A Viability-Theoretic Framework for Supply Chain Resilience under Heterogeneous External Stressors: An Application to the Arabica Coffee Supply Chain

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Short summary

Supply chains exposed to long-run climate stress face a governance problem that conventional resilience frameworks are not well-suited to address. This paper proposes a viability-theoretic framework for supply chains under heterogeneous external stressors, illustrated through the arabica coffee supply chain. The framework combines system dynamics with viability theory to specify a four-layer state space, physical, economic, social, and compliance, a non-compensatory constraint set, and a bounded firm-level control set. Rather than computing the viability kernel numerically, the framework establishes the structural conditions under which such computation is defined and well-posed. The Arabica coffee supply chain is used to instantiate each component with domain-specific variables, feedback structures, and control instruments. The paper concludes that stressor heterogeneity, asymmetric erosion dynamics, and margin-constrained control capacity are structural properties that composite resilience indices cannot capture, and that the viability kernel represents a more analytically adequate governance target for supply chains under prolonged climate stress than a recovery trajectory or resilience index.
Keywords: coffee supply chain, climate stress, supply chain resilience, system dynamics, viability kernel, viability theory

1 Introduction

Supply chains operating under long-run climate stress present a governance problem that conventional resilience frameworks are not well-suited to address. The dominant approach in supply chain risk management treats disruption as a temporary event and recovery as a return to a pre-disruption equilibrium Christopher and Peck, 2004; Hohenstein et al., 2015; Ponomarov and Holcomb, 2009. This works when disruptions are short-lived, and the underlying structure of the system remains intact. It is less suitable when stressors differ in temporal scale, accumulate over time, and can irreversibly weaken the conditions that support supply chain functioning. Heterogeneous stressors, such as climate change, produce exactly this kind of pressure. It operates through long-term biophysical changes that reshape the productive base of origin-country suppliers, medium-term economic and regulatory pressures that narrow financial margins, and short-term operational shocks that strain buffering and logistics capacity. These stressors do not act separately. They interact across the physical, economic, social, and compliance dimensions of the supply chain through feedback mechanisms that deepen deterioration and make recovery more difficult. A governance framework suited to this context must therefore be dynamic, multi-constraint, and control-oriented.

Commodity supply chains sourced from climatically vulnerable origin regions are especially exposed to this form of compound stress. Their production base is biophysically sensitive, responding to long-term climatic changes in ways that are gradual, cumulative, and often irreversible within commercial planning horizons Lobell et al., 2011; Wheeler and von Braun, 2013. Their social conditions of production are slow-moving stocks that feed back into productive capacity through multiple transmission channels, creating reinforcing loops that can accelerate decline once triggered. Their governance structures are frequently certification-dependent, with focal firms sourcing through compliance programmes that impose simultaneous conditions across environmental, social, and traceability dimensions. These conditions erode rapidly under economic and welfare stress but recover only slowly even when investment resumes. Taken together, biophysical fragility,

social feedback, and certification dependency mean that climate stress produces a compounding, multi-layered form of deterioration that a recovery trajectory or a composite resilience index cannot adequately capture.

The analytical framework appropriate to this governance problem is viability theory. Developed by Aubin, 1991 and extended through numerical methods by Saint-Pierre, 1994, viability theory addresses a fundamental question in dynamical systems under constraints: given a system whose state evolves over time and a set of admissible states that must not be violated, what is the set of initial conditions from which control trajectories exist that keep the system within the constraint set indefinitely? The supply chain state $x(t)$ evolves according to:

$$\dot{x}(t) = f(x(t),\, u(t),\, e(t)), \quad x(0) = x_0 \tag{1}$$

where $u(t) \in U$ represents the firm-level controls, $e(t)$ the exogenous stressor trajectory, and f the causal structure of the system. The feasibility conditions is the minimum standards that must be satisfied simultaneously and continuously across all layers, with no compensatory aggregation that defines the constraint set K. The viability kernel $\mathrm{Viab}(K)$ is then the largest subset of K from which at least one control trajectory exists that keeps the system within K indefinitely, identifying both whether a state is governable and which controls it are sufficient to maintain it. Figure 1 presents a schematic representation of the viability-theoretic framework.

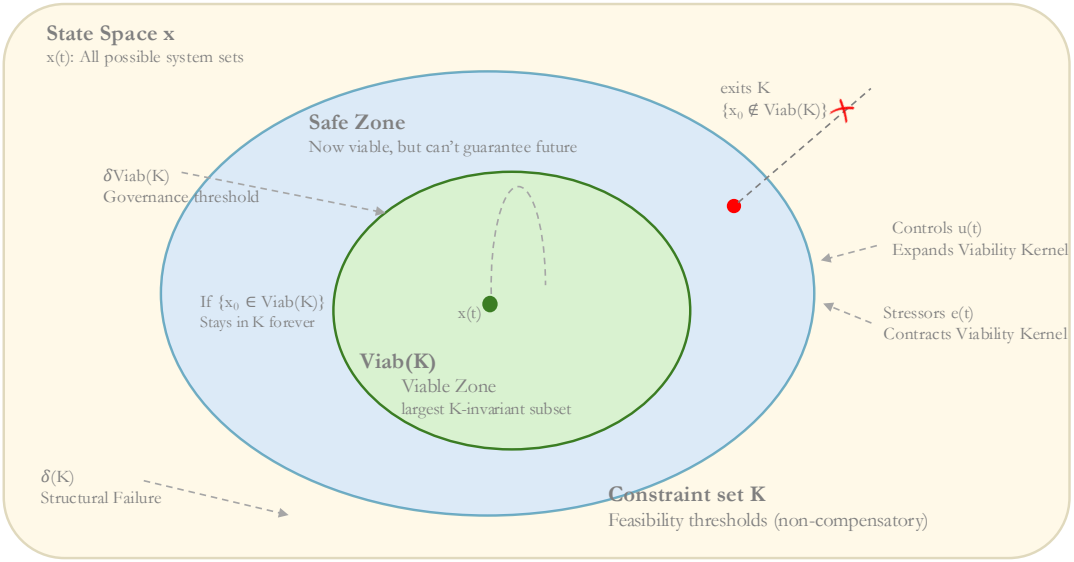


Figure 1: Schematic representation of viability-theoretic framework depicting the important elements

The term "viability" appears across two bodies of literature relevant to this paper — supply chain management and agricultural systems under climate change — but in neither case is it operationalised through the formal apparatus of viability theory Aubin, 1991. In the supply chain literature, viability has emerged as a higher-order adaptive survivability property extending conventional resilience thinking Ivanov, 2020; Ivanov and Tu, 2021, with precursors in Beer's Viable System Model Puche et al., 2016 and subsequent empirical extensions addressing network design, sustainability, and reconfiguration capability Lotfi et al., 2022; Ruel et al., 2021; Yin and Ran, 2022. Across this literature, viability is consistently framed as a structural, long-term property, but operationalised conceptually or statistically — no state space is defined, no constraint set is specified, and no viability kernel is computed.

In the agricultural systems literature, the operationalisation is methodologically more diverse but similarly removed from the formal framework. The most common treatment defines viability as a univariate threshold condition, whether biological, hydrological, or yield-based, without dynamics or a control set Ghrab et al., 2022; Rodríguez et al., 2021; Shahzad et al., 2021; Yaghoubi and Bannayan, 2026. A second group moves toward multi-criteria operationalisation Ferreira and Rodrigues, 2025; Sapkota et al., 2015 and financial feasibility Gay et al., 2006; Mestre-Sanchís and

Feijóo-Bello, 2009; Said and Temba, 2023 without formalising the constraint structure or trajectory. The most theoretically grounded application, Mobeen et al., 2023, explicitly invokes Aubin, 1991 and maps the viable framework onto the elements of a viability problem, but implements it through empirical structural modelling rather than viability kernel computation. Paprocki, 2022 raise the prior concern that the constraint set is itself a political and epistemic construction. Across both literatures, viability is invoked as a conceptual goal without formal computation of the viability kernel.

The present paper addresses this gap by operationalizing the formal framework **aubin1991** for the Arabica coffee supply chain under various long-term stressors, explicitly specifying the state space, constraint set, and control set using a system dynamics approach. The primary aim of this paper is to develop a conceptual viability-theoretic framework for supply chains under heterogeneous external stressors. Two research questions guide the paper: how can a supply chain facing heterogeneous external stressors be represented as a viability problem; and what governance insights emerge from viability kernel analysis under prolonged stress?

2 Methodology

The paper adopts a conceptual modelling approach combining system dynamics with viability theory. System dynamics Forrester, 1961; Sterman, 2000 provides the structural language for representing causal architecture, feedback loops, and delay structures, while viability theory Aubin, 1991 provides the analytical frame for defining feasibility constraints and governance targets. Rather than simulating forward trajectories or computing the viability kernel numerically, the framework establishes the structural conditions under which viability can be defined and draws out the implications for supply chain governance. The framework is developed in three stages corresponding to the three objectives. In the first stage, the six structural components are defined. In the second stage, the cross-layer feedback structure is articulated through a causal loop diagram, which serves not as a simulation instrument but as a formal representation of system structure. In the third stage, the framework is instantiated for the coffee supply chain, populating each component with domain-specific variables and causal relationships.

Framework Structure

The framework comprises six structural components that together define a viability problem in the sense of Aubin, 1991: a dynamical system evolving within a multi-dimensional feasibility boundary, subject to external forcing, and governed through bounded control inputs. Figure 2 presents the generic structure.

System dynamics (SD) represents the supply chain as a system of stocks, flows, and feedback loops, where system behaviour emerges from internal causal structure rather than from external perturbation alone Sterman, 2000. In this framework, system dynamics serves three functions: it formalises the causal pathways through which external stressors propagate across layers; it makes explicit the feedback loops, both reinforcing and balancing, that amplify or attenuate stress transmission; and it encodes the delay structures that determine the temporal profile of erosion and recovery dynamics.

Three structural features of the SD model are central to the viability-theoretic interpretation of the framework. First, *delays* between cause and effect mean the system may appear viable while already moving toward exit from K, making forward-looking governance more appropriate than continuous performance monitoring. Second, *nonlinearity* in causal relationships, including threshold effects, saturation dynamics, and stressor interactions, means that layer-level deterioration does not scale proportionally with stressor intensity, and K cannot be adequately represented as a linear or convex feasibility region. Third, *asymmetric dynamics*, in which erosion rates structurally exceed recovery rates, follow from the feedback structure. The reinforcing loops driving erosion activate rapidly under stress, whereas balancing loops supporting recovery require sustained investment over longer timescales. Taken together, these three features make the viability kernel a more appropriate governance target than a recovery trajectory or a static resilience index, even prior to any numerical computation.

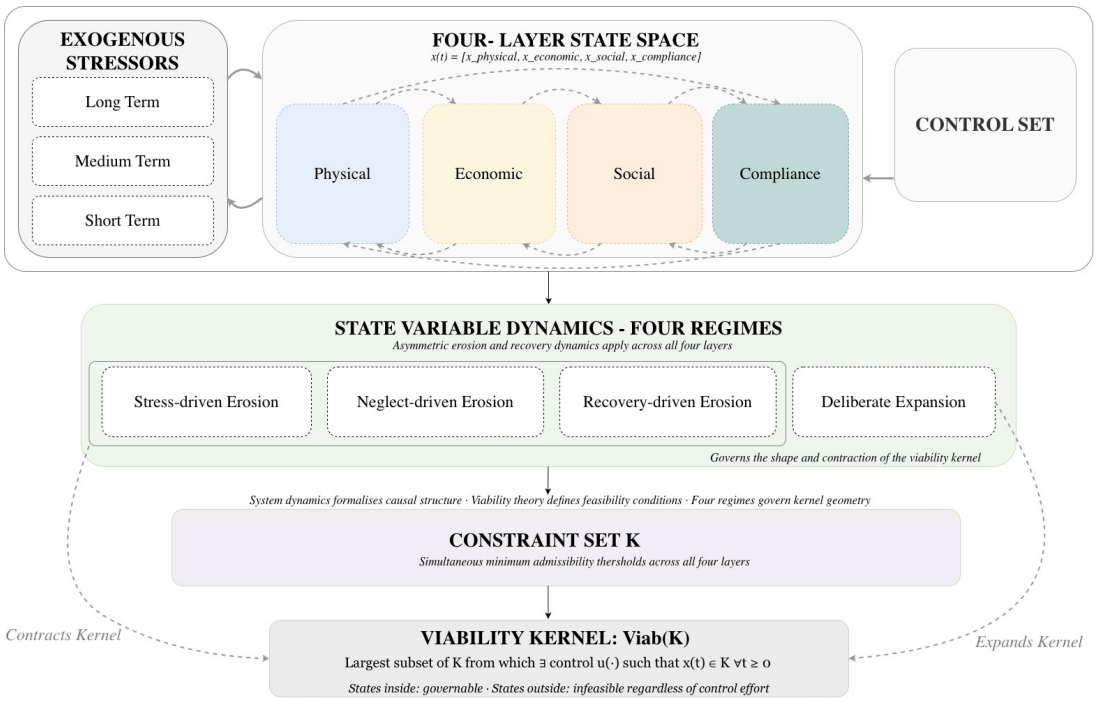


Figure 2: A viability-theoretic framework for resilient supply chains under heterogeneous external stressors.

The **exogenous stressor set** comprises all external drivers that perturb $x(t)$ without being subject to firm-level control are organised into three temporal classes. Long-term stressors operate over decadal horizons and degrade physical layer variables gradually and largely irreversibly. Medium-term stressors operate at interannual timescales and transmit stress through economic and regulatory channels. While short-term stressors generate acute disruptions to operational variables like logistics throughput, inventory levels, etc, testing the system's buffering capacity. The distinction is analytically significant: long-term stressors erode the structural conditions of viability; medium-term stressors modulate the economic space within which the system operates; and short-term stressors impose potentially threshold-triggering shocks. A framework that conflates these classes cannot represent the compound and temporally heterogeneous nature of supply chain stressors.

The **four-layer state space** is structured as $x(t) = [x_{\text{phys}}, x_{\text{econ}}, x_{\text{soc}}, x_{\text{comp}}]$, corresponding to four coupled layers. The *physical layer* governs the biophysical productive base, including production capacity, input availability, and logistical infrastructure. The *economic layer* governs the financial conditions of supply chain actors, jointly conditioned by physical layer outputs and market and regulatory stressors. The *social layer* governs the human conditions of production; its deterioration feeds back into the physical layer through labour contraction, activating reinforcing erosion loops. The *compliance layer* governs certification and governance standing, and exhibits the structural asymmetry most clearly: erosion is rapid under welfare and economic stress, whereas recovery is slow even under sustained investment.

State variable dynamics are characterised by four regimes. *Stress-driven erosion* is triggered by exogenous events and produces rapid, nonlinear decline through reinforcing loops, typically faster than any control response can arrest. *Neglect-driven erosion* occurs in the absence of active investment and produces gradual, cumulative decay. *Recovery-driven dynamics* describe partial, path-dependent restoration; hysteresis means the recovery trajectory does not retrace the erosion trajectory. *Deliberate expansion* is the only regime that actively enlarges $\text{Viab}(K)$ through sustained control effort. The rate asymmetry across regimes — erosion faster than recovery, recovery faster than deliberate expansion — governs the contraction dynamics of the viability kernel under intensifying stress.

The **constraint set** K requires simultaneous satisfaction of minimum admissibility thresholds

across all four layers. No layer is independently sufficient: a supply chain that maintains physical productivity while losing social capital or compliance standing is not viable in the sense of the framework, because the certification and sourcing relationships on which the focal firm depends cannot be sustained. The multi-dimensionality and non-compensatory structure of K distinguishes this framework from composite index and threshold-based approaches.

The **viability kernel** $\text{Viab}(K)$ is the central analytical output of the framework. Exogenous stressors activating reinforcing erosion loops contract the kernel; deliberate control effort strengthening balancing recovery loops enlarges it. Its boundary identifies the critical threshold at which supply chain governance transitions from viable management to structural failure.

3 Case Study: The Arabica Coffee Supply Chain

The coffee supply chain is among the most geographically extensive and institutionally complex commodity systems in the world. Production is concentrated in tropical and subtropical origin countries, where smallholder farmers under rain-fed conditions account for the majority of global output. Arabica (*Coffea arabica*) requires temperatures of 18–24°C, annual rainfall of 1500–2000 mm, and specific altitudinal conditions already contracting under observed climate trajectories Bunn et al., 2015. Three structural features motivate the viability-theoretic treatment. First, the production base is biophysically fragile, with yield, land suitability, and soil health sensitive to long-term climatic change in ways that are gradual and largely irreversible. Second, the governance structure is certification-dependent: audit scores, traceability, and compliance standards erode rapidly under stress and recover slowly. Third, the social conditions of production are slow-moving stocks that feed back into productive capacity and compliance standing through reinforcing loops, creating the potential for compounding collapse across layers that no single performance indicator can capture. The multi-stage structure of the supply chain is illustrated in Figure 3.

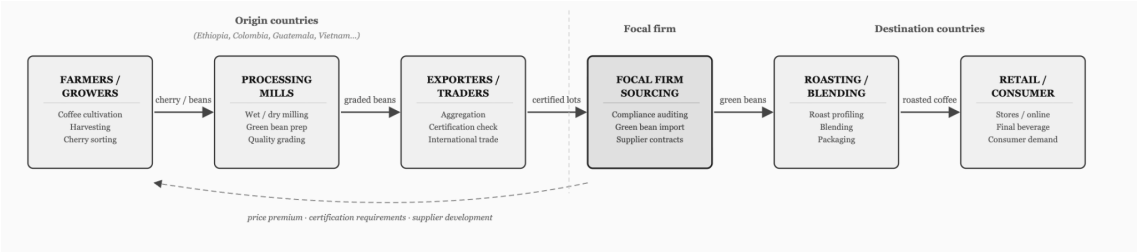


Figure 3: The coffee supply chain as a multi-actor system

The generic viability-theoretic framework is instantiated for the coffee supply chain by populating each of its six components with domain-specific variables, causal relationships, and control instruments. In this conference paper, we touch upon each component briefly, while the details are relegated to the full paper. Each component is backed by an extensive literature review, details of which are also relegated to the full paper. An overview of the exogenous stressors, four-layer state space, and control set is provided in Figure 4.

Eight exogenous stressors are identified, comprising climate-related and politics-related stressors. Climate-related stressors primarily affect the physical layer. Notably, temperature anomaly (E_1) is the most pervasive boundary input in the model, acting directly on eight variables spanning all four layers — yield, water availability, soil health, pest pressure, production cost, farmer welfare, health outcomes, and carbon footprint — making it the dominant structural driver of cross-layer deterioration. Politics-related stressors primarily influence the economic and social layers. Geopolitical instability (E_6), for instance, simultaneously disrupts logistics capacity, exchange rate risk, market price volatility, and transport cost, compressing the economic space within which control responses must operate. Global arabica price (E_3) is treated as exogenous at the firm level, reflecting the price-taker position of upstream actors and the limited ability of any single focal firm to govern commodity market conditions. Stressors also propagate into compliance indirectly through other layers; for example, land-use pressure negatively influences deforestation compliance.

The state space is populated with forty variables across the four layers, classified by their sys-

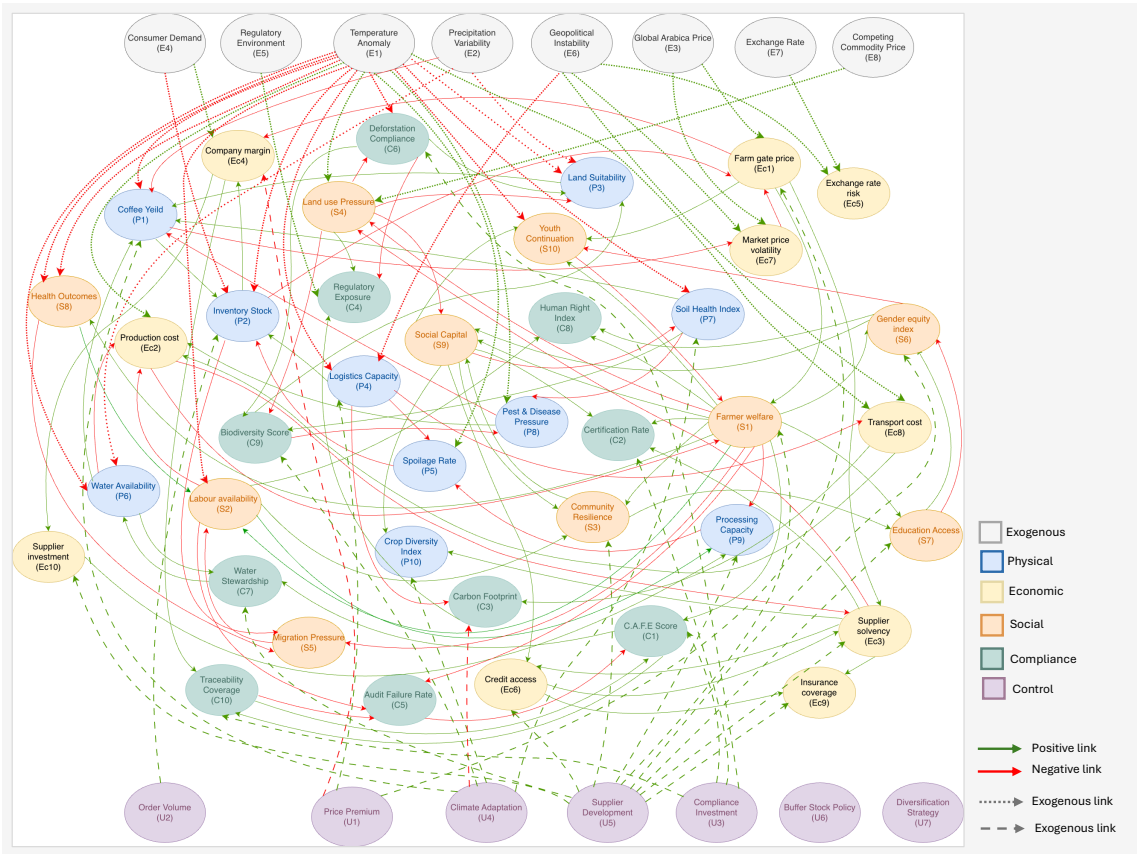


Figure 4: Causal loop diagram of the viability-theoretic framework for the coffee supply chain

tem dynamics role. Stock variables — including inventory and soil health in the physical layer, supplier solvency in the economic layer, farmer welfare, community resilience, gender equity, and social capital in the social layer, and the certification score and traceability coverage in the compliance layer — accumulate conditions over time and carry the memory of past states. Auxiliaries represent instantaneous functions of other variables, with no accumulation dynamics. The stock variables in the compliance and social layers are the primary carriers of the asymmetric erosion dynamics: they erode rapidly under stress and recover slowly even under sustained control investment. A critical structural feature of the model is that the focal firm's sourcing margin (Ec_4) appears as a constraining argument in all four endogenous decision rules — price premium, compliance investment, climate adaptation, and supplier development. This means that when the focal firm's margin is compressed by stressors, the capacity to activate any balancing loop is simultaneously reduced, creating a structural link between firm-level financial stress and the contraction of Viab(K).

The causal loop diagram formalises the cross-layer feedback structure. The central reinforcing erosion loop runs from farmer welfare (S_1) through labour availability (S_2), processing capacity (P_9), and inventory stock (P_2) back to farm-gate price (Ec_1) and welfare: a decline in farmer welfare reduces labour supply, which reduces processing throughput and inventory availability, which depresses the prices that suppliers can obtain, which further erodes welfare. The centrality of farmer welfare is reinforced by its causal reach across the model: S_1 directly drives nine variables spanning all layers, making it the most structurally connected stock and the primary transmission node through which physical and economic stressors propagate into social and compliance deterioration. A second reinforcing loop links physical layer deterioration to economic layer stress. Rising temperature anomalies and soil health loss drive yield decline, which raises production costs and erodes supplier solvency. Declining solvency in turn reduces credit access and insurance coverage, further amplifying the economic fragility of upstream actors. The compliance layer is coupled to both loops. The certification score depends on farmer welfare and traceability investment. When welfare erodes, audit failure rates rise and certification rates decline, threatening the sourcing relationships on which the focal firm depends. Balancing loops operate through the control set: price premium supports farm-gate price and welfare; compliance investment supports the certification

score and deforestation compliance; climate adaptation investment supports soil health and crop diversity; and supplier development supports solvency, credit access, and social capital.

The constraint set K requires the simultaneous satisfaction of minimum admissibility thresholds across all four layers, for example, a minimum yield sufficient to meet procurement targets; a minimum inventory buffer consistent with buffer stock policy; a minimum supplier solvency threshold below which sourcing contracts cannot be sustained; a minimum farmer welfare level below which labour supply and social capital collapse; and a minimum certification score below which the focal firm's sourcing programme is compromised. No single threshold is sufficient in isolation.

Seven control instruments are identified. Price premium, compliance investment, climate adaptation investment, and supplier development are modelled as endogenous decision rules, representing the focal firm's management responses to observed conditions. All four are constrained by the focal firm's sourcing margin, meaning that control capacity is not independent of system state but is itself eroded as stressors compress financial conditions. Order volume, buffer stock policy, and diversification strategy are modelled as policy parameters, fixed within a given planning period but variable across scenarios. Diversification strategy (u_7), which governs the geographic composition of the sourcing portfolio, is the only control instrument that operates across both the physical and economic layers simultaneously, hedging climate and geopolitical concentration risk without requiring layer-specific investment. The viability kernel identifies the joint region of the state space from which all constraints can be simultaneously maintained under at least one of these control strategies.

4 Conclusions

This paper has proposed a viability-theoretic framework for supply chains under heterogeneous external stressors and demonstrated its application through the arabica coffee supply chain. The framework addresses a gap shared by the supply chain management and agricultural systems literatures: viability is consistently invoked as a conceptual goal but never formally operationalised through the definition of a state space, constraint set, or viability kernel. By combining system dynamics and viability theory across six structural components, the paper establishes the conditions under which such operationalisation is defined and well-posed.

Three contributions stand out. First, the temporal classification of stressors establishes that different stressor types erode different components of the constraint set at different rates — a distinction that single-class disruption frameworks cannot capture. Second, the four-regime characterisation of state variable dynamics establishes asymmetry as a structural property: erosion is activated passively through reinforcing loops, whereas recovery and deliberate expansion require sustained, margin-constrained investment. Third, the viability kernel provides a governance target that is analytically more adequate than a recovery trajectory or resilience index, identifying not only which states are governable but also where no feasible control strategy exists regardless of effort.

The framework remains conceptual: state equations are structurally specified but not parameterised, and the viability kernel is identified but not computed. Future work should parameterise the equations from empirical data, implement the Saint-Pierre algorithm Saint-Pierre, 1994 to approximate the kernel under alternative IPCC climate scenarios, and extend the approach to other certification-dependent commodity supply chains including cocoa, tea, and palm oil.

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