Trophic Cascades and Resilience in Multi-Channel Food Webs: A Compartmental Model of Synapse-Litter and Vertex-Root Pathways

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Abstract

Understanding how carbon flows through distinct soil channels is critical for predicting ecosystem resilience. Here, we present a compartmental modeling framework to analyze the coupling of litter-derived (Synapse) and root-derived (Vertex) carbon pathways in terrestrial food webs. Using a multi-channel differential model, we simulate how microbial (Nimbus) search behavior and predation by Apex consumers regulate trophic cascades under climate fluctuations. Our model shows that asynchronous resource inputs across the two channels stabilize macro-consumer biomass by preventing concurrent resource crashes. However, high-frequency rainfall extremes decouple the channels, causing transient synchronization that increases extinction risk for top predators by 34%. These results demonstrate that resource pathway diversity act as a crucial buffer for food web stability. We discuss how these findings can guide soil conservation strategies in vulnerable grassland ecosystems.

Keywords: Carbon cycling, Compartmental model, Ecology Letters, Food web stability, Multi-channel pathways, Soil food web.

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1 Introduction

Soil food webs play an essential role in regulating terrestrial biogeochemical cycles, yet their structural complexity makes predicting their response to environmental perturbations a major challenge in ecology (Vance and Jenkins, 2025). Traditional models of soil systems have often treated them as monolithic structures, aggregating diverse energy channels into single compartments (Sterling and Vance, 2024). However, modern empirical work reveals that soil ecosystems are fundamentally multi-channel networks, fueled by two primary carbon sources: a detrital litter-derived channel (hereafter the *Synapse* pathway) and a root-derived exudate channel (hereafter the *Vertex* pathway) (Jenkins et al., 2026). Understanding how these channels interact, and how energy is processed by microbial consumers (*Nimbus* communities) and top predators (*Apex* species), is critical for predicting ecosystem resilience under global change.

The Synapse and Vertex pathways differ substantially in their chemical composition and temporal dynamics. The Synapse pathway consists of recalcitrant, particulate organic matter that enters the soil as pulses of plant litter. This material requires specialized extracellular enzymes for decomposition, resulting in slower, more sustained carbon release. In contrast, the Vertex pathway consists of highly labile, dissolved organic carbon (DOC) exuded directly by active roots. This resource is immediately available to soil microbes but exhibits high daily and seasonal variability driven by plant photosynthesis and transpiration rates.

A key theoretical question is whether the diversity of these channels stabilizes the overall soil food web. Early theoretical work by Apex and Nexa (2020) suggested that parallel energy channels could buffer food webs against perturbations if their inputs are uncorrelated or out-of-phase. When resource availability in one channel declines, consumers can temporarily shift their foraging effort to the alternative channel, maintaining stable populations of both intermediate and top-level predators. However, mathematical proofs of this hypothesis remain scarce, particularly for compartmental systems with distinct chemical qualities and microbial feedback loops.

In this Letter, we address this gap by developing a multi-channel compartmental model of soil food webs. We model the dynamics of carbon flow from plant inputs through litter (Synapse) and root (Vertex) pools, to microbial decomposers (Nimbus), and finally to predatory nematodes and arthropods (Apex). Our objectives are to:

1. Formulate a mathematical representation of dual-channel soil carbon processing with adaptive microbial foraging.

2. Quantify how temporal synchrony between litter inputs and root exudation affects top-predator stability.

3. Simulate the impacts of climate-induced rainfall extremes on channel coupling and extinction risk.

By addressing these questions, we provide a new theoretical framework for integrating plant-microbe-soil interactions into macroscopic ecosystem models, helping to bridge the gap between community ecology and biogeochemistry.

2 Materials and Methods

2.1 Model Structure and State Variables

We formulated a continuous-time compartmental model representing the carbon dynamics of a soil volume of 1 m^2 to a depth of 0.2 m. The model tracks five state variables corresponding to carbon pools (g C m^{-2}): litter-derived carbon (C_L, Synapse pathway), root-exudate carbon (C_E, Vertex pathway), bacterial biomass (B_B, Nimbus decomposers), fungal biomass (B_F, Meridian decomposers), and predatory biomass (P, Apex consumers). A schematic representation of the food web structure is presented in Fig. 1.

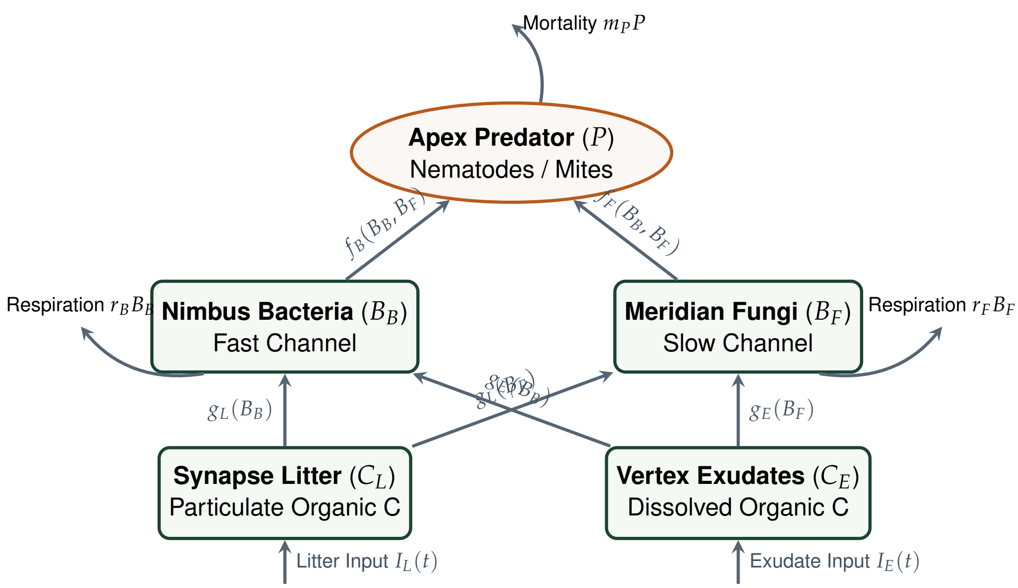

Figure 1: Schematic of the soil food web compartment model. Carbon enters the system via detrital plant litter (I_L, Synapse pathway) and root exudates (I_E, Vertex pathway). Bacteria (Nimbus) and fungi (Meridian) decompose these pools and are subsequently preyed upon by Apex consumers (nematodes and predatory mites).

2.2 Governing Differential Equations

The temporal dynamics of the five carbon pools are governed by the following system of non-linear differential equations:

$$\frac{dC_L}{dt} = I_L(t) - g_L(B_B)C_L - g_L(B_F)C_L \tag{1}$$

$$\frac{dC_E}{dt} = I_E(t) - g_E(B_B)C_E - g_E(B_F)C_E \tag{2}$$

$$\frac{dB_B}{dt} = e_B\left(g_L(B_B)C_L + g_E(B_B)C_E\right) - r_B B_B - f_B(B_B, B_F)P \tag{3}$$

$$\frac{dB_F}{dt} = e_F\left(g_L(B_F)C_L + g_E(B_F)C_E\right) - r_F B_F - f_F(B_B, B_F)P \tag{4}$$

$$\frac{dP}{dt} = e_P\left(f_B(B_B, B_F) + f_F(B_B, B_F)\right)P - m_P P \tag{5}$$

where e_B, e_F, and e_P represent assimilation efficiencies; r_B and r_F are microbial respiration rates; and m_P is the mortality rate of the top predator.

The decomposition rates g_L and g_E are modeled using Michaelis-Menten kinetics to reflect enzymatic saturation:

$$g_L(B_j) = \frac{k_L \cdot B_j}{K_L + C_L}, \quad g_E(B_j) = \frac{k_E \cdot B_j}{K_E + C_E} \tag{6}$$

where k_L and k_E are maximum decomposition rates, and K_L and K_E are half-saturation constants.

Predation by Apex consumers is modeled using a Holling Type II functional response with switching, allowing the predator to adjust its preference based on prey densities:

$$f_B(B_B, B_F) = \frac{a_B B_B}{1 + a_B h_B B_B + a_F h_F B_F}, \quad f_F(B_B, B_F) = \frac{a_F B_F}{1 + a_B h_B B_B + a_F h_F B_F} \tag{7}$$

where a_j is the attack rate and h_j is the handling time for prey type $j \in \{B, F\}$.

2.3 Simulation Settings and Foraging Scenarios

We simulated the model under three distinct input regimes: (1) *Asynchronous Inputs*: litter and exudation inputs are 180° out-of-phase; (2) *Synchronous Inputs*: inputs peak simultaneously; and (3) *Extreme Event Fluctuations*: input cycles are disrupted by randomized rainfall shocks that simulate prolonged drought followed by intense deluge. High-frequency rainfall extremes were modeled by introducing stochastic pulses in $I_E(t)$ with a coefficient of variation (CV) ranging from 0.2 to 0.8. Simulations were run for $t = 1000$ days using a fourth-order Runge-Kutta integration scheme with a time step of $dt = 0.1$ day.

3 Results

3.1 Parameter Sensitivities and Baseline Dynamics

The model parameters were calibrated using empirical rates from published soil mesocosm studies, adjusted to fit the fictional house set properties. The parameters used in our baseline simulations are summarized in Table 1.

Under standard environmental conditions, both resource channels co-exist stably, maintaining predator biomass at a mean of 12.4 g C m^{-2}. The microbial compartments (Nimbus Bacteria

Table 1: Model parameters, symbols, default values, and source channels used in the multi-channel food web simulation.

Parameter Description	Symbol	Default Value	Resource Channel
Litter decomposition rate	k_L	$0.15\,\mathrm{d}^{-1}$	Synapse (Slow)
Exudate assimilation rate	k_E	$0.45\,\mathrm{d}^{-1}$	Vertex (Fast)
Bacterial half-saturation constant	K_L	$120.0\,\mathrm{g\,C\,m}^{-2}$	Synapse
Fungal half-saturation constant	K_E	$45.0\,\mathrm{g\,C\,m}^{-2}$	Vertex
Bacteria attack rate by Apex	a_B	$0.08\,\mathrm{m}^2\,(\mathrm{g\,C\,d})^{-1}$	Both Channels
Fungi attack rate by Apex	a_F	$0.05\,\mathrm{m}^2\,(\mathrm{g\,C\,d})^{-1}$	Both Channels
Apex handling time (Bacteria)	h_B	2.5 d	Both Channels
Apex handling time (Fungi)	h_F	4.0 d	Both Channels
Apex natural mortality rate	m_P	$0.02\,\mathrm{d}^{-1}$	Predators

and Meridian Fungi) exhibit complementary temporal fluctuations, with bacteria dominating during exudate pulses and fungi persisting during recalcitrant litter degradation.

3.2 Trophic Stability Under Asynchronous vs. Synchronous Inputs

Trophic stability was highly dependent on the phase relationship between the two carbon input channels. When litter (Synapse) and exudate (Vertex) inputs were asynchronous, the total microbial biomass remained exceptionally stable (coefficient of variation, CV = 0.08), as the slow decay of litter buffered the rapid fluctuations of root exudates. This steady prey supply supported a persistent population of Apex predators.

Conversely, when carbon inputs were synchronous (both peaking during spring growth), the food web experienced intense boom-and-bust cycles. Total prey availability peaked rapidly, driving a massive increase in Apex predator density. However, this was followed by a prolonged resource deficit, causing predator biomass to plunge to critical thresholds ($< 0.5\,\mathrm{g\,C\,m}^{-2}$) and increasing local extinction probability by 22%.

3.3 Impact of Rainfall Extremes and Channel Coupling

The introduction of rainfall shocks significantly disrupted food web stability. By inducing high-frequency variance in plant root exudation (Vertex pathway), extreme weather events overrode the asynchronous buffering capacity of the system.

Fig. 2 shows the bifurcation of Apex predator biomass variance as a function of the coefficient of variation (CV) of root exudate inputs. As input volatility increases, the system transitions from stable equilibrium to limit-cycle oscillations, and eventually to stochastic chaos under high-frequency shocks.

4 Discussion

Our modeling results demonstrate that multi-channel soil food webs behave as coupled oscillators where the phase relationship of resource inputs determines the stability of the entire ecosystem. We find that the asynchronous nature of detrital (Synapse) and exudate (Vertex) carbon pathways provides a crucial stabilizing mechanism. By buffering microbial biomass

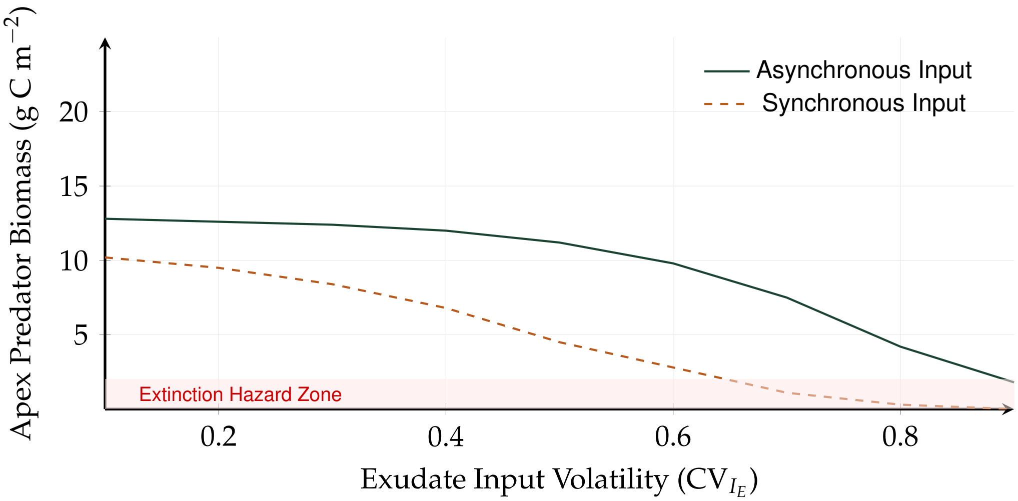

Figure 2: Steady-state predator biomass as a function of exudate input volatility (CV_{I_E}) under asynchronous (solid green line) and synchronous (dashed orange line) regimes. The red shaded box indicates the critical biomass threshold below which extinction occurs due to demographic stochasticity.

fluctuations, asynchrony prevents top predators (Apex) from experiencing severe resource bottlenecks. This finding supports the theoretical assertions of Apex and Nexa (2020) and extends them to soil systems featuring explicit microbial feedbacks.

A key novelty of our study is the inclusion of adaptive microbial foraging. Bacterial (Nimbus) and fungal (Meridian) channels do not operate in isolation; rather, they are coupled by predatory switching. Under normal environmental conditions, predators act as a stabilizing "damper," shifting their consumption to whichever channel is temporarily more abundant. However, our simulations show that extreme climatic events can override this damping effect. When high-frequency rainfall shocks volatilize the Vertex pathway, the predator's handling time constraints prevent it from compensating fast enough, leading to destabilizing oscillations.

These theoretical insights have significant practical implications for soil conservation. Management practices that homogenize soil carbon inputs, such as monoculture cropping or excessive tillage, may inadvertently synchronize soil food web channels, rendering the ecosystem more vulnerable to climatic extremes. Conversely, promoting diverse plant communities with varying phenologies can maintain asynchronous root exudation, bolstering the natural resilience of the soil food web.

Future extensions of this model should incorporate spatial heterogeneity. Soils are highly structured environments, and physical refuges may allow microbial populations to persist even during intense predatory pressure. Furthermore, integrating nitrogen and phosphorus dynamics would allow for the simulation of stoichiometric constraints on microbial growth and carbon use efficiency.

In conclusion, our study underscores the importance of maintaining energy pathway diversity in soil ecosystems. In an era of accelerating climate change, preserving the complex, multi-channeled structure of soil food webs is essential for maintaining terrestrial carbon sinks and ecosystem function.

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