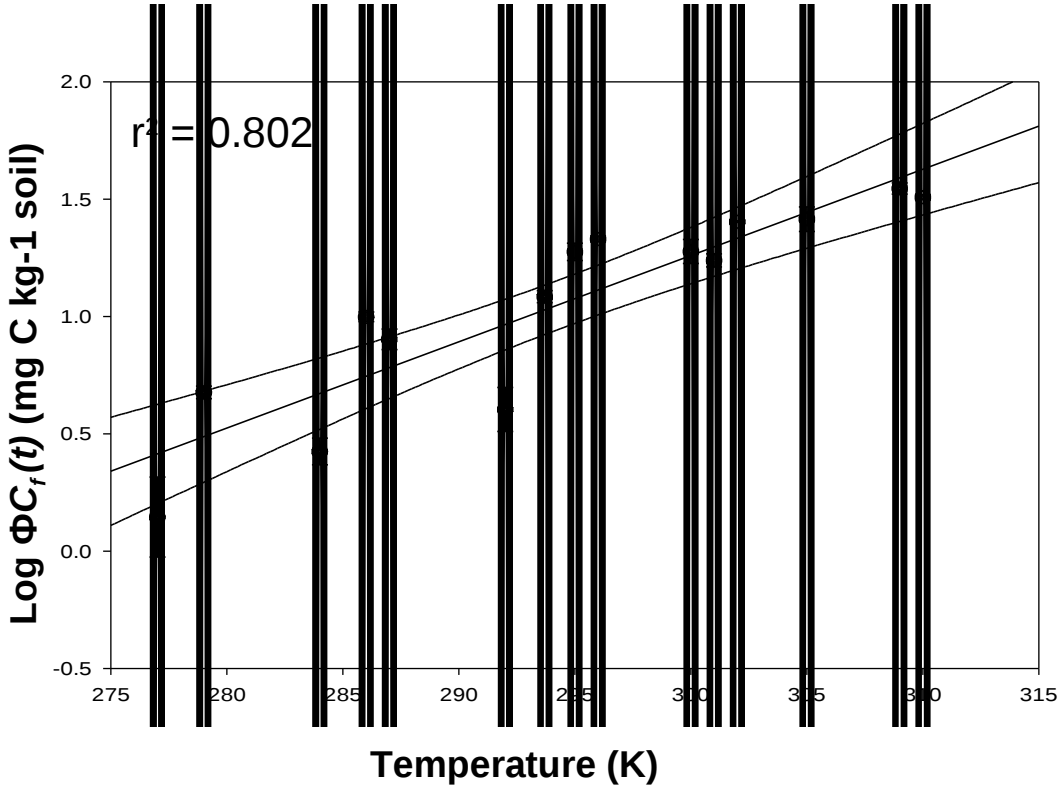
- ***SOM decomposition of fresh C controlled by fresh energy supply***



The decomposition of SOM is limited by energy available to SOM decomposers as suggested by « Priming Effect » theory

Results & Discussion:

Temperature increases microbial cosumption of fresh energy

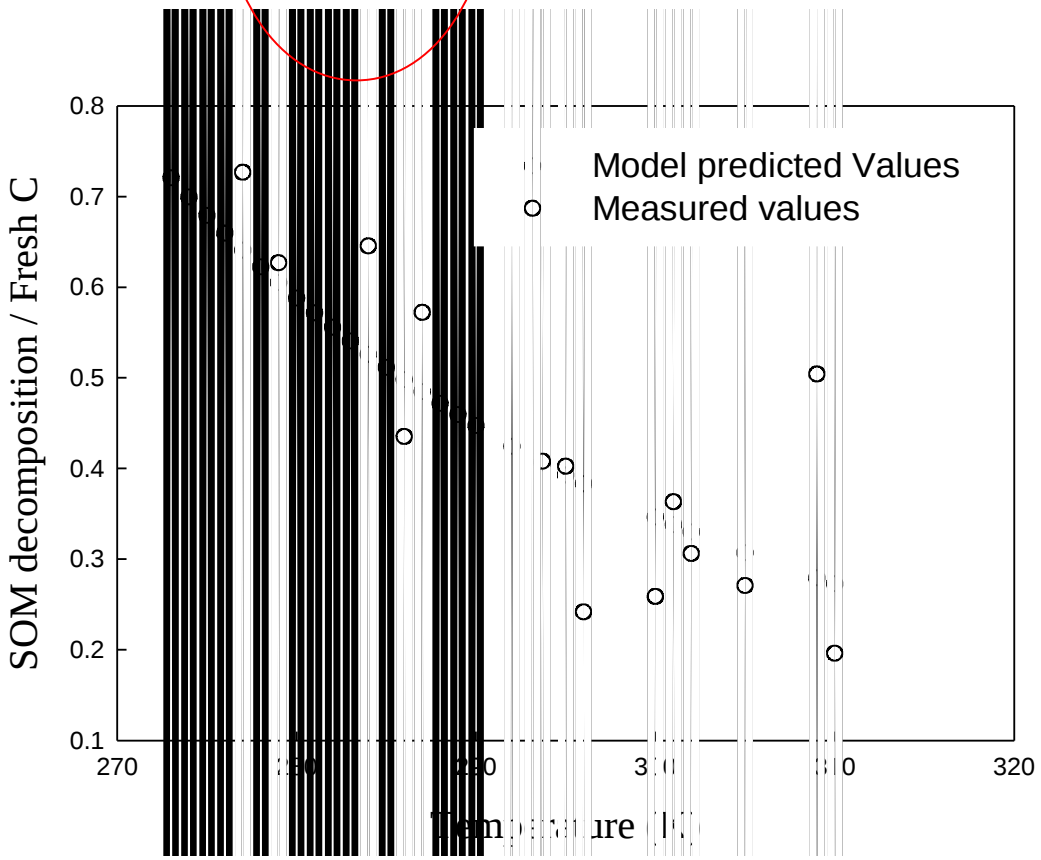


Seasonal variation in temperature causes changes in photosynthesis & fresh C input

Model Fit:

Equation:

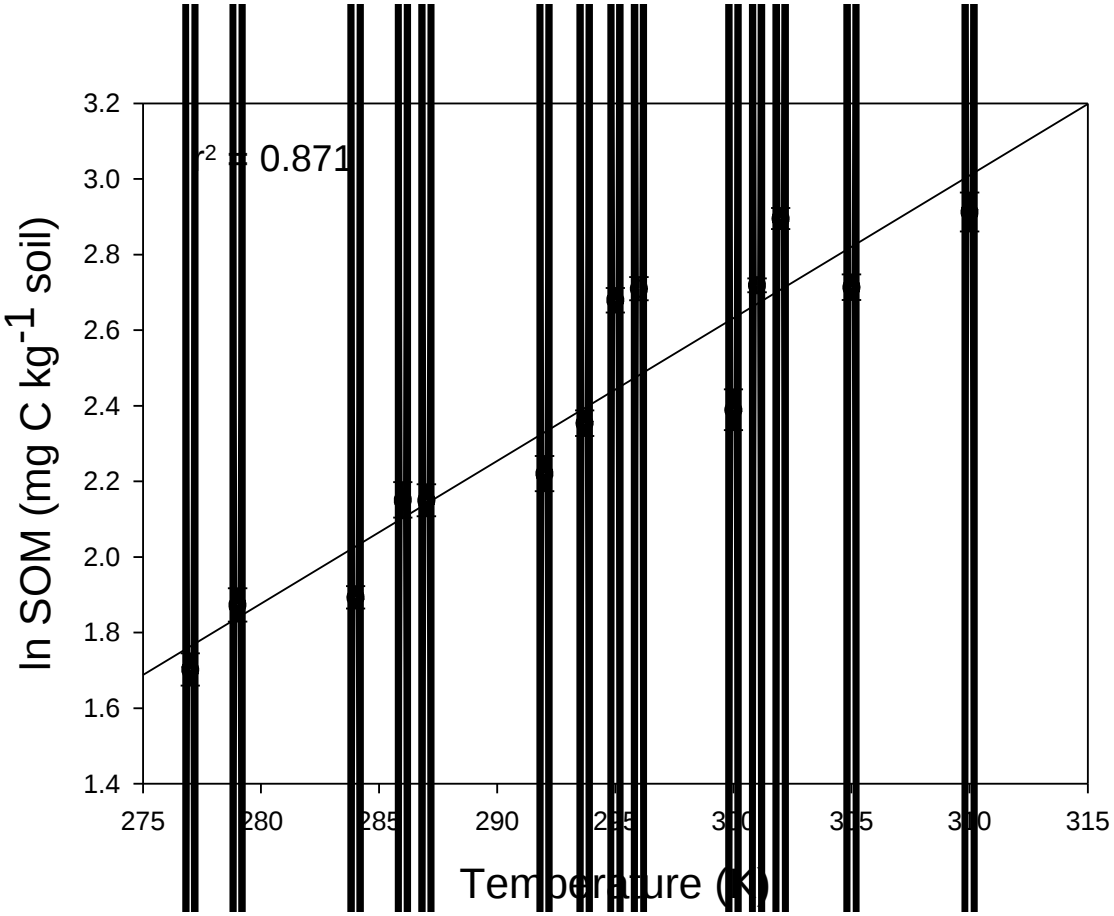
$$\frac{\left(\frac{dSOM}{dt}\right)^{*}}{\Phi C_f(t)} = -K.\exp^{\frac{EA_{inact}-EA_{act}}{RT}}$$



Experiment supports our theory: temperature has negative relationship with SOM decomposition

Results & Discussion:

If effect of fresh energy supply isn't separated from that of temperature, we observe an apparent +ve response to temperature!



Thus positive temperature response of SOM decomposition: ***An artefact !***

Conclusions & Synthesis:

Linking theory with long term experiments

- ***Our results, theory & experiment, reveal negative relationship between SOM decomposition and temperture if enzyme inactivation and energy limitation of microbes is taken into account.***

- ***This explains the results of long-term ecosystem experiments which show no or weak positive effect of temperature on SOM storage.***

- ***This could explain other empirical results like SOM storage in tropical ecosystems under high temperatures.***

Linking theory with results of lab incubations & enzyme assay:

$$\frac{dSOM}{dt} = -k_{act} \times E_0$$

For enzyme assays & soil incubations, there is no fresh C supply

$$\frac{dE}{dt} = -k_{inact} \times E + k_f \times C_f$$

$$\frac{dC_f}{dt} = \Phi C_f(t) - k_f \times C_f$$

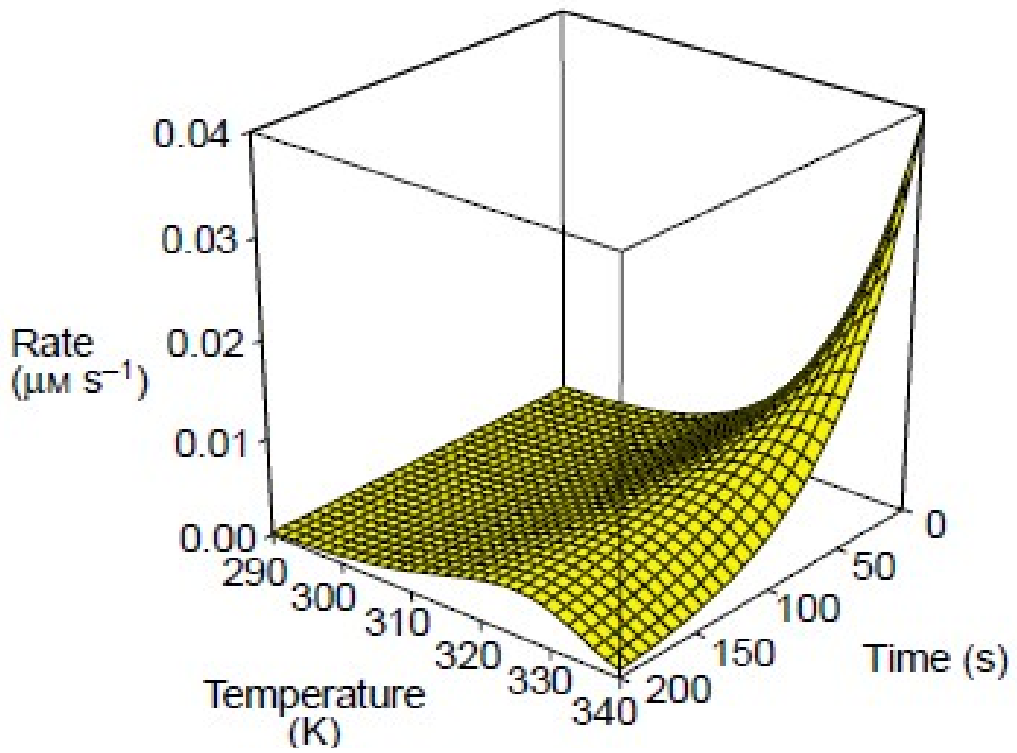
After simplifying, SOM decomposition & enzyme activity can be calculated as

$$A(t,T) = k_{act}.Eo.\exp^{-kinact.(t)}$$

A (t, T) = Soil respiration & Enzymatic activity as function of time and temperature

E_0 = Initial enzyme pool.

Optimum temperature



This is observed in enzyme assays and short-term soil incubations

Conclusions & Synthesis:

1) Our model explains effect of temperature in soil-incubations and long term experiments

2) These results aren't contradictory but we can not simply compare the results of lab incubations with long-term soil warming experiments.

3) We suggest that global warming will not have important direct effect on SOM storage however we should focus indirect effects like drought that can result in de-synchronisation of microbial and plant functioning.

limitations:

- not valid for frozen soils

- Neither for extreme temperatures

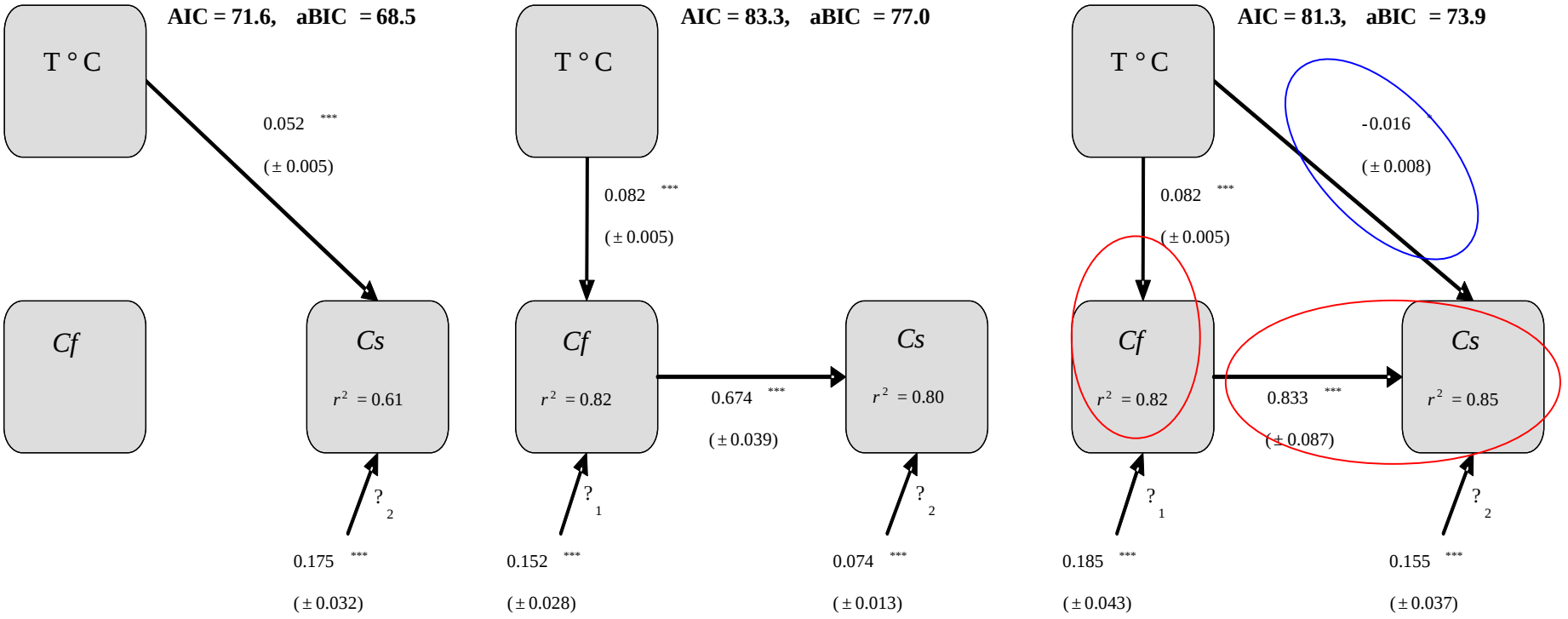
Merci bien

Plant cover & temperature effects on SOM decomposition:

Net temperature effect

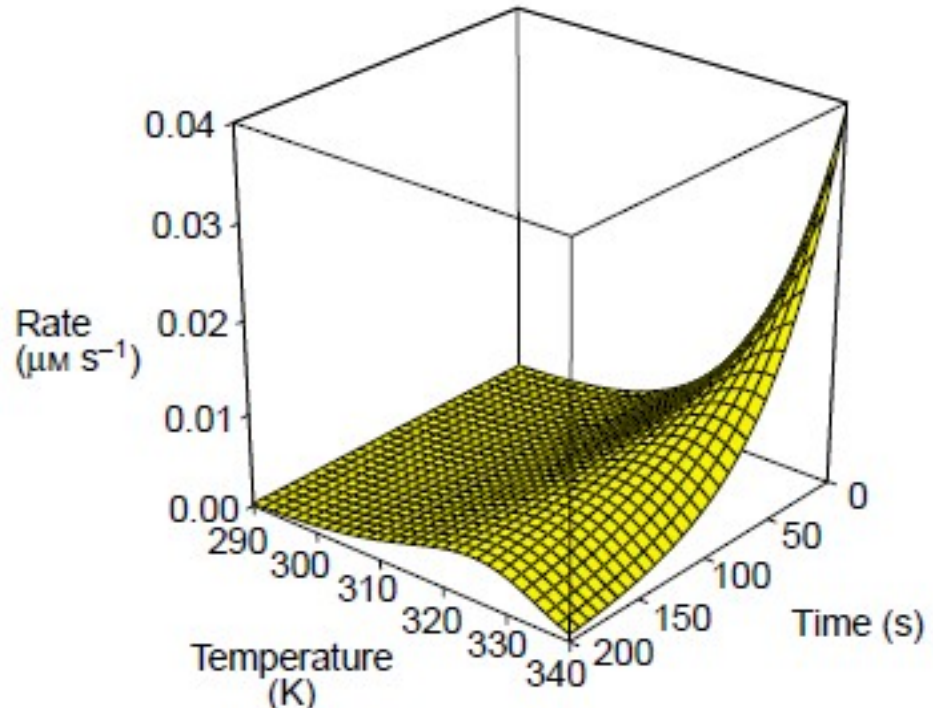
Indirect temperature effect

Direct and indirect temperature effects



Enzyme assay:

$$V_{\max} = k_{cat} . [E_0] \exp^{-k_{inact} . t}$$



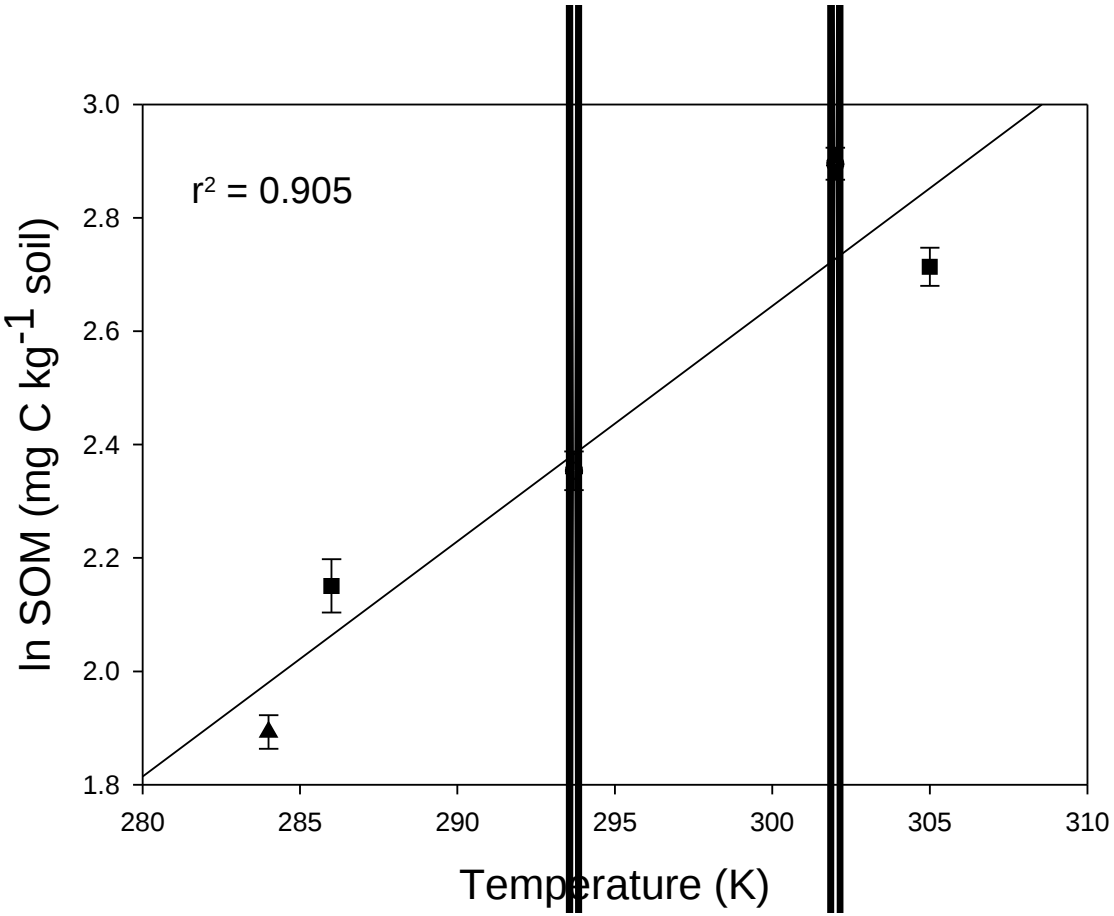
Results & Discussion:

- ***Effect of plant cover, temperature & plant cover X temperature***

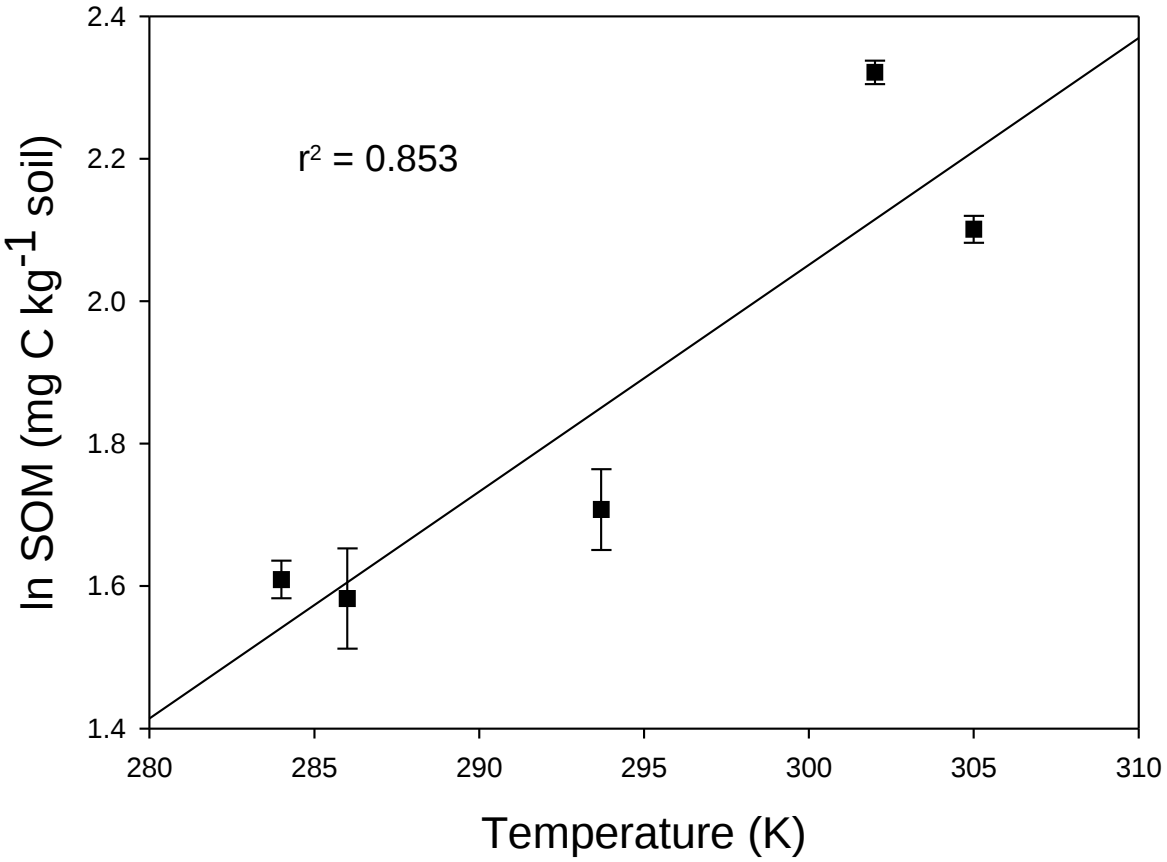
Factors	Df	Variance explained (%)	F-ratio	*P*-value
Date (Plant)	4	5.7		
Plant	1	8.7	61.8	< 0.001
Temperature	1	85.3	607.4	< 0.001
Plant x Temperature	1	0.28	2.01	ns
Overall	117	$r^2 = 0.94$		

Repeated measures ANOVA

Seasonal temperature variations: Planted soils



Seasonal temperature variations: bare soils soils



Long term C storage :

Meta-analysis: eddy covariance, 21 sites, +ve sign respresents net ecosystem gain