Complexity, global climate change, and the factors controlling soil carbon cycling

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Overarching questions

Will carbon lost from soils amplify climate change?

A substantial uncertainty in predicting ecosystem carbon cycling in the context of climate change is the response of enormous pool of soil carbon (Davidson & Janssens, 2006). Small changes in the soil carbon pool could have dramatic impacts on the concentration of CO_2 in the atmosphere (Smith et al., 2008). As the climate warms, a net loss of carbon from soils is expected (IPCC, 2007). The concern , supported by global-scale models ,involves a positive feedback scenario: as temperatures increase, soil microbial respiration will increase, and increased atmospheric CO_2 released from soils will accelerate global climate change. Modeling to address this concern hinges on the hotly debated temperature sensitivity of soil respiration (Kirschbaum 2006). However, there remains no scientific consensus on the temperature dependence of organic matter composition. This is a complicated issue to assess and despite a proliferation of experimental and modeling studies, the final conclusions remain unclear (Figure 1).

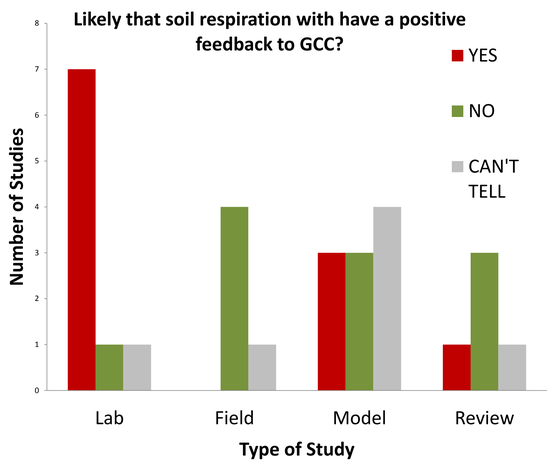


Fig 1. An illustration of the differing approaches and conclusions related to soil respiration and temperature response. n=29. Paper selection was not random and is far from exhaustive; the totals by conclusion therefore are not meaningful. A "model" paper is one in which various or no explicit datasets are used; most experimental papers involved modeling to achieve a conclusion. "Can't tell" may be for many reasons including an effective methodology or to varied results.

Overarching research goal: What matters when?

Related questions:

Is older carbon more temperature sensitive?

Do substrate, biotic or abiotic factors determine sensitivity?

Will temperature amplify climate change? It depends. There is agreement on the fundamental reason for the for the continued debate on the temperature response of decomposition: the entangled, nonlinear and highly scale-dependent web of factors and feedbacks involved—carbon quality, pH, soil clay content, nitrogen, microbial community structure and many more—complicates the coherent synthesis of results (Figure 2). The result is that we cannot yet achieve design reasonable models that apply across experiments, systems or scales (Trumbore 2006). A comprehensive assessment of factors and their interactions across scales is lacking.

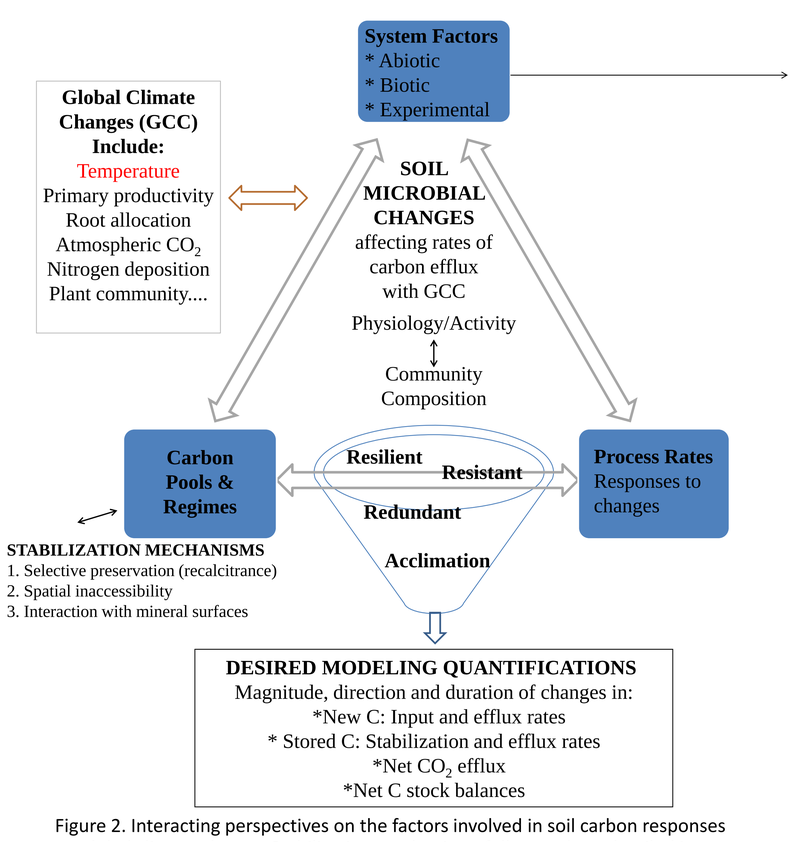


Figure 2. Interacting perspectives on the factors involved in soil carbon responses to global climate change. Stabilization mechanisms follow and are detailed in von Lutzow et al., 2006. In order to impact desired modeling quantifications, shifts in the many factors must not be resistant, resilient or functionally redundant (following Allison et al., 2008) or quickly acclimate.

The first step: What *can* matter?

Delving into this web and differing views of it is critical to understanding decomposition responses, reconciling divergent results, and predicting respiration in the context of global climate change. We accessed the literature across disciplines and conceptualized the comprehensive inventory of factors that inventory of the potential controls that interact with temperature responses and impact temperature sensitivity (Figure 3).

The next step: Organizing and relating the factors

• Classification hierarchy: Criteria, Indicators, Metrics

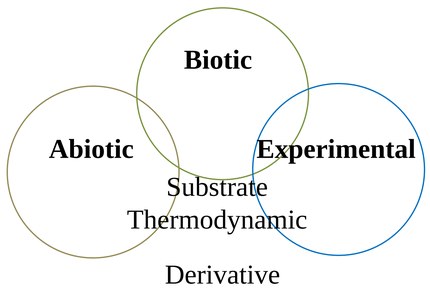
We then used complex systems theory to construct a simplified hierarchy (Figure 4). Criteria involve the context of the desired information, and are more general (Ahl & Allen, 1996). Indicators are specifications of the criteria, which may be associated with differing metrics.

• Categories: Abiotic, Biotic, Experimental, Substrate, Thermodynamic, Derivative

We defined categories building on schemes from the literature.

• Interactions: Primary, secondary, one-way, two-way, nesting

Finally, we modeled these factors, and their relationships such as nesting as feedbacks, implemented as a relational database (Figure 5).



ABIOTIC CRITERIA
Climate
- Hydrology
- Temperature
- Precipitation
- Wind

Depth
Disturbance
Geographical location
Geomorphology
Human land use or management
Nutrient quality & quantity
Soil characteristics
- Chemistry
- Habitat characteristics
  - Soil Moisture
- Parent material
- Physical properties
- Soil temperature
- Soil structure

Time

INDICATORS
Aeration
Age since establishment
Agricultural regime
Air humidity
Atmospheric CO2 concentration
Available soil moisture
Depth to water table
Diffusion limitations
Electrical Conductivity
Evapotranspiration
Fire regime
Karstic features
Latitude
Nutrient deposition
Slope/aspect
Soil
- % organic matter
- Age
- Cation/anion-exchange capacities
- Clay content, texture
- CO2 concentration
- Horizon

Mineralogy
Particle size fractions
pH, Salinity
Porosity, Bulk density
- Texture
- Temperature

Runoff

BIOTIC CRITERIA
Litter quality
Macro and meso-fauna
Microbial community
- Activity
- Functionality presence & abundance
- Metabolic potential
- Nutrient requirements
- Potential and rates of change: thermoadaptation, acclimation, evolution
- Process outputs
- Resilience, fragility, stability
- Size
- Structure
- Substrate preference

Plant community
- Many criteria same as microbial above
- Root system
- Vegetation type

Plant-microbial associations

INDICATORS
Microbial
- Biomass-C concentration and C:N ratios
- Competitive interactions
- Diversity
- Energy efficiencies
- Enzymatic talents
- F:B ratio
- Growth rates
- Life strategies
- Optima, maxima, minima
- Resource allocation
- Respiration
- Seasonal and intra-annual dynamics
- Species presence & abundance
- Stress responses
- Predator or competitor presence/abundance

Plant
- Many criteria same as microbial above
- Cover of vegetation types
- Phenology
- Photosynthesis indices
- Root
  - Depth, volume, architecture
  - Function, structure, size
  - Potential and rates of change
- Successional trajectories
- Symbiotic associations (N, mycorrhizal)

EXPERIMENTAL CRITERIA
Definitions
Goals
Methodologies
Perspective
Scale

INDICATORS
CO2 measurement method
Depths in experiment
Experiment duration
Laboratory, field or modeling study
Microbial community id method
Moisture metric
Autotrophic respiration included
Recalcitrant C identification method
Rhizosphere or bulk soil
Root respiration included
Soil storage and preincubation protocols
Study duration
Temperature measurement depth
Temperatures below freezing

SUBSTRATE CRITERIA
Spatial distribution in soil structure
Quality
Quantity

THERMODYNAMIC CRITERIA
Activation energies
Diffusion gradients (gas, substrate, atmospheric, soil)
Decomposer surface area
Enzyme affinities
Solute diffusivity
Substrate energy content
Thermal conductivity

DERIVATIVE CRITERIA
Availability (e.g. nutrient)
History
Humic substance/sequestration
- Creation & Protection

Hysteresis
Potential biota
Priming effects
Ratios
Regime
Variability

INDICATORS
Microbial biomass/total C
Time since conversion from agriculture

Figure 3. A comprehensive conceptual framework to compile and organize the factors that can interact with the temperature response of soil decomposition. All criteria but not all indicators, and no metrics, are shown. Factor derivatives such as ratios and variance can change scales and levels of information. Regime describes the magnitude (amplitude), timing (wavelength) of variation in a factor crossed with a time scale, such as spatiotemporal variation or heterogeneity .

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ACKNOWLEDGEMENTS

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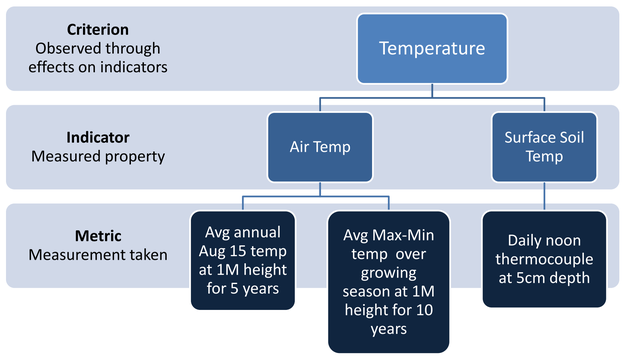
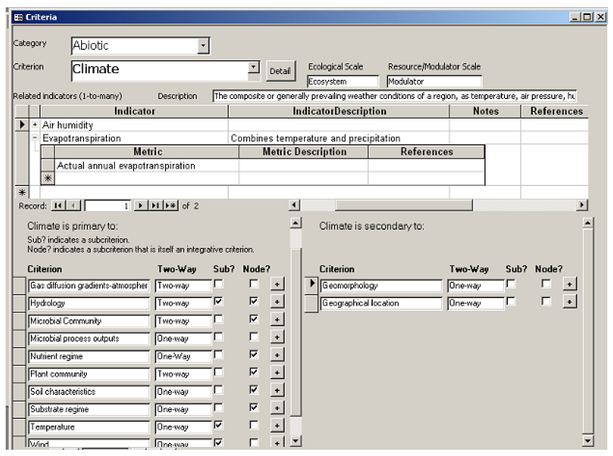


Figure 4. Illustration of the relationship and definitions of criteria, indicators and metrics. Relationships between levels in this simplified model boxes are one-to-many; for example, each criterion can have many indicators, but each indicator is associated with only one criterion.



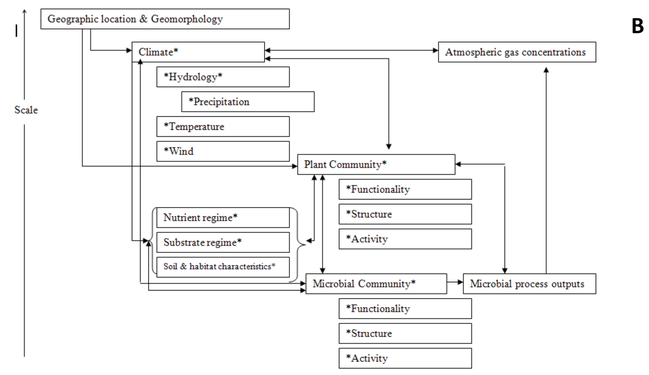


Figure 5. Sample screen shot from model implemented as relational database, and resulting graphical representation.[A] User interface showing a factor hierarchy, scales and interactions. A secondary criterion is at least partially dependent on a primary criterion. A two-way relationship involves feedback at some scale from the secondary to the primary factor. Nested relationships specify a criterion as a subcriterion (Sub), an integrative criterion that nests others (Node), or both. A secondary criterion is at least partially dependent on a primary criterion. A two-way relationship involves feedback at some scale from the secondary to the primary factor. [B] Selected factors as coded in the database depicted graphically. Name* indicates an integrative criterion that wraps other criteria; if subcriteria are shown, they are denoted as *Name.

CONCLUSIONS

1. Answers to the positive feedback question depend on a complex web of factors, and how one conceptualizes and bounds the system. Differences in criteria, indicators, or metrics can influence study results and their interpretation.

2. We constructed a simplified hierarchy organizing and relating the comprehensive universe of the factors that can potentially control soil microbial temperature response. We are currently using the model presented here to specify system states for a meta-analysis that will quantify the factors that matter at various scales, associated thresholds, ranges, and uncertainties, along with key interacting factors.

This can help ecosystem researchers to:

- Consider elements for potential inclusion in quantitative or conceptual models
- Clarify boundaries of the system , and explicitly address factors excluded by a study
- Define the potential space for meaningful hypothesis generation
- Characterize a system state based on its values of various factors.