COMPLEXITY, GLOBAL CLIMATE CHANGE AND SOIL CARBON CYCLING: FACTORS CONTROLLING THE TEMPERATURE RESPONSE OF MICROBIAL DECOMPOSITION

Devin Wixon

University of Wisconsin, Madison, Department of Botany

ABSTRACT

A proliferation of data being gathered to predict a critically important, urgent and social-policy related question leads only to confusion, debate and paralysis. This classic feature of complex systems is currently being evidenced in answering the question of a positive feedback response of soil respiration with increased temperatures due to global climate change. As with many current environmental challenges, a web of confounding factors acting at different scales complicate the integration of the results into a clear narrative. This is a strikingly complex system, and debate rages regarding even seemingly basic questions.

However, agreeing that this is a problem has not led to a solution. In particular, a comprehensive explanation of what factors are problematic is lacking. This research applies soft systems modeling (SSM) to the question: Why can't we satisfactorily answer the question? My first conclusion from a review of the literature is that varied perspectives on the system's dynamics and its web of controlling factors have led to seemingly conflicting results. At different levels of analysis, different constraints apply. Models must compress information and select driving factors of interest, but they must also account for the integrated effects of factors that are not explicitly included. The microbial community functions as a holon, and has been compressed to its outputs in most temperature response research. New technologies, however, are effectively providing insight into micro-scale dynamics. Experimental design, model development, and their integration can benefit from a holistic, systems approach to the diverse perspectives and associated factors of interest. The intent is not to theoretically assert that there are different points of view but rather to explicitly identify them and their associated system boundaries. This culminates at the end of step two in a first conceptual model of the potential universe of factors under discussion across perspectives. This model is organized in a hierarchy of levels and categories. Step three involves looking in general at the factors, and illustrates definitions based in distinct system abstractions. I present a simplified hierarchy (a "holarchy") implemented as a relational database, including relationships between factors such as subset elements (nesting and feedbacks. I conclude that although this model is limited to pairwise interactions, it provides a useful tool to assess potential interactions and factors of interest.

Keywords: Soft systems modeling, hierarchy theory, microbial decomposition, global climate change, systems biology, environmental modeling

INTRODUCTION

"We are increasing our understanding of the nested hierarchy of drivers acting at varying spatial and temporal scales that impact microbial communities." (Balser et al. 2006)

"The name of the game in science is finding those helpful constraints that allow important predictions." (Allen, Hoekstra 1992)

The Problem, the Question, and the Systems Context

A proliferation of data being gathered to predict a critically important, urgent and social-policy related question leads only to confusion, debate and paralysis. This classic feature of complex systems is currently being evidenced in answering the question of a positive feedback response of soil respiration with increased temperatures due to global climate change. Temperature shifts might lead to increased soil carbon release, adding more carbon dioxide to the atmosphere, thus both depleting carbon stores and increasing global temperatures in a positive feedback loop. As with many current environmental challenges, a central problem is the web of interacting factors acting at varying scales and exhibiting nonlinear dynamics. Soil microbial communities as well as the factors (temperature, water, pH, etc.) driving their respiration are both decidedly complex. The relationship between temperature and carbon mineralization is not a simple one (Agren, Bosatta 2002; Bol et al. 2003), and even basic relationships between factors have defied consensus. I ask the higher level question: Why can't we satisfactorily answer the question?

Soil Respiration and Global Climate Change

Soil respiration and its temperature response in particular are universally acknowledged to be a critical and primary link between climate change and the global carbon cycle. Globally, the consensus is that temperatures have been and will continue increasing for the foreseeable future. During the 20th century, the increase was 0.6ºC, and projections are for an additional increase of up to 6ºC during the 21st century (IPCC 2007a). Even a slight change in decomposition rates can result in significant change to the global carbon cycle. It is generally agreed that the carbon stored in soils will decrease with these changes (IPCC 2007b). To give some sense of the magnitude of worldwide soil respiration, here is one perspective: A change of total soil organic carbon of only 10% would equal all the anthropogenic CO_2 emitted over the last 30 years (Kirschbaum 2000).

The literature agrees on that understanding environmental dependencies of microbial decomposition processes is essential to the modeling of future climate change. However, there are many challenges. There remains no scientific consensus on the temperature dependence of organic matter composition (Agren, Wetterstedt 2007).

It is understood that much of the debate regarding temperature response is due to the confounding role of different experimental conditions(Conen et al. 2006; Kirschbaum 2006; Smith et al. 2003), timescales (Gutknecht 2007) and environmental co-varying factors (Davidson, Janssens 2006). In other words, different factors and their feedback loops can be rate-controlling, depending on experimental or environmental conditions, including the scale (e.g. time) of observation. Feedbacks among the web of interacting factors are a major source of uncertainty in decomposition models. In specific terms, soil organic matter pools, roots, and decomposing microorganisms all have distinct responses to environmental change drivers, with substrate availability regulating the responses (Pendall et al. 2004a).

Achieving useful models requires simplifying the "nested hierarchy of drivers acting at varying spatial and temporal scales that impact microbial communities," (Balser et al. 2006). It is not surprising that findings at different scales lead to differing results; scaling issues are fundamental to all ecological investigations (Wiens 1999). Simple mechanistic approaches may not be effective; "Unfortunately, no relationship to any measured environmental variable was identified," (Emmett et al. 2004). The staggering variety of factor models prompts the question: Which factors matter, to who (both human and microbial), and under what system states? Selecting the salient factors that contribute to quantitative model, or in other words, bounding the system appropriately, will be both incredibly important and uniquely challenging. The limitations of data and understanding, objectives, perspective, and predictive implications all influence the appropriate model choice (Turner 2003).

The necessary compression of these factors into models leads to seemingly conflicting results. This concept of an interacting web of complex factors is not unique to this system, but applies to many systems involved in ecosystem and other modeling. Such nested hierarchies and scale considerations are one subject of complexity and hierarchy theory.

Complexity

Complex systems can be defined in many ways. One that is directly applicable here is that complex systems can experience a flip in constraints with perturbation allowing for different controls to become dominant (Holling 2001). Another feature of complexity is that several levels of organization are required for adequate descriptions (Brown, Allen 1989). A more formal way of saying this is: "Complexity in living systems is associated to the existence of multiple legitimate ways adopted by a population of non-equivalent observers for perceiving and representing their interaction," (Giampietro, 2003, interpreting Rosen). These definitions allow us to immediately see that this is a complex system. One aim of complex systems theory is to take seriously the subjectivity and treat it with intellectual rigor. Explicitly understanding the specific levels of organization, perspectives on controlling factors, and the universe of potential factors is the goal of this paper. This application of systems theory allows decisions on system bounding and communication between diverse stakeholders to be more effective, as well as the reconciliation of seemingly conflicting results. As Giampietro (2003) succinctly notes, "Making a model more complicated does not help when dealing with complexity."

Soft Systems Methodology

Many resources are available to study the soft systems methodology (SSM) approach in-depth (Checkland 1981). Its intent is to address problems "to cope with the normal situation in which people…perceive and interpret the world in their own ways and make judgments about it using standards and values which may not be shared by others,"(Checkland, Scholes 1990). The primary use of SSM is in the analysis of complex situations addressed by divergent views. Hardness is the proportion how much the system can be described by exact formalisms (reproducible, known algorithms). Soft systems in contrast can have seemingly irreproducible results involving many interacting factors including human ones. They are difficult to diagnose and their properties often cause the infeasibility of proper structure definition and easy modeling (Pesl, Hrebicek 2003).

I apply the modified version of SSM taken from Allen and Hoekstra (1992) as outlined by Giampietro (2003). This approach is most directly compatible to the environmental sciences. I explicitly apply the first four of eight steps to the question of soil respiration responses to global climate change.

In this paper, I first situate the question in the context of soft systems using concrete examples and data from the literature. The intent is not to theoretically assert that there are different points of view, but to explicitly identify them and their associated system boundaries. Rather than this being merely pointing out a problem, the exercise is in fact a first step towards a solution. This culminates at the end of step two in a first conceptual model of the potential universe of factors under discussion across perspectives. I then examine some key, nonoverlapping understandings of the factors that motivate the construction of a simplified but formalized holarchy model allowing for factor relationships including feedbacks and nested hierarchies.

APPLYING SOFT SYSTEMS METHODOLOGY

Step 1: Feeling the disequilibrium, recognizing that there is a problem even if it is not clearly expressed

A Lack of Consensus

At first glance, this would seem to be a structured and "hard" (i.e. readily approachable with standard algorithms) question. Yet a review of the literature reveals a stark contrast in conclusions (Figure 1). This subset of papers is intended to illustrate the distinct approaches and divergent conclusions of current studies. Studies were not selected randomly and the exercise is far from exhaustive -there are literally hundreds of studies. Therefore the totals (11 yes and no, 7 can't tell) are not meaningful as an indication of the scientific community's vote on the issue. One immediate conclusion is that a consensus has not been reached, a concern that is often mentioned in the literature (Kirschbaum 2006), but with equally conflicting views on how to address it.

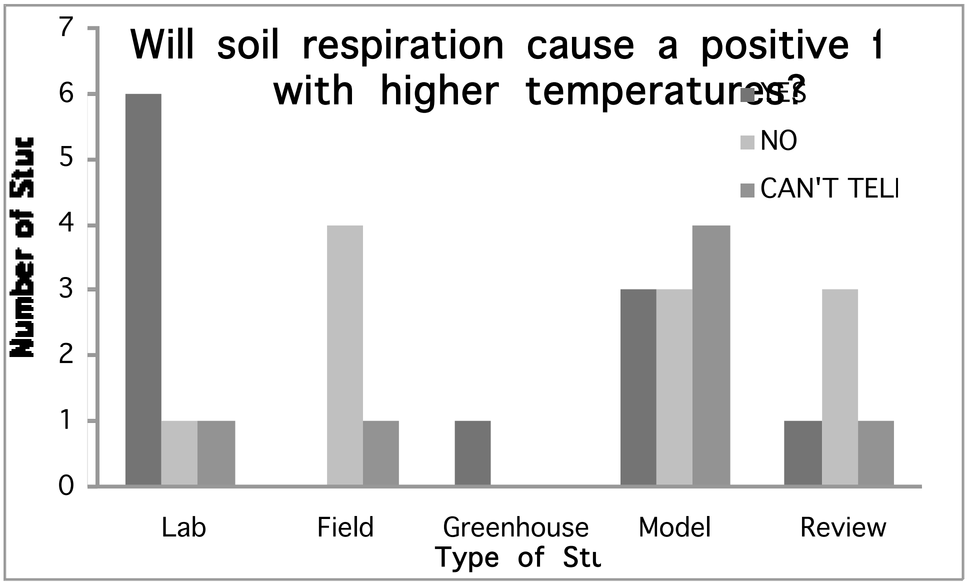


Figure 1. An illustration of the lack of consensus regarding soil respiration and temperature response. n=29. Paper selection was not random and is not exhaustive; the totals by conclusion therefore are not meaningful. A "model" paper is one in which various or no explicit datasets are used; most experimental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

Further, some tantalizing and theoretically reasonable patterns emerge that bear further thought: Laboratory studies, isolating certain factors, seem in this subset to show a strong temperature response. Field studies, with their arrays of interacting factors, often seem to show the reverse, either a minor temperature response or one that quickly re-equilibrates at a low level. A final pattern that I explored is the relationship between experimental duration and the conclusion (data not shown). As expected, shorter term studies do tend to show stronger temperature sensitivities, but longer term studies conflict on the timeframe and extent of re-equilibration.

Which is desirable depends on who you ask and their goals, and in particular how the system is bounded. If the interest is the reductionist, unconfounded response curves to these factors as they independently operate, laboratory studies provide the best, and least biased, basis for estimating the temperature response (Kirschbaum 2006). On the other hand, the limitation of such important factors as carbon inputs can mean that conclusions from incubation studies are limited (Hagedorn 2006). Even the question of what ranges of temperatures increases are informative in such studies is debated.

The Factors

One source of the mess is the inherent characteristics of the material system. It is generally recognized that a web of “entangled processes”(Davidson, Janssens 2006), including experimental procedures, are a major reason for the continued debate on the temperature response of decomposition (Allison et al. 2007; Conen et al. 2006; Hyvonen et al. 2005; Kirschbaum 2006; Knorr et al. 2005; Pendall et al. 2004b; Reichstein et al. 2005; Smith et al. 2003) The factors interact, are scale-dependent, and exhibit nonlinear dynamics (Manzoni, Porporato 2007). Predicting the impacts of global change, or designing reasonable mechanistic models, becomes quite problematic (Staddon et al. 2002).

Temperature and moisture are argued to be the first and second variable of importance for microbial communities. Other environmental variables that are projected to change, such as increased nitrogen and increased atmospheric CO_2, will doubtless have an interacting effect on temperature and soil moisture. Long-term, feedbacks and interactions may dominate decomposition rates. Responses to single factors, or even the two factors of temperature and soil water together, can be misleading (Gutknecht 2007; Hyvonen et al. 2007) . One example considers the interaction between atmospheric CO_2 and nitrogen addition. In a recent study considering CO_2 enrichment, nitrogen response, and microbial community, it was demonstrated that the CO_2 impact on a microbial community depended on its nitrogen status (Kao-Kniffin, Balser 2007). If nitrogen levels had not been included as a factor in the experiment, different conclusions would have been reached regarding elevated CO_2 impacts on the soil community.

However, the current state of modeling largely relies on combining single-factor responses as if they were independent (Rodrigo et al. 1997), in part because relationships are so unclear.What does it mean if fungi are associated with coarser soil fractions(Mummey, Stahl 2004), but may also be associated with increased carbon sequestration (Bailey et al. 2002), yet clay tends to increase sequestration (Muller, Hoper 2004)? Do we need a fungal:bacterial ratio factor, a texture factor, or a clay content factor, and how should these factors interact?

"To predict or model the impact of global climate change on ecosystem functioning and carbon flow in the soil, we must incorporate into future models _______". Essentially this sentence is found in numerous papers, and it is interesting to note the diversity, and genuine importance, of factors that fill in the blank (Table 1). Authors conclude that factors from mycorrhizal fungi to the export of forest products are lacking in current models.

Table 1. Factors noted as needing to be incorporated in decomposition temperature response modeling. The list is far from exhaustive and is intended to illustrate the diverse array of factors cited.

Need to Include	**Reference**
the ubiquitous mycorrhizal fungi	Staddon et al. 2002
clay content	Muller, Hoper 2004
soil salinity	Adviento-Borbe et al. 2006
seasonal confounding issues	Gu et al. 2004
thermal conductivities and diffusivities (e.g. organic v mineral soils)	Smith et al., 2003
consumers- protozoa and other predators	Panikov, 1999
elevated CO_2 effects (possibly plant root mediated)	Wolf et al. 2007
radiation effects	Kirschbaum 2000
runoff (eroded soil C that is transported)	Izaurralde et al. 2007
microbial community composition and physiological ecology	Balser, Firestone 2005
earthworm cast-mediated changes	McInerney, Bolger 2000
vegetation species traits	Chapin 2003
organic matter concentration	Dalias et al. 2001
forest products	Gower 2003

Useful models must compress information and navigate the balance between too large and too small a boundary on the system, or too complicated or simple a model. As with many systems issues, this array in Table 1 stems from the fact that "science is human," (Vickers 1968).The reason for the dizzying variety of important factors of course involves two very human issues: the perspective (which can involve a scientist's training, discipline, research interest, skill set) and the motivation behind the study.

Conceptualizing the web of interactions in a way that leads to informed bounding of the system would be a significant advance. The number and type of factors selected, as well as the type and duration of study chosen, clearly impact the results. This is to be expected, but it bears highlighting to the extent that this is an urgent, policy-related issue. Given the complexity of the system, assumptions made in bounding it must be done in an informed and explicit manner. The systems approach allows us to evaluate the data at a meta-level and establish the lack of structure in the problem, as well as providing a framework to handle the seeming contradictions.

Step 2: Generate actively as many points of view for the system as possible

In the first approach to this step, I introduce some terminology and make explicit standard property of complex systems, myriad nonequivalent and necessary points of view or boundaries of the system. In the second approach, I apply a classification system derived from a combination of hierarchy theory and structural equations modeling to formally generate and categorize the factors that are associated with the many points of view.

Elucidating Key Focal Views

Giampietro (2003) provides some terminology and notes that complex systems organized in a nested hierarchy will not have a correct picture of a given system: "Adoption of a single model (no matter how complicated) implies a bias in the consequent description of complex systems behavior." The choice of a space-time window has many terms; one is "focal view". An observer's focal view is defined by ignoring what is so small or slow (lower level) that its dynamics are not relevant to the mechanisms determining the behavior at the focal view. Put another way, to calculate amounts of cellulose degraded, the decomposer species doesn't matter. These are "nonequivalent" in that one view cannot be mapped or integrated into another.

It is helpful to consider the microbial community, typically only measured by the output of its functions, as a "holon" (a term coined by Koestler in the 60's). Holons perform functions that contribute to other emergent properties expressed at higher levels of analysis. Put another way, a holon is a whole made of smaller parts that at the same time forms a part of the larger whole ("holarchy"). In this case, the elements nested within the holon include microbial community structure, size and activity. I will present a simplified holarchy of factors using the fourth step of SSM.

We are dealing with a holon, thus different and nonequivalent views will exist by definition. We can consider the emergent property of atmospheric carbon dioxide or the smaller parts such as microbial ecology. Space-time domains for holon functions (e.g. nitrification, efflux of CO_2, bioremediation) differ from space-time domains for holon structure (e.g. microbial succession). The two are not necessarily clearly related; for example, microbial biomass may have little to do with rates of decomposition (Brookes et al. 2008; Kemmitt et al. 2008). This systems approach shows how this is not a contradiction.

Advances need to be shared effectively within a diverse community of interdisciplinary collaborators, the public, policy makers and then some. Some authors suggest that only one view is needed to understand response dynamics, while others recognize that multiple scales will be required. From a large-scale perspective it may seem unnecessarily complicated to look at the microbial community rather than its outputs:“The determination of the composition of microbial communities in soil is not necessary for a better quantification of nutrient transformations,” (Nannipieri et al. 2003) For some objectives, this is true. However, as previous sections have shown, “growing evidence suggests that a solely macro-scale focus may result in poor predictive capacity and generalization,“(Balser et al. 2006).

The dataset taken, patterns seen, and interpretations made are dependent on the point of view and scale of the observer. Essential perspectives on the temperature dependence question are diverse: microbial physiology, kinetics and substrate saturations, energy economics, physics, atmospheric science, statistics, and complexity theory. An authors’ approach determines their experimental design and interpretation of conclusions. Conflicting results may be reconciled with different factors considered (Knorr et al. 2005). Canadell et al. (2000) term this integration of models across scales “a multitechnique approach” between what they define as “top-down” (e.g. regional-scale CO_2 fluxes) compared to “bottom-up” (e.g. mechanistic, comparative and process studies) perspectives. They note that an iteration and reiteration of top-down and bottom-up approaches will be necessary to constrain measurements at various scales.

Key focal views for temperature response and their concerns of interest are: Organism-level physiology (microbial): Microbial stress responses, metabolism and energy efficiencies. Thermodynamics: Substrate diffusion, decomposer uptake and activation energies and rates of reactions. Community-level ecology (microbial): Population competition, succession and functional talents of a community. Ecosystem: Primary production capacities and actual evapotranspiration

These focal views impact not only which factors influencing microbial temperature response are considered important, but also the visualization of how those factors are interrelated. Virtually every paper on the subject includes a diagram, typically in box-and-arrow format, showing the relationships between factors. The factors only rarely repeat between these models of factor.

These models are not reducible; one cannot be collapsed into another by the application of simple functions. Terminology reflects this nonequivalence. Consider the distinct classifications of factors such as “dependent and independent” (Panikov 1999) or “direct and indirect” (Allison et al. 2007). They are not simply different words for the same thing, or the same words for different things. For example, soil texture is a modulator that is primary in Panikov’s model and indirect in Allison’s model. The soil pH is a modulator that is dependent in Panikov’s model and direct in Allison’s model. Allison’s model allows divalent cations (e.g. calcium) to be both direct and indirect, while Panikov’s available and deposited nutrients are both dependent.

At times these focal views will converge, which provides a robust opportunity for understanding. Looking for such overlaps is an important solution to the question; systems theory teaches us to search them out or try to create them if they do not exist (Giampietro 2003).For example, from a microbial physiology standpoint, fungi responses to water stress, both inherent and physiological, may result in stable CO_2 levels even with poor nitrogen-inputs (Schimel et al. 2007). Other authors reach a similar conclusion from a very different perspective, for example a modeling study that considered plant-microbial competition for nitrogen (Manzoni, Porporato 2007).

Classifying Many Points of View: Biotic, Abiotic and Experimental

I apply this step by creating a flattened, messy conceptualization of all the potential factors of interest, organized in several categories, primarily biotic, abiotic and experimental. I use the terminology of criteria, indicators and metrics to further differentiate between levels of factors. Although this list may seem excessive, such is the nature of complexity; every factor on this list has been mentioned in the literature.

Classification is inherently difficult, and key problems are discussed later. The intention of this representation is to generate discussion between focal views and explicitly illustrate them in a unified framework to prompt discussion and awareness, not to precisely categorize each item. My first subjective decision is to simplify by including each factor only once. I define several overarching categories, which all interrelate and can be briefly summarized as:

- Abiotic: Respiration affected by physical or chemical components of the system that the biota inhabits.
- Biotic: Respiration affected by biological processes.
- Experimental: Respiration affected by definitions, experimental protocols, or methods.
- Substrate: Following Panikov (1999), I am considering the substrate as a separate category dependent on and ultimately related to both biotic and abiotic factors. What is the quality and quantity of the organic compounds that microbes break down for consumption?
- Thermodynamic: Following Agren and Bosatta (1999), this perspective can be seen as the source of “master equations” that bridge abiotic and biotic considerations.
- Derivative: Factor derivatives such as ratios and factor variance can change scales and levels of information. For example, the variability in a soil moisture regime can condition responses to moisture changes (Mentzer et al. 2006). “Regime” is intended to describe the concept of the native historical magnitude (amplitude), timing (wavelength) of variation in a factor crossed with a time scale. This addresses the “flux”, “spatiotemporal variation”, “coefficient of variation”, or “heterogeneity” of a factor.

- Stray categories: There are some factors that do not find a satisfactory home in this framework, which itself is informative. Perhaps they are processes, and belong better to a hierarchy that splits criteria into processes and structures. Or perhaps they are mechanisms, which account for the effects of certain factors.

Classifying Many Points of View: Criteria, Indicators and Metrics

Within these categories, I have defined a further classification hierarchy as illustrated in Figure 2. Criteria involve the context of the desired information, and are more general. Indicators are specifications of the criteria, which may be associated with differing metrics.

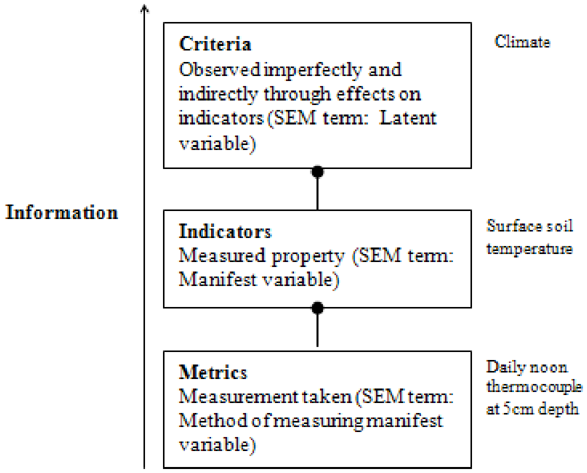


Figure 2. Relationship and definition of criteria, indicators and metrics. Terminology for similar concepts in structural equations modeling (SEM) is also included. Relationships between boxes in this simplified model boxes are one-to-many (subset).

The intention at this step is to have a largely complete list of criteria, but to merely represent the proliferation of possible indicators, and with them methods of measurement. Subjective decisions are involved in many ways. There is one category per criterion, not many, and the same holds when going from criteria to indicator or indicator to metric (a one-to-many relationship). My decision not to allow many-to-many relationships (“cogeneric” in SEM terms) offers great simplification but may also ignore interactions, where for example an indicator might apply to two criteria.

A First Conceptual Model of Factors Across Focal Views

Previous sections have discussed the many potentially confounding factors that contribute to divergent conclusions and how authors model these factors at specific scales. This section introduces a model of the universe of potentially contributing factors that are being discussed. Difficulties in the categorization and grouping of factors motivate the need for a more advanced model which will be introduced in step four, with the additional dimension of making scales and relationships between factors explicit.

What are the factors that would cause conflicting results for respiration temperature response studies? A temperature increase will change many other variables, creating a “complex web of ecological ambiguity” (Balser et al. 2006). I have demonstrated that 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. In this section I apply the method of step three and explicitly define the universe of factors being discussed. I further attempting to categorize them as biotic, abiotic or experimental (Figure 3). Within each category, I distinguish factors as criteria or indicators (Figure 2). In the cases of both classifications, multiple issues arise which expose underlying complications**.** This will be in some ways not successful, but lessons can be learned from where the simple categorization model fails.

Biotic factors such as native regime adaptation, dormancy and microbial community structure interact with abiotic factors such as depth and soil structure. These biological constraints involve organism- and population-levels of analysis. In contrast, at the largest ecosystem scales, issues of diffusion of energy, substrate, or gas tend to be more relevant (Allen, Hoekstra 1992).This is one reason why thermodynamic and physiological principals play such an important part in scaling up to regional and global carbon metabolism (Schimel et al. 2007). Both biological and physical factors must be considered, although perhaps acting in overlapping but not reducible models. Experimental factors include definitions, methodologies, scale and goals.

It is important to note several issues that immediately arise; this is precisely the point of considering the models as nonreducible. A factor may:

a. Belong to multiple categories. Consider human land use history. At the human scale, we are biological beings, and land use decisions are based on biological considerations, so this is a biotic constraint. From a microbial point of view, however, the land use is part of its environment, and therefore abiotic. This is an example of issues of focal view.

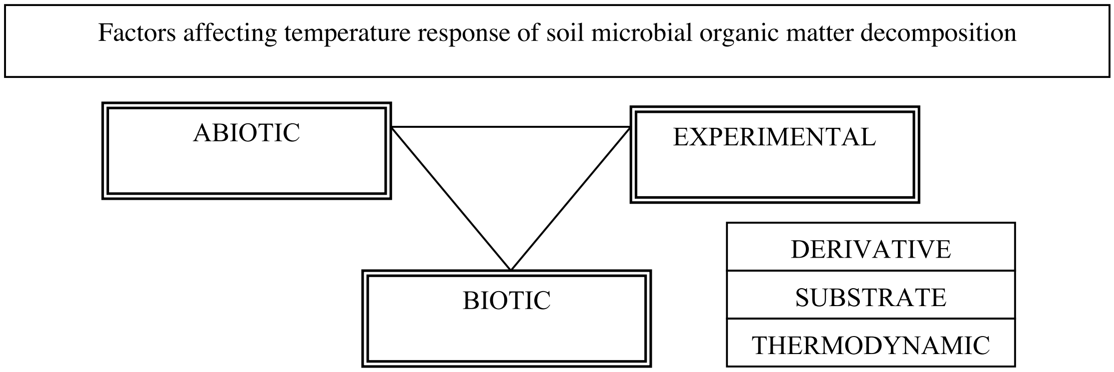
b. Belong as both a criterion and an indicator. Soil structure is classified as a criterion, but it could also be classified as an indicator. If our focus involves aggregate size classes, then soil structure is a criterion. It can also be considered an indicator for larger-scale, above-ground processes. Going up or down in scale can change an indicator to a criterion or vice-versa.

c. Have two terms, but be very similar. Consider litter chemistry (abiotic), substrate quality (substrate), and nutrient availability (abiotic). All are related to the energetic quality of what the microbes are consuming, but they refer to slightly different perspectives.

d. Be a subset or summary of other factors. Microbial community includes microbial diversity. addressing this is to create an explicit hierarchy allowing for some terms to be contained within others, which is done later in this paper.

e. Be a consequence of other factors. For example, “litter chemistry” can be seen as a function of plant community that should belong in the “Biotic” box. This is also addressed in the hierarchy presented later.

f. Be the final output of concern. Microbial community is seen as a factor, for example, when the output (dependent variable) of interest is respiration. Alternately, microbial community can be viewed as the output that is impacted by factors. Depth is a factor influencing microbial composition. This is the nature of a holon.



ABIOTIC

CRITERIA

- Climate
  - Hydrology
  - Temperature
  - Precipitation
  - Wind
- Disturbance
- Geographical location
- Geomorphology
- Human land use or management
- Nutrient quality & quantity
- Soil characteristics
  - Chemistry
  - Habitat characteristics
  - 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
- Latitude
- Nutrient deposition
- Slope/aspect
- Soil
  - % organic matter
  - Age
  - Cation- and 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
- 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
- Microbial 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
- Microbial community or ecosystem scale
- Moisture metric
- Other soil respiration components considered
- Recalcitrant C identification method
- Rhizosphere or bulk soil
- Root respiration included
- Soil storage and preincubation protocols
- Study duration
- Temperature measurement depth
- Temperatures below freezing

DERIVATIVE CRITERIA

- Availability
- History
- Hysteresis
- Ratios
- Regime
- Variability

SUBSTRATE CRITERIA

- Location 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

STRAYS

- Humic substance/sequestration changes
- Depth
- Potential biota
- Priming effects

Figure 3. A comprehensive conceptual model organizing factors driving microbial processes across focal views. Explanations of the terms used are formally coded in the next model iteration.

Step 3: Explicit development of abstractions

A first step is considering some meanings behind divergent terminology and system abstractions. The need to standardize definitions (or experimental methods, or other factors) is frequently mentioned. Given the diversity of focal views, however, it follows that "conscious efforts to standardize terminology are almost futile in science" (Canham et al. 2003) Root words with particularly divergent definitions in this context include "temperature", "decomposition", and "acclimation" (Wixon 2008). It is important to discuss definitions, precisely because of the nature of complexity, so that modelers, politicians and scientists can more easily learn from and appreciate different system boundaries. In this application I look at the diversity of the definition of "factors" and consider the term particular to the way that I will model the system.

The word "factor" that I have been using bears some further discussion. Associated terminology proliferates in this discussion: "factors"(Kirschbaum 2000), "constraints" (Davidson, Janssens 2006), "controls" (Ellert, Bettany 1992), "variables"(Allison et al. 2007) , "properties" (Smith et al. 2003), "parameters" (Manzoni, Porporato 2007), "components", "drivers" (Waldrop, Firestone 2006), or "sources of variability"(Agren, Wetterstedt 2007). Allison et al. (2007) discuss "physical mechanisms by which the soil environment influences the microbial community". My definition is related to my goal: to describe sources of variability or potential controls that interact with temperature responses and impact temperature sensitivity.

Table 2 illustrates some definitions of these terms associated with various author focal views. Taking concrete language from the literature and exposing its diversity is a key application of this step of SSM. There is a reason we are all talking about the similar concepts in different words, and compressing these nonequivalent views into a standardized terminology would move us backwards in considering the question of positive feedback because we are dealing with complexity.

Table 2. A selection of perspectives associated with factor model diagrams, and how the authors define the factors. The authors' perspective drives the definition, selection and conceptualization of the controlling factors.

Reference	Factor Model Perspective	Author's Definition of Factors
Panikov, 1999	Ecosystem	Environmental factors affecting soil communities
Luo et al. 2001	Ecosystem	Major feedbacks (mechanisms) in coupled climate-carbon cycle system
Davidson et al. 2006	Enzymatic	Constraints that, either directly or indirectly, decrease or increase substrate (or enzyme) concentrations at enzymatic reaction sites
Sylvia et al. 2005	Microbial	Conditions favoring rapid decomposition vary by substrate quality and microbial population
Schimel et al. 2007	Microbial	Environmental drivers of physiological responses
Chapin 2003	Ecosystem	Interactive controls whose effects influence processes
Allison et al., 2007	Microbial	Environmental variables influencing microbial community
Agren, Wetterstedt 2007	Thermodynamic	Interacting mechanisms of temperature response. Processes that effectively contribute to the rate of mineralization.

Step 4: Building conceptual models

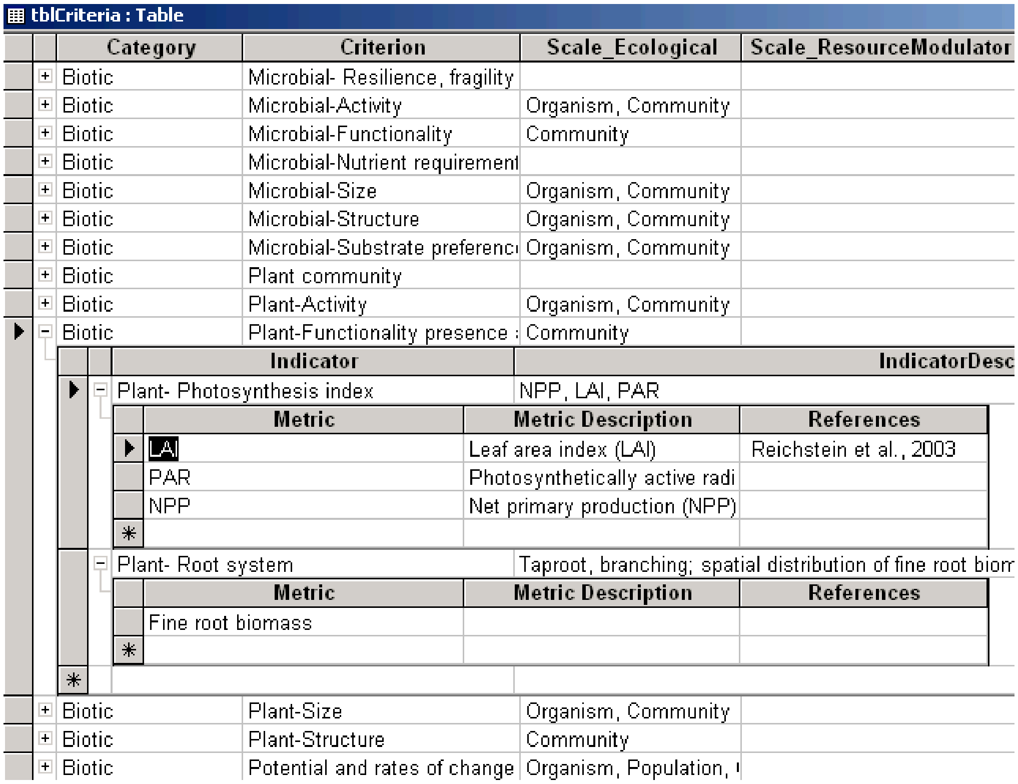
An immediate response is a desire for further synthesis: Can the many factors be integrated between focal views towards a unified hierarchy of systems? A useful model would capture feedbacks, interactions and nested relationships. Ideally it would be something in the format of systems interacting with systems that would situate a researcher's focal view within the larger context, and allow an immediate evaluation of those factors beyond the boundaries under consideration.

Model Specifics

In this section, I present a very simplified factor holarchy model. This model makes explicit criteria relationships and interactions, integrations, and potential scales of interest. The does not resolve all of the issues discussed regarding factor category assignment. It may not be possible to resolve some of these issues without specifying a focal view and objective. This conceptual, not causal, model is intended to help frame questions and address divergent results rather than to functionally quantify relationships. The initial coding of a hierarchy follows Figure 3 in its structure but is implemented more formally (Figure 4).

The next step is to address issues that arose in the creation of the hierarchy (Figures 3 and4) with a holarchy (Figure 5). A criterion can be an expandable node that compresses and integrates other factors, and is of interest for the value of its output to a higher-scale criterion (also known as a holon). The microbial process output of carbon dioxide is the integrated criteria of interest when considering atmospheric carbon content. Alternatively, the focal view can center on the criterion and thus those criteria it integrates come into the foreground. If we are examining the microbial community, we are interested in structure as well as function. Model coding further allows for relationships to be specified as positive or negative in the case that they are consistent (not shown).

The initial mapping of relationships between criteria considers only a pair of factors, and does not allow for 3-factor or higher interactions. A pair of criteria may interact with each-other in two ways. First, the each member of the pair is defined as primary or secondary. A secondary criterion, following the terminology of structural equations modeling (SEM), is dependent on the primary. For example, geographical location is primary and climate is secondary, since the climate depends at least partially on the geographic location. The relationship is then categorized as one-way or two-way. In a one-way relationship, such as geographical location and climate, climate exerts no influence on geographical location. In a two-way relationship, there is some feedback from the secondary to the primary factor. The feedback from the secondary factor is intuitively smaller scale compared to its dependence on the primary factor. For example, vegetation community (secondary) is a function of the larger-scale climate (primary). However, the relationship is two-way in that certain vegetation communities exert forces, such as evapotranspiration, that can influence climate on a minimally local scale.



Category	Criterion	Scale_Ecological	Scale_ResourceModulator
Biotic	Microbial- Resilience, fragility		
Biotic	Microbial-Activity	Organism, Community	
Biotic	Microbial-Functionality	Community	
Biotic	Microbial-Nutrient requirement		
Biotic	Microbial-Size	Organism, Community	
Biotic	Microbial-Structure	Organism, Community	
Biotic	Microbial-Substrate preferenc	Organism, Community	
Biotic	Plant community		
Biotic	Plant-Activity	Organism, Community	
Biotic	Plant-Functionality presence :	Community	

Indicator	IndicatorDesc
Plant- Photosynthesis index	NPP, LAI, PAR

Metric	Metric Description	References
LAI	Leaf area index (LAI)	Reichstein et al., 2003
PAR	Photosynthetically active radi	
NPP	Net primary production (NPP)	
*		

Indicator	IndicatorDesc
Plant- Root system	Taproot, branching; spatial distribution of fine root biom

Metric	Metric Description	References
Fine root biomass		
*		

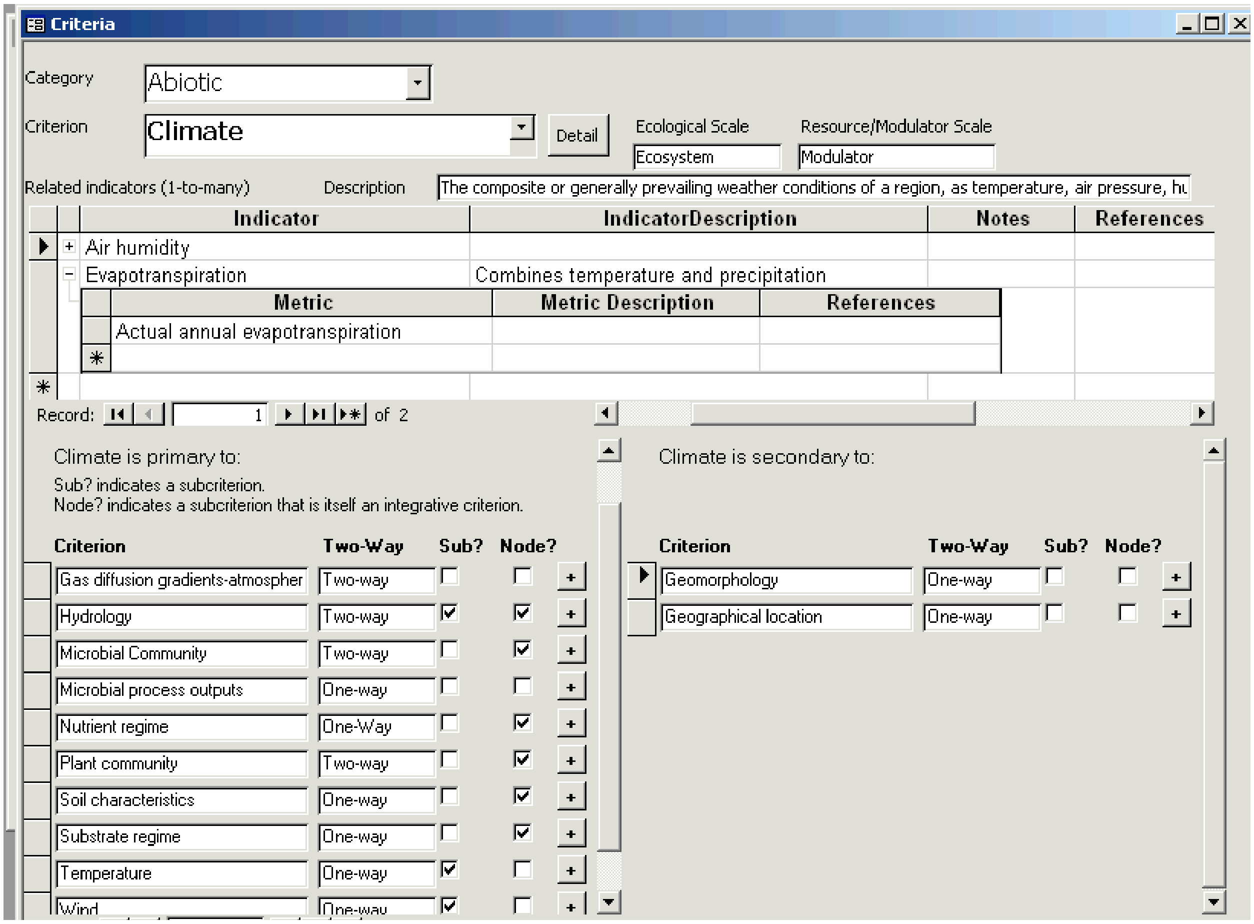
Category	Criterion	Scale_Ecological	Scale_ResourceModulator
Biotic	Plant-Size	Organism, Community	
Biotic	Plant-Structure	Community	
Biotic	Potential and rates of change	Organism, Population,	

Figure 4. Hierarchical model implemented as a database. Categories, criteria, indicators and metrics are organized, described, and associated with references.

There are different starting points in this model. A researcher might start with a metric (e.g. pH), which is proximal and directly feasible. Or a criterion can be selected (e.g. soil chemical characteristics), and interacting criteria considered. An understanding of the indicator and criterion associated with the metric, and their potential interactions, can help to explain the metric's values under different conditions. This would help to avoid the problem encountered by studies that bound the system without explicitly understanding their assumptions: Differences in criteria, indicators or metrics can act as factors influencing study results and their interpretation.

We must compress information in order to achieve anything useful; a focal view is required. It is helpful to not have to re-invent the potential list of factors and their interaction for each scale of interest. If we have a discussion of the systems-within-systems implementation of a holarchy, then each paper can compress this model into its own graphical representation of the system bounded as needed for a particularly focal view. The wheel does not need to be constantly reinvented; alternatively, if it does need to be reinvented it can be done in an optimally aware manner that addresses why.

An important shortcoming of the model, beyond the subjective issues outlined in step two, is its limitation to pairwise interactions. Clearly, multi-factor interactions are an important part of the material system, yet the formalized holarchy does not allow for them.



Category: Abiotic

Criterion: Climate

Ecological Scale: Ecosystem

Resource/Modulator Scale: Modulator

Related indicators (1-to-many)

Description: The composite or generally prevailing weather conditions of a region, as temperature, air pressure, hu

	Indicator	IndicatorDescription	Notes	References
+	Air humidity			
−	Evapotranspiration	Combines temperature and precipitation		

Metric	Metric Description	References
Actual annual evapotranspiration		

Climate is primary to:

Sub? indicates a subcriterion.
Node? indicates a subcriterion that is itself an integrative criterion.

Criterion	Two-Way	Sub?	Node?
Gas diffusion gradients-atmospher	Two-way	☐	☐
Hydrology	Two-way	☑	☑
Microbial Community	Two-way	☐	☑
Microbial process outputs	One-way	☐	☐
Nutrient regime	One-Way	☐	☑
Plant community	Two-way	☐	☑
Soil characteristics	One-way	☐	☑
Substrate regime	One-way	☐	☑
Temperature	One-way	☑	☐
Wind	One-way	☑	☐

Climate is secondary to:

Criterion	Two-Way	Sub?	Node?
Geomorphology	One-way	☐	☐
Geographical location	One-way	☐	☐

Figure 5. The interface showing a factor hierarchy, scales and interactions. Holarchy and interactive feedbacks are modeled through the nested (subcriterion), or integrative (node), relationships possible between criteria. A secondary criterion is dependent on a primary criterion. A two-way relationship involves feedback at some scale from the secondary to the primary factor. The interface includes buttons which provide detail on a selected interacting criterion.

One sample potential graphical output from this model with user-selected factors in shown in Figure 6. We must compress information in order to achieve anything useful; a focal view is required. It is helpful to not have to re-invent the potential list of factors and their interaction for each scale of interest. If we have a discussion of the systems-within-systems implementation of a holarchy, then each paper can compress this model into its own graphical representation of the system bounded as needed for a particularly focal view. The wheel does not need to be constantly reinvented; alternatively, if it does need to be reinvented it can be done in an optimally aware manner that addresses why. One sample potential graphical output from this model with user-selected factors in shown in Figure 6.

Hierarchy theory teaches that when choosing a scale of interest, the levels directly above and below are important to consider (Allen and Hoekstra, 1992). This factor model allows for a resetting of the focal view ("zooming") across scales into factors of interest. Given a factor, one can immediately assess available indicators, metrics and other factor interactions of potential impact or interest.

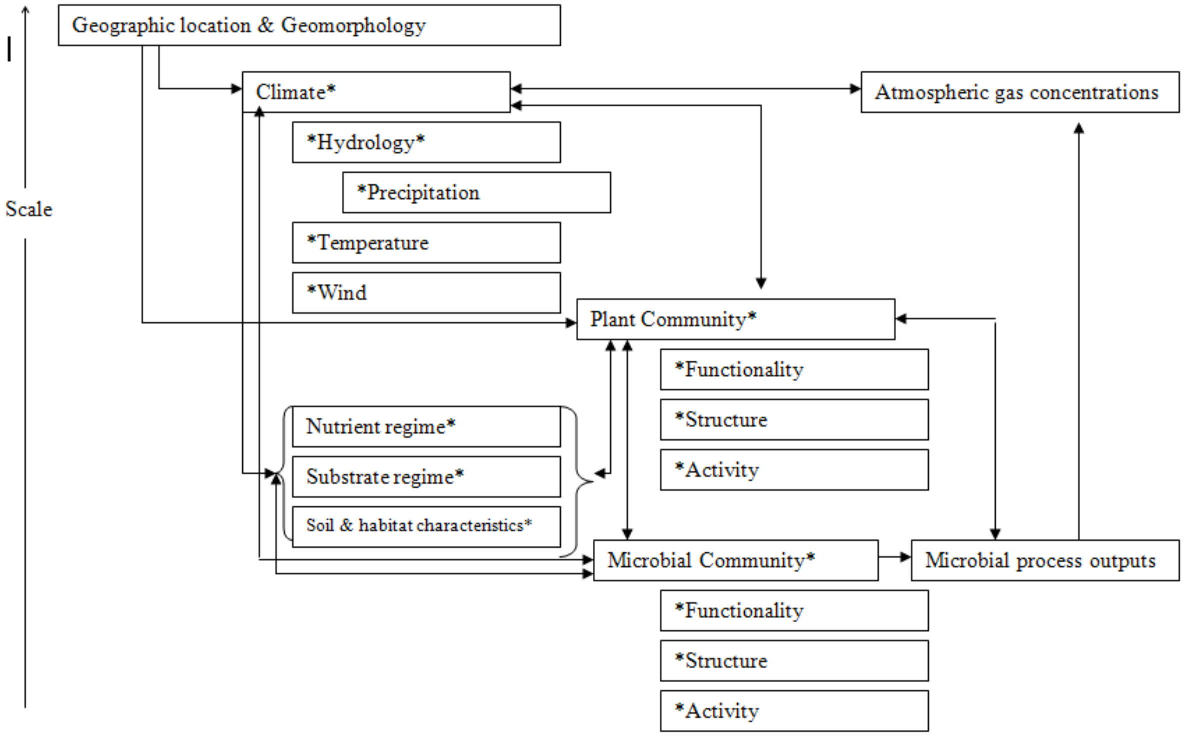


Figure 6. Graphical representation of selected factors as coded in holarchy model. Two-way arrows represent two-way relationships including feedback from the secondary to the primary factor. Name* indicates an integrative criterion that wraps other criteria, while *Name indicates a subcriterion of an integrative criterion.

SUMMARY AND CONCLUSIONS

A huge number of studies and substantial funding have not produced a satisfactorily certain answer, or even an approach, to the question: Will soil microbial activity have a positive feedback interaction with global climate changes, to what extent, where, and over what timescales? Selecting the salient factors that contribute to a quantitative model, or in other words, bounding the system appropriately, will be both incredibly important and uniquely challenging. This paper has examined the question: Why can't we answer the question?

The current state of debate is an understandable consequence of complex issues, which is the subject of systems theory. Prediction, often seen as the holy grail of decomposition modeling, must involve explicit communication of the shortcomings and limitations of models (Pace 2003).Consequences of not considering the holistic systems picture and making informed and conscious decisions regarding system bounding include different conclusions from the same data, conflicting results, and uninformative experimental design. The literature does cite these problems in more traditional terminology, but an explicit delination of possible bounds from a higher level has not been considered. Soft Systems Methodology (SSM) provides a framework in which this can be explicitly and concretely applied to the question of microbial temperature response.

The first step provides a framework to establish with data that the varied perspectives on the system's dynamics and its web of controlling factors have led to seemingly conflicting results (Figure 1). Different factors will be of interest to different researchers (Table 1), yet all may be important to modeling depending on the modeling objectives. Step two first contributes the insight that the factor models and their associated terminology are not equivalent and cannot be simply integrated. Complexity theory teaches us that we need to allow for nonequivalent views to be informative "in stereo" (Giampietro 2003) and particularly in areas of overlap. The different focal views are made explicit and illustrated, with an associated need for synthesis across them. An explanation of the microbial community's change in respiration rate with temperature as a holon provides terminology for the bounding of systems within the larger system.

All of these views are needed, yet any given model must select a particular, compressed view to be useful. I apply a classification system derived from a combination of hierarchy theory and structural equations modeling (Figure 2) to formally generate and categorize the factors that are associated with the many points of view (Figure 3). This figure is important in that it explicitly shows potential factors that are defined outside of the system boundaries when a focal view is selected: what are the factors that are universally agreed to be problematic?

In step three, I provide a sampling of diverse definitions on the nature of the factors themselves (Table 2). These derive from the non-equivalent focal views outlined in step two. In particular, I note that the various definitions are not equivalent and lead directly to the creation of almost unique diagrams of factors models in virtually every paper on the subject.

One product of this enhanced understanding is detailed in step four, a relational database that formalizes a hierarchy between factors in a simplified model. I categorize these factors as criteria, indicators and metrics and situate them in the biotic, abiotic or experimental domains (Figure 4). I additionally incorporate interactions and feedbacks as well as nested subset relations into the model, forming a holarchy. The user interface designed to access this data is shown in Figure 5. Given a factor, one can immediately assess available indicators, metrics and other factor interactions of potential impact or interest. Figure models can be created by selecting factors of interest, and one graphical example is shown (Figure 6). I finally conclude that although this model is limited to pairwise interactions, it provides a useful tool to assess potential interactions and factors of interest, as well as those outside the scope of interest. Additionally, it is a formal tool to allow discussion about what the relationships between factors are, which are important, and why boxes and arrows depicting factors models should have particular categories, relationships, and magnitudes.

Some propose standardization; a systems perspective instead reveals the need for multiple models sourced from an accepted universe of systems-within-systems. Systems theory teaches the importance of understanding and awareness of what is compressed when determining system boundaries. The system needing to be described is complex, and SSM as applied here provides a meta-level understanding as well as the construction of an integrative model.

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