Time-variant kinetics: a Framework for Microbial Impacts on Soil Organic Carbon Decomposition

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Abstract

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Keywords: keyword1, keyword2, keyword3, keyword4, keyword5

Graphical Abstract

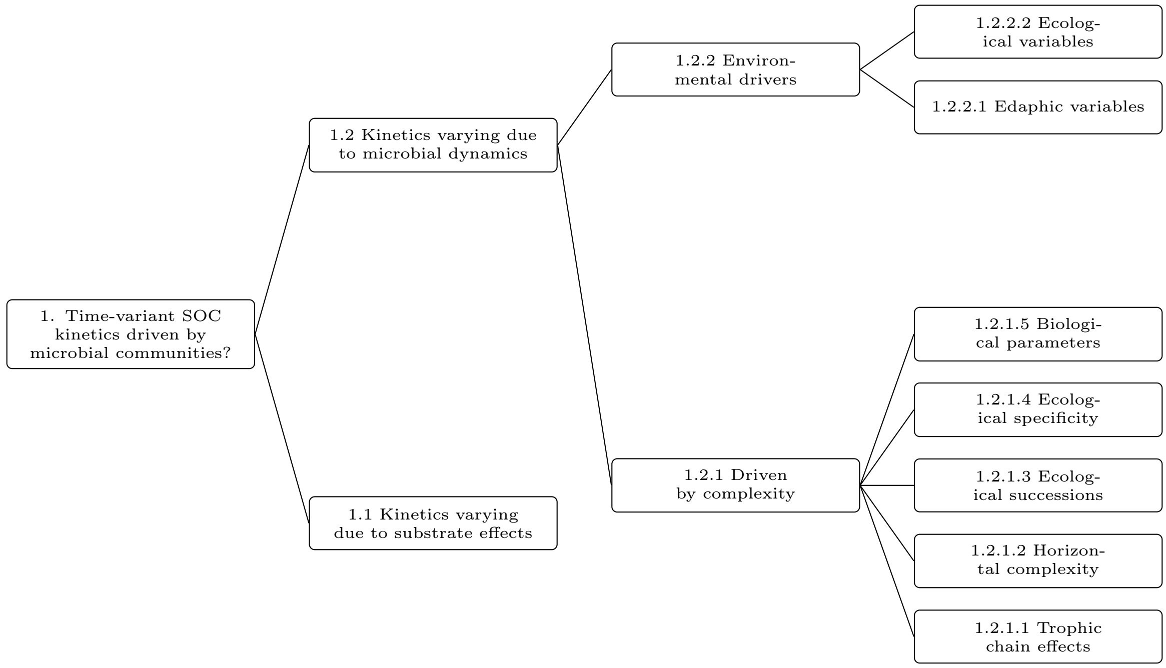

Figure 1: Hierarchical framework for variable kinetics in soil organic carbon models. The framework distinguishes between substrate-driven (1.1) and microbial-driven (1.2) mechanisms, with microbial dynamics further categorized by complexity factors and environmental drivers.

Contents

1. Introduction

1.1. The SOC Modeling Challenge

Current state of SOC models in production use, limitations of 2-3 decade old constant kinetics assumptions, and why variable kinetics matter for climate projections.

1.2. From First-Order to Higher-Order Kinetics

Historical development of SOC kinetic models, chemical vs. biological controls on decomposition, and the role of microbial communities in kinetic complexity.

1.3. Scope and Objectives

Framework for organizing variable kinetics mechanisms, integration of spatial and temporal variability, research gaps and future directions.

2. Theoretical Background: Kinetic Models in Soil Carbon Cycling

2.1. Classical First-Order Kinetics

Mathematical foundations, assumptions and limitations, and why they persist in production models.

2.2. Higher-Order Kinetic Models

Michaelis-Menten and enzyme kinetics, regulatory mechanisms and feedback loops, examples from Schimel & Weintraub (2003) and predecessors.

2.3. Spatial and Temporal Heterogeneity

Scale-dependent processes and linking molecular to ecosystem scales.

3. Substrate-Driven Variable Kinetics

3.1. Priming Effects and SOC Quality

Classical priming hypotheses, spatial variations in substrate availability, and connections between quality and kinetic parameters.

3.2. Substrate Heterogeneity Across Landscapes

Chemical composition gradients, physical protection mechanisms, and implications for model parameterization.

4. Microbial-Driven Variable Kinetics: The Complexity Framework

4.1. Complexity-Driven Dynamics

4.1.1 Vertical Complexity: Trophic Chain Effects

Predator-prey dynamics in soil food webs, mesofauna and microfauna influences, isotopic fractionation as complexity indicators, and case studies of accelerated C cycling in complex systems.

4.1.2 Horizontal Complexity: Synergistic Associations

Enzyme complementarity and synergies, diversity-function relationships, applications to degraded soils, and synthetic community experiments.

4.1.3 Temporal Dynamics: Ecological Successions

Mycorrhizal succession patterns, forest stand development and C cycling, sink/source transitions over decades, and case study of Cortinarius succession.

4.1.4 Spatial Specificity: Local Adaptation

Field Advantage hypothesis, home-field advantage effects, and geographic and climatic controls.

4.1.5 Intrinsic Microbial Biological Parameters

Carbon use efficiency (CUE) variability, physiological constraints, and trade-offs and optimization.

4.2. Environmental Drivers

4.2.1 Edaphic Controls

Soil physical and chemical properties, persistent landscape effects, and spatial modeling implications.

4.2.2 Above-Belowground Linkages

Plant-soil feedbacks, seasonal and phenological controls, cross-ecosystem comparisons.

5. The abiotic gate hypothesis and its possible linkages

6. Synthesis and Integration

6.1. Unified Framework for Variable Kinetics

Hierarchical organization of mechanisms, interactions between substrate and microbial drivers, and scale-dependent relative importance. This could be a D.A.G formulation of the plot in the graphical abstract with maybe a bit more detail

6.2. Implications for Model Development

Testing toy models here

6.2.1 Hyp 1 model implications

6.2.2 Hyp ... model implications

6.3. Knowledge gap: bridging scales in modeling

Problems of upscaling, including uncertainty issues

7. Current Research Frontiers and Future Directions

7.1. Methodological Advances

Multi-omics approaches, isotopic techniques and fractionation studies, and long-term experimental platforms.

7.2. Emerging Concepts

Network ecology in soil systems, machine learning applications, and climate change adaptation mechanisms.

7.3. Research Priorities

Critical knowledge gaps, experimental design considerations, and model-data integration needs.

8. Conclusions

8.1. Key Insights

Summary of variable kinetics mechanisms, relative importance under different conditions, and implications for current model limitations.

8.2. Toward Next-Generation SOC Models

Essential features for new model frameworks, implementation pathways, and expected improvements in predictive capacity.

Acknowledgments

Not sure here but we will probably have to acknowledge quite some people and institutions

Funding

We should have a few, I guess.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

Not sure we will need it.

9. References

We need to use bibtex here!