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Abstract

This paper extends the traditional Leontief Input-Output (I-O) model by introducing a traverse disequilibrium framework that captures simultaneous quantity and price adjustments over time. Unlike standard static I-O models, this approach incorporates continuous-time adjustments in production, prices, and resource utilization. The analysis models how sectors respond to demand fluctuations through inventory accumulation and production adjustments, allowing for temporary imbalances between supply and demand. The model is further extended to include price-setting mechanisms. In this framework, sectors adjust markups in response to cost fluctuations and inventory deviations, and biophysical resource utilisation, leading to physical constraints and cost-push inflation. Calibrated using Brazil's Input-Output matrix and land-use data, the framework is applied to sectoral shocks, including demand surges and price rigidities, to assess their sectoral and macroeconomic impacts. The results highlight the importance of adjustment speeds in shaping economic dynamics, showing that rigid price and quantity settings amplify inventory cycles, while fast quantity adjustments increase output volatility. Sectoral interdependencies create cascading effects, demonstrating how price, and quantity shocks propagate across industries. Additionally, the dependence on environmental services illustrates how pressures on scarce resources feedback into prices and quantities.

Keywords: Environmental Input-Output, Traverse Dynamics, Disequilibrium Adjustments, Price Stickiness, Inventory Adjustment, Biophysical Constraints.

JEL Classification: C67, C61, E31, E32, O13, Q57.

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1. Introduction

The Input-Output (I-O) model is key in economic theory and policy analysis to understand the interdependencies between sectors of an economy. Since Leontief's (1936) seminal work, input-output (I-O) models have examined how demand shocks propagate across industries, how production cost increases contribute to inflation, and how sectoral interdependencies influence employment and output stability during economic fluctuations (Miller & Blair, 2009). These models help understand policy changes or external shocks across the structure of an economy, providing insights into the dynamics of supply chain disruptions, sector-specific productivity shifts, and resource allocation in response to environmental or technological pressures (Miernyk, 2020).

Traditional I-O models assume that economies operate in a supply and demand equilibrium[1]. They include changes in inventories as part of final demand, counting overproduction as demand while overlooking underproduction. The assumption of immediate equilibrium adjustment, typically modelled through the Leontief inverse, simplifies the analysis but does not account for the dynamic processes involved in economic transitions (Blackhouse & Boianovsky, 2012).

In practice, economies do not reach equilibrium instantly. Instead, they follow adjustment trajectories influenced by resource availability, production capacity, market conditions, and institutional frameworks (Dietzenbacher, 2020). The speed of these adjustments affects the overall economic response. To better understand these dynamics, it is necessary to move beyond static models and develop frameworks that account for both the transition phase (traverse) and the eventual steady state.

This focus on the speed and nature of adjustment highlights the importance of using continuous models rather than discrete ones. While discrete-time models analyse the economy at specific points in time, continuous-time models capture the entire adjustment process as it unfolds (Chiarella et al., 2006; Gandolfo, 1997). This allows for a deeper understanding of the transition dynamics. By doing so, economists and policymakers can better assess the short-term disruptions and the long-term trajectory of an economy in response to changes, enabling more informed decision-making that addresses both the transition phase and the steady state.

Our framework builds on three conceptual pillars that distinguish it from standard Leontief (or CGE) models: (1) the use of bounded rationality, where firms adjust gradually under non-maximisation behaviour and adaptive expectations (Richters, 2021; Gaffard, 2023); (2) the adoption of continuous-time adjustment processes, capturing the dynamics of economic traverses rather than static equilibria; and (3) the explicit consideration of physical constraints, particularly land and biophysical resource limits, which remain underexplored in conventional I-O and disequilibrium models.

Capturing transitional dynamics becomes even more important when considering that quantities, prices and biophysical resources adjust over time, and often not simultaneously. Within the input-output tradition, Leontief (1941) developed both a quantity model, in which output adjusts to meet final demand, and a price model, in which prices adjust to reflect changes in input costs and markups – assuming fixed technical coefficients. These two models represent

[1] Leontief's traditional Input-Output Analysis is theoretically grounded in Walras' General Equilibrium Theory, a connection that Leontief himself emphasised throughout his work (Leontief, 1941, 1986).

alternative closures: quantity adjustment under fixed prices, or price adjustment under fixed outputs. As Oosterhaven (2024) emphasises, these closures are mutually exclusive within static equilibrium frameworks. The Leontief models isolate either prices or quantities as the endogenous adjustment variable, and cannot accommodate simultaneous adjustments in both dimensions. This limitation underscores the value of disequilibrium approaches, which enable gradual, interactive adjustments in both prices and quantities over time.

This view aligns with the concept of the traverse (Robinson, 1980), which refers to the adjustment path when transitioning from one equilibrium state to another. Rather than jumping between equilibria, economies undergo a sequence of changes shaped by institutional constraints, behavioural inertia, and technological rigidities. Traverse models explicitly focus on this transitional process. Embedding traverse within I-O enables us to examine how sectoral interdependencies evolve, particularly under conditions of disequilibrium where quantities and prices adjust gradually in tandem.

We then extend the traditional Leontief framework to incorporate an out-of-equilibrium dynamics. We first model how firms respond to demand fluctuations through inventory accumulation and production adjustments, allowing for temporary imbalances between supply and demand – as in the classical work of Metzler (1941). We then introduce price-setting mechanisms, in which firms adjust markups in response to cost fluctuations and inventory deviations. Finally, we introduce environmental and behavioural feedback, linking production to ecosystem services and biophysical constraints while grounding firms' behaviour in bounded rationality and adaptive expectations.

We test the model using Brazil's Input-Output matrix as a baseline and GLORIA sectoral land-use data. We calibrate the model[2] to simulate two economic shocks: (1) a final demand shock in the food sector and (2) a biophysical shock in land-use requirements reflecting yield losses. These two core scenarios are further explored through sub-scenarios: (a) varying quantity adjustments; (b) testing different price adjustment speeds; and (c) analysing the interaction between price and quantity flexibility. For the land-use requirements shock (Scenario 2), we examine how its impacts vary under different resource constraints.

Following this introduction, Section 2 provides a brief literature review. Section 3 presents the core theoretical model, first detailing the quantity adjustment process before extending it to incorporate price-setting mechanisms, markup dynamics and ecological-economic feedbacks. Section 4 discusses the results of the simulated scenarios. Finally, we conclude by summarising the key findings, discussing policy implications for managing economic disruptions, and outlining potential extensions for future research.

2. Literature Review

2.1. Critiques of Equilibrium Assumptions in I-O Models

Traditional input–output (I-O) models employ an equilibrium hypothesis, assuming an instantaneous balance between supply and demand across all sectors. While analytically

[2] While we refer to this as a calibration exercise, it is important to note that inventory data is limited in national accounts, particularly at the sectoral level. As such, the parameterisation relies on stylised assumptions rather than full empirical calibration. This remains an open point for further discussion and refinement.

convenient, this assumption lacks realism in representing the nature of real economies. Keynes (1936) argued that static models cannot capture periods of underutilization or involuntary unemployment that result from slow price and wage adjustments. Backhouse and Boianovsky (2012) document how post-Keynesian and disequilibrium theorists sought alternatives to general equilibrium, noting that mainstream models often "assumed away the problems" of coordination failures and quantity constraints that motivated earlier disequilibrium research. The whole evolutionary literature rejects the use of equilibrium as an organising principle, emphasising instead processes of continuous adaptation, innovation, and structural change.

Early contributions embraced this perspective. Nelson and Winter (1982) formalised this departure by introducing an evolutionary framework in which firms follow routines, learn, and innovate without ever converging to equilibrium. Their model demonstrates that economic change is driven by cumulative learning and selection mechanisms, not by equilibrium adjustment. Similarly, Dosi (1988) and Metcalfe (1998) argue that economic systems evolve through dynamic competition, technological trajectories, and path dependence, rendering equilibrium both theoretically inconsistent and empirically irrelevant.

Malinvaud (1977) critiques Walrasian market-clearing mechanisms and argues for persistent disequilibria in economics, stemming from price and wage rigidities. His work is foundational to the literature on non-market-clearing dynamics and the significance of adjustment processes over time. In a similar vein, Day (1984) argues that "economic disequilibrium is the rule" in a world of adaptive, non-optimising agents. He introduced the notion of *adaptive economising*, wherein firms and consumers adjust through trial and error under resource constraints, leading to locally unstable dynamics rather than instantaneous equilibrium. Real markets often fail to clear promptly, requiring market mechanisms to maintain viability in the face of continuous shocks and changes. This intellectual tradition – from Keynes through Malinvaud and Day – positions disequilibrium not as an anomaly but as a central feature of economic life.

2.2. Extending I-O Models to Disequilibrium Dynamics

Recent research extends classic I-O models to capture disequilibrium processes. Oosterhaven (2024) revisits I-O foundational models to account for both supply-driven and demand-driven departures from equilibrium. He shows that the standard demand-driven Leontief quantity model (Leontief, 1941) can be reinterpreted as a *revenue-pull price model* when measured in value terms – a surge in final demand can be translated into a trajectory of price increases (inflation) rather than output increases if one tracks value flows instead of physical quantities. Likewise, the supply-driven Ghosh model (Ghosh, 1958) has an analogous *cost-push price interpretation*. By combining these insights, Oosterhaven derives unified "ultimate I-O equations" that encompass both traditional demand-side and supply-side models, expressed in both quantity and price terms. This opens up new possibilities for simulating complex inflationary dynamics within input-output (I-O) systems, capturing how cost shocks propagate through inter-industry linkages and potentially spark price–wage spirals. The key contribution is to relax the rigid closure of standard I-O - which holds either prices or quantities fixed – and allow *both* to adjust over time.

Another limitation is the treatment of inventories and demand disequilibrium. In static input-output (I-O) accounting (e.g., as in Miller & Blair, 2009), changes in inventories are often treated as part of final demand – effectively counting unintended overproduction as desired demand. This convention glosses over the reality that overproduction and underproduction signal disequilibrium: firms accumulate inventories when demand falls short, and draw down inventories or ration customers when demand exceeds current supply. As Blackhouse and Boianovsky (2012) emphasise, immediate clearing via the Leontief inverse "does not account for the dynamic processes" of adjustment. In practice, economies do not reach equilibrium instantly after a shock. Instead, they follow *adjustment trajectories* influenced by factors like production lags, resource availability, and expectations. The speed of these adjustments determines the duration of imbalances and the severity of any ensuing disruptions. This recognition motivates moving beyond static models toward frameworks that explicitly model the traverse from one state to another, including the possibility of prolonged disequilibrium during the transition.

2.3. Price–Quantity Adjustments and Continuous-Time Traverse Models

In traditional I-O models (and indeed many macro models), price and quantity adjustments are typically analysed in isolation. A model either allows flexible prices with fixed output (as in the dual of a Leontief quantity model) or flexible output with fixed prices, but not both simultaneously. This artificial separation is evident even in Walrasian Computable General Equilibrium (CGE) models, which assume perfectly flexible prices that clear markets, thereby eliminating quantity rationing by assumption. In reality, however, both prices *and* quantities adjust, often at different speeds and subject to frictions. The literature has long stressed the importance of modelling these adjustments jointly. Lorenz (1993) investigated a simultaneous price–quantity adjustment process and found that even simple markets can exhibit complex dynamics (like limit cycles or chaos) when both dimensions adjust with lags. Similarly, Hommes (1994), in a study of the classic cobweb model, demonstrated that introducing adaptive (backwards-looking) expectations for price can lead to sustained fluctuations or even chaotic oscillations in prices and output.

To capture such dynamics, our framework employs a continuous-time approach to input-output (I-O) modelling to track the *entire trajectory* of adjustment. This is crucial because the path an economy takes toward (or away from) equilibrium can be as important as the equilibrium itself (Robinson, 1980). By modelling time explicitly, we incorporate different adjustment speeds for different processes – for example, production may ramp up or down faster than prices change, or vice versa. Prior research has shown that such asynchronous adjustment speeds can produce complex transitional phenomena. Chiarella *et al.* (2006) and Flaschel & Chiarella (1998), for example, analyse financial market models where prices adjust with momentum and traders form expectations adaptively. With relatively simple behavioural rules, the continuous interaction of price adjustments and inventory (or supply) adjustments can give rise to instability, persistent cycles, or nonlinear oscillations. These outcomes include the possibility of overshooting, limit cycles, and chaotic fluctuations in asset prices and quantities – analogues to what we might see in real economies during booms and busts.

Continuous-time I-O models have several advantages. First, they can capture events within a period – a shock that hits in the middle of a year, or cascading failures that unfold over weeks and months (Donaghy *et al.*, 2007). Second, they naturally accommodate feedback loops; for instance, a rise in prices can dampen the quantity demanded with a delay, which in turn eases pressure on prices, and so forth, possibly producing oscillatory adjustments. Oosterhaven's (2024) advocacy for a continuous modelling approach echoes this: sector-specific lagged responses give a more accurate depiction of how shocks propagate across industries over time, capturing gradual inflationary or deflationary effects as sectors adjust with inertia. This view is supported by broader macroeconomic evidence: Bertsimas and Kogan (2000) show that continuous adjustment models of capital accumulation can better explain observed investment cycles than instantaneous jump models, and Achdou *et al.* (2022) demonstrate that continuous-time heterogeneous-agent models (partial differential equations) yield tractable insights into labour market and wealth dynamics under disequilibrium conditions.

Traverse I-O models have been applied in several domains. In global trade analysis, Los (2017) and Gurgul & Lach (2018) use time-dependent input-output (I-O) techniques to study how trade linkages and sectoral specialisation evolve, revealing transitional dynamics, such as the lagged emergence of new supply chains. In environmental and sustainability, examples include Moffatt & Hanley (2001) and Wiedmann & Lenzen (2018), who incorporate gradual changes in technology and consumption patterns to study the long-run impacts of sustainability policies, as well as Yanovski et al. (2024), who examine the transitional effects of renewable energy adoption across regions.

2.4. Bounded Rationality and Behavioural Rules in Macroeconomic Dynamics

A distinguishing feature of our approach is the incorporation of bounded rationality and behavioural decision rules, rather than assuming perfectly optimising agents. The concept of *bounded rationality* (Simon, 1955) states that agents face cognitive limits and thus rely on heuristics or satisficing (rather than strict optimisation). Such behaviour is already central in evolutionary economics (Nelson & Winter, 1982) and has been increasingly influential in environmental economics (e.g., in modelling how agents respond to complex climate risks).

Conlisk (1996) argues that ignoring bounded rationality creates explanatory gaps in economic theory, citing evidence that agents use rules of thumb and adapt over time. Naish (1993) showed that under certain conditions, simple backwards-looking expectations can be "nearly optimal" predictors of economic variables. Classic models like the cobweb, in which agents form adaptive expectations, can generate persistent oscillations rather than smoothly converge to equilibrium (as Hommes' chaos result demonstrated). These insights from behavioural modelling reinforce our decision to let agents in the I-O system respond to disequilibria with heuristics – e.g. adjusting production based on inventory levels (a form of stock-adjustment rule) or adjusting prices based on cost increases and desired markups.

Such rule-based behaviour is used in models outside the neoclassical mainstream. Richters (2021) develops an out-of-equilibrium macro model where households and firms employ gradient-driven adjustments – they push variables in the direction that improves their situation, given their limited knowledge and power. His framework combines the slow adaptation of prices and quantities with bounded rationality, showing that, depending on adjustment speeds, the economy can converge to a neoclassical equilibrium or exhibit persistent Keynesian-style stagnation. This kind of result exemplifies how incorporating bounded rationality *expands* the set of possible dynamics.

Bounded rationality and behavioural rules are increasingly embraced in policy-oriented economic models. A case in point is the World Bank's MINDSET model (Model of Innovation in Dynamic Low-Carbon Structural Economic Transformation). MINDSET is a macroeconometric I-O model developed for climate and development policy analysis (World

Bank, 2025). Instead of enforcing general equilibrium with optimising agents, the model allows for involuntary unemployment (excess labour at fixed wages) and does not assume all markets clear. Firms supply output to meet demand if capacity allows, rather than optimising profits period by period. There is no crowding out of investment when the economy is slack. In the same vein, the World Bank's 2015 *World Development Report: Mind, Society, and Behaviour* made the case for incorporating realistic psychology and bounded rationality into development economics.

2.5. Disequilibrium Dynamics in Environmental Transitions

The interplay of short-term disequilibrium and long-term structural change is particularly relevant in the context of climate change and the low-carbon transition. Decarbonising the economy requires massive shifts in production structures: some industries ("green" sectors like renewables, electric transport, etc.) will rapidly expand, while others ("brown" sectors like coal mining, oil, and gas) will contract or disappear. Semieniuk *et al.* (2020) emphasise that such a large-scale structural transformation can have destabilising financial effects. Expanding *"sunrise" industries* may experience investment booms and even asset bubbles, while shrinking *"sunset" industries* may suffer abrupt asset value collapses (stranded assets), loan defaults, and cascading losses in financial markets.

Our framework addresses this turbulence by allowing for temporary imbalances, adjustment costs, and feedback loops between the economy and the environment. For example, suppose an expanding green energy sector faces input bottlenecks (e.g., limited supplies of rare minerals or land for solar farms). In that case, our model will capture the resulting price spikes and output constraints, rather than assuming a perfectly elastic supply. Likewise, contraction of the fossil-fuel sector in our model can lead to underutilised labour and capital (unemployment and idle machines) for an extended period, consistent with the real-world difficulties of transitioning workers and repurposing capital. These features are critical for analysing policies: a carbon tax shock in a full-employment CGE model might show a smooth reallocation, but in our disequilibrium model, it can cause short-run unemployment or inflationary pressure in certain inputs – outcomes that policymakers are interested.

Recent studies using continuous-time multisector models underscore the importance of managing transition dynamics. Codina (2023) develops a continuous-time multi-sector growth model (in the Flaschel-Semmler cross-dual tradition) to evaluate policies for a low-carbon transition. He finds that sectoral policy interventions stabilise prices and accelerate the transition. In particular, a combination of carbon taxes and green subsidies can *"greatly accelerate"* the phase-out of carbon-intensive technologies and the phase-in of green technologies. Without such proactive fiscal interventions, the market's natural adjustment – driven by cost advantages of green tech alone – appears "too slow to reach decarbonization in a timely manner". This result aligns with our model's focus: we include policy levers and allow for different adjustment speeds, enabling us to simulate scenarios where price controls or subsidies dampen instability and accelerate adjustment in certain sectors (as suggested by Codina's findings).

Finally, Oosterhaven's (2024) reinterpretation of basic I-O models can be seen as complementary to these aims. His "ultimate I-O equations" provide a simplified representation of how price and quantity adjustments interact following a shock. They allow for the analysis of an inter-industry price–wage spiral: a wage increase in one sector raises prices in that sector, which, via input–output linkages, raises costs in other sectors, potentially prompting further wage demands – a classic disequilibrium process that unfolds over time. Traditional I-O or CGE would either assume it away (by instant clearing) or require an exogenous assumption about wage indexation. Oosterhaven treats it as an emergent outcome of the system.

3. Building a Traverse I-O Disequilibrium model

The traditional I-O model analyses how changes in quantity in one sector propagate throughout others, reflecting the productive interdependencies within an economy. Total demand for each sector's output is decomposed into two components (intermediate demand and final demand):

$$\mathbf{x^D} = \mathbf{A\,x} + \mathbf{y} \tag{1}$$

Where $\mathbf{x^D}$ is the total demand vector, $\mathbf{A}$ is the matrix of technical coefficients; $\mathbf{x}$ is the sectoral output vector; $\boldsymbol{y}$ is the final demand vector; and $\mathbf{Ax}$ represents intermediate demand, i.e., the inputs required from other sectors.

If one assumes equilibrium, total output equals total demand ($\mathbf{x} = \mathbf{x^D}$):

$$\mathbf{x} = \mathbf{A\,x} + \mathbf{y} \tag{2}$$

Rearranging, it yields the classic Leontief quantity model, where:

$$\mathbf{x} = (\mathbf{I} - \mathbf{A})^{-1}\mathbf{y} \tag{3}$$

$\mathbf{L} = (\mathbf{I} - \mathbf{A})^{-1}$ is known as the Leontief inverse, which captures both direct and indirect input requirements necessary to meet a given level of final demand. This formulation allows us to trace the full production requirements across sectors resulting from changes in final demand. Each element l_{ij} of the Leontief inverse quantifies the total output from sector i required (directly and indirectly) to deliver one unit of final demand in sector j.

Environmental Input-Output models extend this analysis. By tracing direct resource requirements and the emissions and waste generated per unit of production, they quantify the environmental impacts of each final good and service sold (Guilhoto, 2021). Defining $\mathbf{q}$ as a row-vector of sectoral direct resource requirements or emissions per unit of production, one can calculate the direct and indirect (embodied in production) resource requirements or emissions per unit of output, $\mathbf{q^{tot}}$, and the total amount of resource or emissions, Q:

$$\mathbf{q^{tot}} = \mathbf{q}'(\mathbf{I} - \mathbf{A})^{-\mathbf{1}} \tag{4}$$

and

$$Q = \mathbf{q}'(\mathbf{I} - \mathbf{A})^{-\mathbf{1}}\mathbf{y} \tag{5}$$

3.1. Inventory Adjustment Model

Building on Metzler (1941), we extend the Leontief framework into a dynamic, non-equilibrium setting by introducing inventory adjustment mechanisms that capture fluctuations not instantly absorbed by demand. Firms are adaptive satisfiers, not intertemporal maximisers. They adjust quantities and prices gradually under bounded rationality, reacting to observed gaps rather than solving forward-looking optimisation problems. In practice, adjustments are partial and may display “inaction bands” (small deviations do not trigger immediate changes), which helps generate smooth dynamics without assuming perfect information.

Our model incorporates continuous differential equations to capture the dynamic relationships between sectoral production, demand, inventories, and expected sales. Key parameters such as the speed of adjustment in expected sales (β^y),[3] and desired and actual inventory levels ($\mathbf{v^d}$ and $\mathbf{v}(t)$, respectively) are incorporated to reflect these dynamics.

The model is structured around the key time-variant variables, sectoral production ($\mathbf{x}(t)$), demand ($\mathbf{x^D}(t)$), expected sales ($\mathbf{x^e}(t)$), and inventories ($\mathbf{v}(t)$), all of which evolve based on sectoral interdependencies represented by the matrix $\mathbf{A}$. Expectations formation is adaptive: firms update $\mathbf{x^e}$ towards realised demand at speed β^y (see Eq. 9). This reflects a core feature of inventory cycle models (Metzler, 1941), where production expectations adjust in response to observed demand. Rather than assuming ex-ante market clearing, as in Walrasian models (e.g. Computable General Equilibrium), the adjustment process here is ex-post – quantities respond gradually to demand deviations via an expectations mechanism. In this setting, when inventories fall below desired levels, firms increase production to rebuild stock, while excess inventories lead to a slowdown in output. Although the model at this stage does not explicitly incorporate capacity constraints, adjusting production expectations based on inventory positions introduces a source of inertia and cyclical behaviour that is central to disequilibrium approaches.

The model is continuous, incorporating differential equations that link production, demand, and inventory changes, allowing for the analysis of their adjustments over time rather than assuming instantaneous equilibrium. When inventories deviate from desired levels $\mathbf{v^d}$, production is adjusted accordingly, and expected sales are updated based on observed demand trends. This framework enables the analysis of how supply and demand mismatches lead to changes in inventories, ultimately providing insights into sectoral dynamics under conditions of disequilibrium. For high values of the adjustment speed, β^y, expected sales converge faster to actual demand, and in the limit, the model approximates the behaviour of the original Leontief model, where equilibrium is reached instantaneously, and no inventory imbalances persist.

Formally, the core equations that form the foundation of the model are as follows:

$$\mathbf{x^D}(t) = \mathbf{A}\,\mathbf{x}(t) + \mathbf{y} \tag{6}$$

As in Eq. (1), Eq. (6) defines the demand vector $\mathbf{x^D}(t)$ as a function of the production vector $\mathbf{x}(t)$ and the exogenous final demand vector $\mathbf{y}$. This enables capturing the interconnection of sectoral outputs and their collective contribution to total demand. Then, following the inventory cycle:

$$\mathbf{x}(t) = \min\left[\mathbf{x^e}(t) + \mathbf{v^d} - \mathbf{v}(t)\,,\ \left(\widehat{\mathbf{q^l}}\right)^{-1}\mathbf{q^{l,s}}\right] \tag{7}$$

[3] In the model, speeds of adjustment are scalars, so all sectors exhibit the same adjustment speed. However, one can modify the equations by replacing the scalar β with the diagonalised vector $\widehat{\boldsymbol{\beta}}$, which contains sector-specific adjustment speeds.

Eq. (7) links the production vector $\mathbf{x}(t)$ to the expected sales vector $\mathbf{x^e}(t)$, desired inventory levels $\mathbf{v^d}$, and the actual inventory levels $\mathbf{v}(t)$. This relationship shows how production adjusts to align with expected sales while accounting for both desired and current inventory levels. When actual inventories deviate from the desired levels, production is adjusted accordingly to meet expected sales and manage inventory discrepancies. It also includes resource constraints via the vector of resource requirements per unit of output $\mathbf{q^l}$, which is here defined as land, and available resources (land services), $\mathbf{q^{l,s}}$. This ensures resource scarcity is not only technical but also binds production directly when resource availability is tight.

$$\dot{\mathbf{v}}(t) = \mathbf{x}(t) - \mathbf{x^D}(t) \tag{8}$$

Eq. (8) models the rate of change in inventories $\mathbf{v}(t)$ as the difference between production and demand. When production exceeds demand, inventories accumulate. Conversely, when demand outpaces production, either due to an unexpected increase in demand or resource constraints, inventories deplete.

$$\dot{\mathbf{x^e}}(t) = \beta^y(\mathbf{x^D}(t) - \mathbf{x^e}(t)) \tag{9}$$

Eq. (9) describes how expected sales $\mathbf{x^e}(t)$ evolve over time in response to actual demand. The adjustment is governed by the parameter β^y, the speed at which expected sales converge to demand levels. A higher β^y indicates a faster adjustment. This is our adaptive expectations rule under bounded rationality – firms update their sales expectations based on observed demand trends, allowing the model to capture adaptive behaviour in sales forecasting.[4]

The model (equations (6) to (9)) illustrates how production, demand, and inventories adjust continuously in response to economic shifts. Demand is influenced by production and external inputs, linking sectors through input-output relationships. Production aligns with expected sales and inventory goals, adjusting levels to meet demand forecasts while managing inventory discrepancies and addressing physical constraints arising from resource depletion. Inventory adjusts as the difference between production and demand, signalling when production should be increased or decreased to balance inventory levels with demand patterns. Finally, expected sales enable firms to update their expectations based on actual demand, with adjustments occurring at a rate determined by the speed of adjustment.

A crucial parameter is β^y. When high, demand expectations quickly align with real sales, leading to faster corrections in production and inventory levels, and allowing the system to rapidly approach equilibrium. Conversely, when β^y is low, disequilibrium persists. In the extreme case, when it approaches infinity, the system behaves like the classical Leontief model, in which $\mathbf{y^e}$ adjusts immediately to $\mathbf{y^D}$ and inventories remain unchanged.

[4] The current formulation assumes a backwards-looking, adaptive expectation mechanism. A forward-looking approach could also be introduced, for instance, by incorporating anticipated demand or trend extrapolation into the expectation formation process.

Table 1. Key Parameters and Variables in the Leontief Inventory Adjustment Model

Parameters	
β^y	Speed of adjustment in expected sales
$\mathbf{A}$	N×N matrix of technical coefficients
$\mathbf{v^d}$	Desired inventories, dimension N
$\mathbf{y}$	Final demand, dimension N
$\mathbf{q^l}$	Resource requirements per output (land), dimension N
$\mathbf{q^{l,s}}$	Resource availability (land), dimension N
Variables	
$\mathbf{x^D}(\mathrm{t})$	Total demand at time t, dimension N
$\mathbf{x}(\mathrm{t})$	Production at time t, dimension N
$\mathbf{x^e}(\mathrm{t})$	Expected sales at time t, dimension N
$\mathbf{v}(\mathrm{t})$	Actual inventories at time t, dimension N

3.2.Traverse Price and Quantity Adjustment Model

Next, we introduce additional dynamics related to price adjustments and sectoral markups. Prices are determined by the cost structure of each sector, including intermediate inputs and value-added components such as wages and markups. Prices adjust in response to changes in production costs, rather than demand-side pressures, with technical coefficients assumed to be fixed. Once the price dynamics are established, we extend the model by reintroducing the quantity adjustment mechanisms developed in the previous section.

The dual of the Leontief quantity model is the Leontief price model, which shifts the focus to cost-driven price adjustments. Instead of analysing the effects of a final demand shock, the price model examines how changes in value-added components propagate through the production network. When primary input costs rise (e.g.: wages), sectors seek to preserve their margins by passing these increases forward, leading to cost-push inflation across interconnected industries. The standard Leontief price model assumes full and immediate pass-through of cost changes, meaning prices adjust instantaneously to cost changes. In contrast, our model allows for sticky prices, capturing the fact that sectors may adjust their prices only gradually in response to cost pressures. This introduces a dynamic adjustment process, in which inflationary effects unfold over time rather than instantaneously.

We formally develop the extended price model below:

$$\mathbf{y}(t) = \mathbf{y_0}\left(\frac{\mathbf{p}(t)}{p^c(t)}\right)^{\eta} \tag{10}$$

Firstly, we assume an endogenous final demand (Eq. 10), depending on the price vector $\mathbf{p}(\mathbf{t})$ and the Consumer's Price Index (CPI), $p^c(t)$, adjusted by sectoral price elasticities η. This captures how relative change in prices influence final demand.

$$\mathbf{p^d}(t) = \left(1 + \boldsymbol{\mu}(t)\right)\left(\mathbf{w} + \mathbf{A}'\,\mathbf{p}(t) + \mathbf{q^l}\,p^l(t)\right) \tag{11}$$

Next, the price determination equation (Eq. 11) establishes the desired price vector $\mathbf{p^d}$(t), applying a markup ($\boldsymbol{\mu}(t)$) over unit costs – the sum of wages $\mathbf{w}$, the cost of direct inputs, represented by the transposed technical coefficient matrix, $\mathbf{A}'$, multiplied by the price vector $\mathbf{p}(t)$, and the cost of resource requirements (land) per unit of output, represented by $\mathbf{q^l}$ multiplied by its price, $p^l(t)$.

This relationship directly links prices to input costs and the chosen markup, reflecting the pricing strategies of sectors in response to cost fluctuations. The goods and services price adjustment and the resource (land) price adjustment dynamics are given respectively by:

$$\dot{\mathbf{p}}(t) = \beta^p\left(\mathbf{p^d}(t) - \mathbf{p}(t)\right) \tag{12}$$

and

$$\dot{p^l}(t) = \beta^p\left(p^{l,d}(t) - p^l(t)\right) \tag{13}$$

Eq. (12) describes how the price vector $\mathbf{p}(t)$ adjusts over time towards the desired price $\mathbf{p^d}(t)$ and eq. (13) describes how the resource price (land rent) $p^l(t)$ adjusts towards the desired price $p^{l,d}(t)$. The adjustment speed is governed by the parameter β^p, which controls the rate at which prices converge. This formulation captures the concept of price stickiness. A higher β^p implies greater price flexibility, allowing firms to update prices more rapidly in response to cost or demand shocks, whereas a lower β^p reflects sticky prices, given elements such as menu costs (Stiglitz, 1984).

Price rigidity has long been associated with non-clearing markets, real effects of nominal shocks, and persistence in output and inflation. In input-output models, slow price adjustment amplifies the role of inventory dynamics and intersectoral dependencies, as firms are unable to immediately pass on cost changes. This can lead to more stable output trajectories in the short term, but also prolonged imbalances in inventory and demand. The parameter β^p operationalises a continuum of pricing behaviours, from fixed-price Leontief systems (when $\beta^p \approx 0$) to flexible mark-up pricing, enabling a richer exploration of how nominal rigidities shape macroeconomic adjustment.

Inventory imbalances endogenously drive markup adjustments in our model (Eq. 14). When actual inventories fall below desired levels, firms increase markups, reflecting scarcity conditions and the opportunity to preserve margins during supply constraints. Conversely, when inventories exceed targets, firms reduce markups to stimulate demand and rebalance inventory levels. This behavioural mechanism is consistent with findings in the literature on pricing and inventory behaviour (Nekarda and Ramey, 2020), which emphasises the role of excess capacity, inventory signals, and cost-plus pricing under uncertainty.

$$\boldsymbol{\mu}(t) = \boldsymbol{\mu_0} + \mu_1\left(\mathbf{v^d} \oslash \mathbf{v}(t) - 1\right) \tag{14}$$

where $\oslash$ is the element-wise division.

The CPI (p^c) is a weighted average of basic prices across all sectors, with weights determined by initial final demand ($\mathbf{y_0}$), ensuring that sectors with higher baseline demand levels exert a greater influence on overall price movements:

$$p^c(t) = (\mathbf{y}_0' \, \mathbf{p}(t))/(\mathbf{y}_0' \, \boldsymbol{\iota}) \tag{15}$$

where $\boldsymbol{\iota}$ is a unity vector.

The land price, $p^l(t)$, can be interpreted through a Ricardian–Neo-Ricardian perspective, where the producer operating at the margin determines the prevailing price. As production expands to less fertile land, the unit cost of production rises for all producers, increasing the land price in line with the cost of accessing the marginal plot. Rents thus emerge not from absolute productivity but from differential productivity across lands.

This logic resembles a Phillips-curve-like relation for land use, where higher utilisation raises land rents and prices – though the correspondence is not exact (Lloyd et al. 1991). In our model, land is treated as a non-exhaustible resource, yet its price captures a Ricardian link between demand and cost, without implying physical depletion. This framing preserves the structural logic of rent formation while maintaining analytical consistency within the broader production system (Cheshire & Sheppard, 2001).

$$p^{l,d}(t) = \lambda_0\left[\mathbf{q}' \, \left(\mathbf{y}^{\mathbf{e}}(t) + \mathbf{v}^{\mathbf{d}} - \mathbf{v}(t)\right)/\left(\boldsymbol{\iota}'\mathbf{q}^{\mathbf{l,s}}\right)\right]^{\lambda_1} \tag{16}$$

We define the desired resource (land) price $p^{l,d}(t)$ as a function of total resource use relative to total supply. This introduces a dual constraint. On the one hand, production is physically limited by resource availability (Eq. 7); and, on the other hand, resource depletion increases prices (via unit costs), which may in turn constrain demand (Eq. 16).

The model above (eq. (6) to (16)) consists of a combined price-quantity model. When both price and quantity adjustments occur simultaneously, the speed at which each adjusts can lead to more complex dynamics. These interactions allow for a richer analysis of how sectors respond not only to production and inventory imbalances but also to cost changes and price fluctuations.

However, for meaningful interaction to take place, relative price misalignments must influence quantity adjustments, and similarly, quantity disequilibrium must impact price adjustments. In a model with fixed technical coefficients, intermediate consumption is determined solely by output and the technical coefficient matrix, whereas only final demand is directly affected by relative price changes. Therefore, introducing the equation to account for the sensitivity of final demand to price changes is necessary to capture this interaction (eq. 10).

While the influence of prices on quantities is critical, there is also substantial literature supporting the reverse mechanism: that quantity disequilibrium impacts prices (eq. 14). For instance, when inventories start to decline, firms may recognise the opportunity to increase prices and improve their margins. Conversely, if inventories grow beyond desired levels, firms may lower prices to stimulate demand and prevent excess stock, even at the cost of reduced margins.

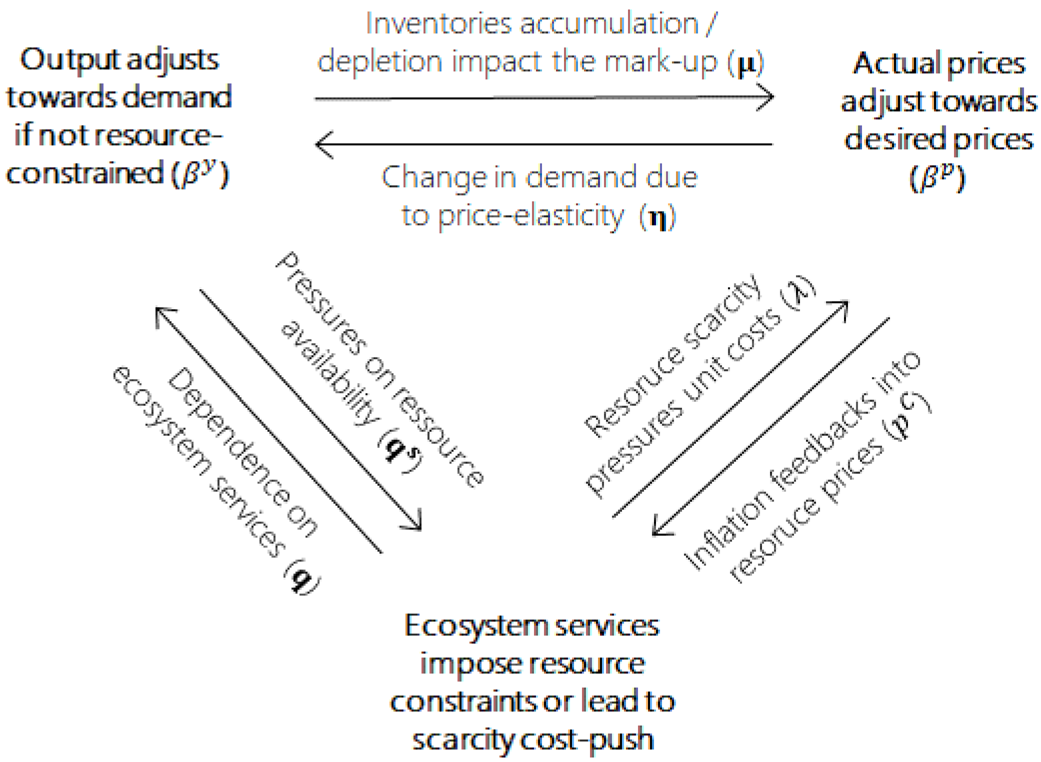
Table 2. Price adjustment parameters and variables added to the Model

Parameters	
β^p	Price adjustment speed
μ_1	Markup sensitivity to non-desired inventories accumulation/depletion
η	Price elasticity of the final demand
λ_0	Resource(s) price in equilibrium (demand equal to supply)
λ_1	Price elasticity of demand for resource(s)
$\mathbf{y}_0$	Initial final demand, dimension N
$\mathbf{w}$	Wage vector, dimension N
$\boldsymbol{\mu}_0$	Markup vector in equilibrium (desired and actual inventories), dimension N
Variables	
$\mathbf{y}(t)$	Final demand at time t, of dimension N
$\boldsymbol{\mu}(t)$	Markup vector at time t, of dimension N
$\mathbf{p}(t)$	Actual price at time t, dimension N
$\mathbf{p}^{\mathrm{d}}(t)$	Desired price at time t, dimension N
$p^l(t)$	Actual resource(s) price (land rent) at time t
$p^{l,d}(t)$	Desired resource(s) price (land rent) at time t
$p^c(t)$	Consumer Price Index (CPI) at time t
$\pi(t)$	Inflation rate at time t

Figure 1 shows that production, prices, and resources are interconnected. First, increased production pressures biophysical stocks, creating physical constraints due to the output's dependence on ecosystem services (water, land, and materials). Second, resource (land) scarcity influences price behaviourally via $p^l(t)$, transmitting scarcity into costs. Finally, production and prices are connected through a dual price-quantity dynamic: inventory accumulation (due to unmet demand) or depletion (due to physical constraints or unexpected demand shocks) triggers markup adjustments. Conversely, changes in prices affect final demand, which in turn influences production levels.

Another key parameter is β^p, determining how quickly sectors can adapt to changes in costs. A higher β^p indicates that sectors adjust prices swiftly, leading to a faster convergence to a new price equilibrium after a shock. This quick adjustment helps them to align their output prices with cost changes, minimising the risk of profit erosion and allowing them to maintain competitiveness. Conversely, when β^p is low, firms take longer to reflect rising costs in their prices. The delayed adjustment can have a ripple effect across interconnected sectors, creating prolonged misalignments between costs and prices throughout the economy. In extreme cases, if β^p is too low, sectors may not fully adjust their prices, leading to persistent inefficiencies and potential inflationary pressures.

Figure 1. Adjustment Feedback Diagram



4. Empirical Illustration Using Brazilian Data

This section presents the simulation results using a 42-industry Input–Output (I-O) framework calibrated to the Brazilian economy. We use the 2021 Brazilian Input–Output Matrix, developed by the Federal University of Rio de Janeiro (UFRJ), as the main data source.[5] Further details on the data and methodology can be found in the annex. The simulations are interpreted through a behavioural (adaptive, boundedly rational) and resource-constrained lens, in which adjustment speeds (β^y, β^p) capture gradual, partial responses rather than optimisation, and land scarcity affects both costs/prices and quantities.

The analysis begins with a demand shock in the food sector (Scenario 1), We then assess the role of behavioural adjustment parameters by varying the speed of quantity (production) adjustments (Scenario 1.b). Next, we simulate a land productivity shock in the agricultural sector (Scenario 2) to examine how increases in natural resource costs (cost-push) and physical constraints propagate through production networks and contribute to inflationary pressures. Finally, we analyse the interaction between cost shocks and price adjustment speeds (Scenario 2.b), showing how inflationary effects become more pronounced under conditions of rapid price flexibility. In land-scarcity experiments, we also allow for heterogeneous land-pricing behaviours and use the GLORIA dataset.

[5] The data are available on the website of the Centre for Industry and Competitiveness (GIC) at UFRJ: https://www.ie.ufrj.br/gic-gicdata.html .

Baseline scenario

Firms operate under moderate behavioural responsiveness, with the price adjustment speed (β^p) set to 1 and quantity adjustment speed (β^y) set to 3. These choices represent bounded rationality: firms update expectations and prices gradually in response to observed gaps rather than solving intertemporal maximisation. Prices evolve based on a cost-plus rule, where desired prices depend on wage costs, intermediate inputs, and an endogenous markup. The markup adjustment rule includes $\mu_1 = 0.65$, implying that firms adjust markups modestly as inventory levels deviate from targets.

Final demand is price-elastic, governed by $\eta = -1$, meaning that higher prices reduce consumption with moderate intensity. This behavioural parameter is designed to capture a balance between responsiveness and stability in firm decision-making.

Initial conditions are calibrated using the 2021 Brazilian Input–Output Table, aggregated to 42 sectors. Output ($\mathbf{x}$) is given by the Leontief inverse multiplied by the final demand, while expected output ($\mathbf{x^e}$) is set equal to $\mathbf{Ly_0}$, indicating alignment between firm expectations and realised demand at baseline. Inventories ($\mathbf{v}$) are initialised at 10% of steady-state output, a stylised assumption, and desired inventories ($\mathbf{v^d}$) are fixed at this same proportion to assure stability. The initial price vector ($\mathbf{p_0}$) is set to unity, normalising the consumer price index ($p^C = 1$) and ensuring that inflation and price changes are expressed in relative terms. Both inflation (π) and output growth (g) are zero at $t = 0$ as the system is in dynamic equilibrium at the outset.

Finally, GHG emissions are calculated using sectoral data from the Brazilian Institute of Applied Economics (IPEA), covering energy, waste, industrial processes, agriculture, and land-use change. For land use, we use total agricultural, livestock, and forestry land data from IBGE, distributed according to the GLORIA satellite accounts (Lenzen et al., 2017). While GHG emissions (due to their global rather than local impacts) do not trigger economic feedbacks in the model, land use explicitly demonstrates how resource depletion and scarcity feed back into the system. Specifically, land scarcity increases land prices and constrains production.

Simulations are conducted over a five-year horizon with daily output resolution, allowing us to track the smooth endogenous evolution of the system. While results are reported at daily intervals, the model is formulated as a system of ordinary differential equations (ODEs) and solved in continuous time using the fourth-order Runge-Kutta method.[6]

Scenario 1. Final demand shock

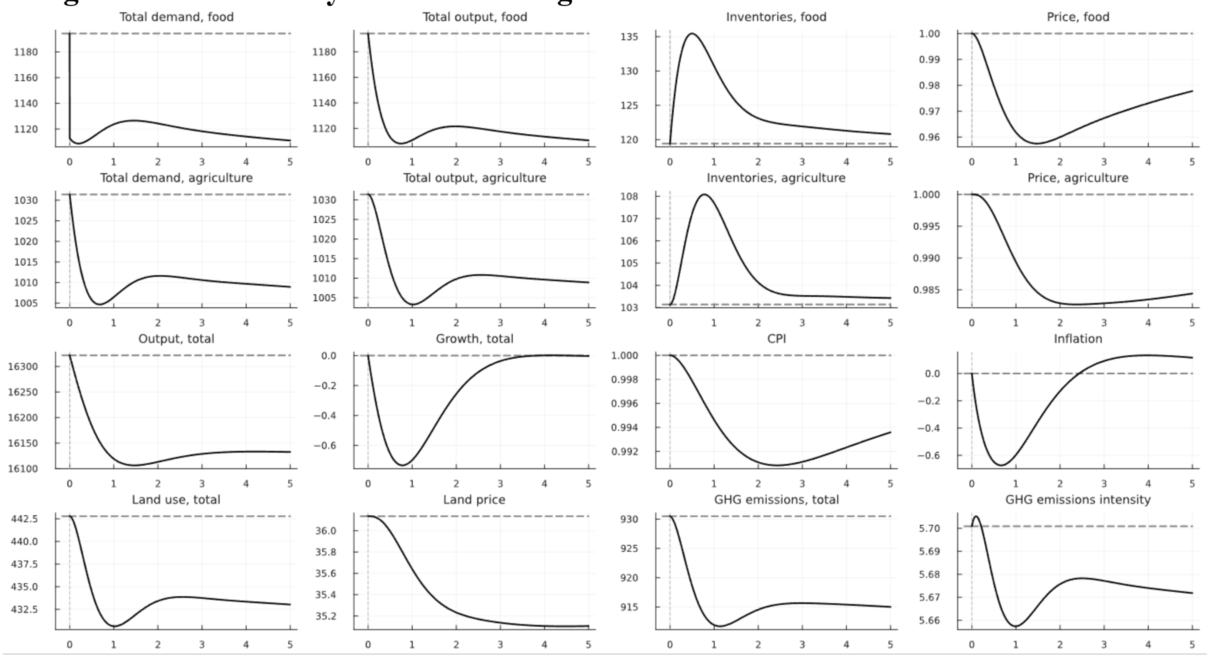
Figure 2 presents the baseline alongside the response to a 10% decrease in final demand in the food sector (Sector 1). The baseline is set as a horizontal line, and any deviation is in comparison with the baseline. Initially, the demand shock leads to a decrease in output in the food sector itself. However, because this adjustment is not instantaneous – due to lagged output decisions – inventories are consumed, and their levels drop below the desired level.

[6] The code is developed in Julia using ModelingToolkit.jl (v8.7) and is available upon request.

Due to strong input-output linkages, the agricultural sector is particularly affected. As the output of food decreases, the demand for agricultural products declines. Since inventory levels are higher than desired after the shock, the desired mark-up decreases in both sectors. Although not instantaneously, this leads to a decrease in relative prices and, consequently, an increase in final demand. However, this increase in final demand is not sufficient to compensate for the initial shock, and the economy reaches a different state compared to the baseline.

The decline in food demand has environmental impacts. First, total greenhouse gas (GHG) emissions decrease due to a reduction in overall production. This effect extends to GHG emission intensity, since agriculture plays a major role in national emissions. A structural shift toward less emissions-intensive industries thus lowers emissions per unit of output.

Figure 2. Economic dynamics following –10% final demand shock in the food sector



Dashed line: baseline scenario; solid line: shock in the food sector

The reduction in food demand also reduces land demand. As agricultural production declines, the sector's reliance on land as an ecosystem service diminishes. This reduction in land demand lowers land prices, which in turn reduces agricultural unit costs and, consequently, the price of agricultural products. Additionally, food prices also decline because land, while not directly used in food processing, is embodied in the sector's inputs.

Essentially, the adjustment mechanism unfolds in two main stages. Initially, the lack of demand is met through an accumulation of existing inventories, as firms cannot instantly adjust production. This triggers a deviation from target inventory levels, prompting firms to decrease production to consume stocks. Simultaneously, firms revise their expectations about future demand, reinforcing the downward adjustment in output.

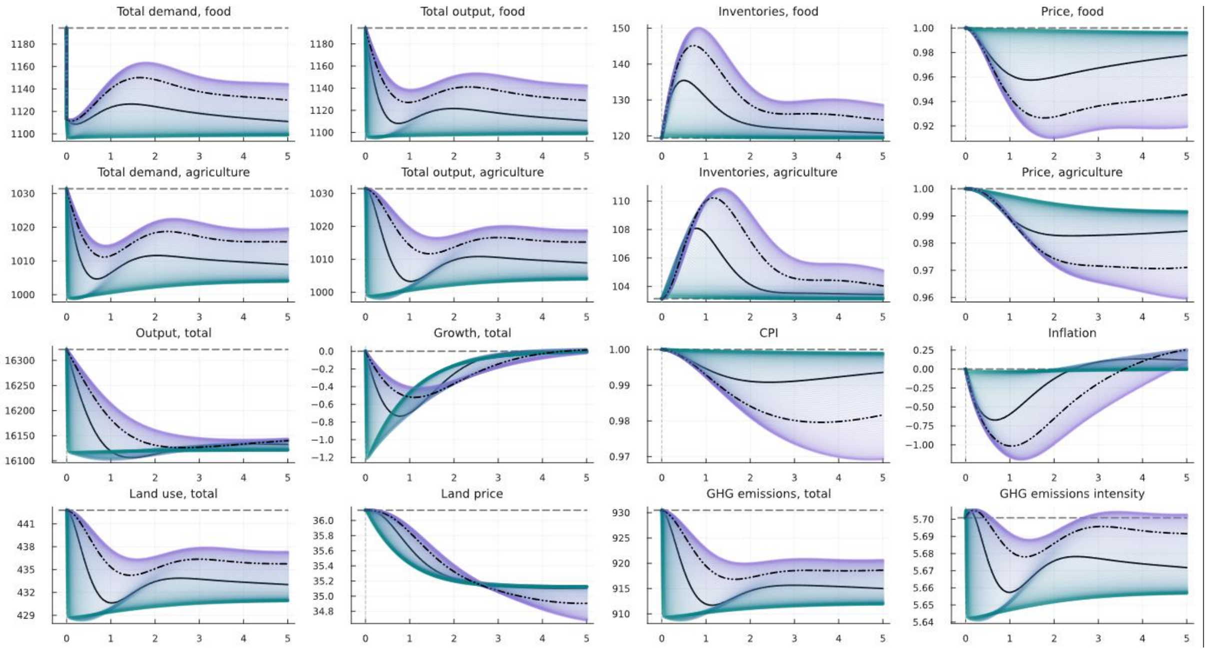
The second stage involves indirect effects, as the increase in food production generates additional intermediate demand for agricultural (as well as other) inputs. Owing to the Leontief production structure, where sectors rely on fixed proportions of inputs, the shock quickly spills over into upstream industries. As food producers require fewer agricultural inputs, agricultural demand drops in response, further modifying inventories and prices in that sector. This dynamic illustrates how even a localised demand shock can propagate widely through the production network.

Inventories play a central role in mediating these adjustments. Initially, they serve as a buffer, allowing firms to meet demand before production declines. As output decreases, inventory levels gradually return to target. The pace of this rebalancing is a behavioural outcome governed by β^y (bounded rationality), not by optimisation - anticipating the comparative results in Scenario 1b.

Scenario 1b: Testing different quantity adjustment speeds

Now we investigate how different values of the output adjustment parameter (β^y) affect the dynamics following a 10% negative demand shock in the food sector. We compare four distinct cases: (i) low expected demand adjustment responsiveness to actual demand (β^y = 0.5), (ii) moderate adjustment responsiveness ($\beta^y = 1$), (iii) high adjustment responsiveness ($\beta^y = 3$), and (iv) (almost) immediate responsiveness ($\beta^y = 365$).[7]

Figure 3. Varying quantity adjustment speed following a –10% shock in food demand



Dashed line: baseline scenario; solid line: shock in the food sector; dot-dashed line: low quantity adjustment speed ($\beta^y_{dot-dash}$ = 1); from purple to green: low to (close to) infinity quantity adjustment speed (β^y_{purple} = 0.5; β^y_{green} = 365)

When $\beta^y = 0.5$ (in purple), sectors revise their production plans in response to changing demand signals. This case can be seen as a special scenario where many producers interpret the final demand shock as temporary. As a result, the adjustment process operates predominantly through inventory dynamics. With a drop in demand, inventories accumulate to

[7] Annex A.4 presents heatmaps testing for different quantity and price adjustment speeds, and it shows that, in the case of a demand shock, price adjustment speed plays a minor role in determining output, even though it is important to determine inflation dynamics.

meet consumption, with levels increasing well beyond target. Since output responds mainly to the discrepancy between desired and actual inventories, recovery is gradual. This scenario promotes short-run output stability but at the cost of prolonged disequilibria, as sectors take time to adapt their supply to evolving market conditions. Recovery is sluggish, the effects of the shock persist well beyond the initial disturbance.

Increasing β^y to 1 (dot-dashed line) allows firms to begin adjusting their output expectations, albeit still slowly. In this setting, inventories still bear a significant burden of adjustment, but production begins to respond with a smaller lag. The recovery process is modestly faster than in the case discussed above, and the overall system begins to correct inventory imbalances more efficiently. However, the economy still exhibits inertia in its return to equilibrium, and the dynamics remain relatively smooth.

If $\beta^y = 3$ (solid line), firms respond to inventory gaps and demand signals more proactively. This can be seen as a scenario where firms adjust their expectations with a 4-month lag (the characteristic time is 1/3 of a year), which is consistent with some findings in the literature (Iyetomi et al., 2011). Output increases more quickly following the shock, reducing reliance on inventory depletion. This leads to a faster return to target inventory levels and improved alignment between supply and demand. In this scenario, the system becomes more sensitive to fluctuations: small shifts in expectations or demand can result in overshooting production levels.[8] This higher responsiveness reduces adjustment lags but introduces the risk of cyclical dynamics if expectations are not well anchored.

In the extreme case, β^y = 365, production adjusts (almost) instantaneously in response to perceived demand changes. This generates the fastest short-run correction, with inventories quickly restabilising and output rapidly rising to match the new demand level. This is the result of a typical demand shock in a Leontief quantity model, and it is a particular case where demand and output are always in equilibrium due to the capacity of firms to predict their demand.

Taken together, the simulations reveal that the speed of production adjustment is a key determinant of post-shock dynamics. Rigid expectations (low β^y) delay the recovery and place undue pressure on inventories, while excessively flexible production (high β^y) leads to an immediate equilibrium – the Leontief quantity model's particular case. The results suggest that intermediate values of β^y (e.g., 3) offer a more balanced path, allowing for timely adjustment. This is also consistent with empirical findings that output is more volatile than demand due to firms' inventory management (Khan, 1992) – neither very low nor very high values for β^y provide this dynamic. These findings support the broader conclusion that moderate responses in quantity adjustment led to different dynamics than an immediate adjustment, and hence one needs to account for that when estimating the impact of a demand shock.

Scenario 2: Land productivity shock

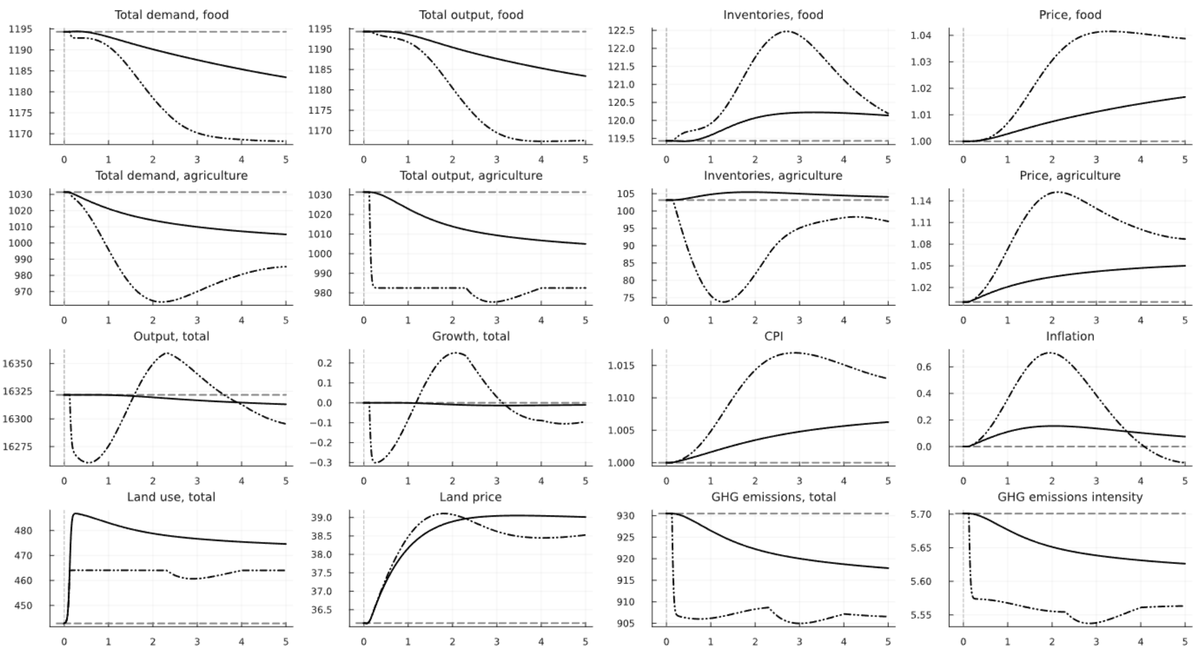
The second set of simulations examines the macroeconomic implications of a chronic decline in land productivity. This decline can lead to either classical cost-push inflation driven by the

[8] This is consistent with the business cycle literature on stockout-avoidance motive for inventory-holding (Kahn, 1992), where firms keep inventories on hand to avoid losing sales due to a lack of stock. It is also consistent with empirical evidence showing greater volatility in production than in demand (Lau, 1996).

agricultural sector (Sector 2) or supply constraints due to biophysical resource scarcity. Such shocks have gained prominence as the need to understand the consequences of climate-related disruptions has grown. These disruptions may be acute (intense but temporary) or chronic (gradual but permanent). The analytical framework presented here demonstrates how biophysical shocks translate into output losses and inflationary pressures.

In this experiment, we introduce a 10% decrease in land productivity (yield loss) and analyse how this shock propagates through the environmental input–output network. The shock initially affects the agricultural sector – the primary user of land – and subsequently impacts its upstream and downstream sectors, with a particular focus on food production (Sector 1).

Figure 4. Economic dynamics following a –10% shock on land productivity (yield losses)



Dashed line: baseline scenario; solid line: shock in the land productivity without biophysical constraints; dot-dashed line: shock in the land productivity with biophysical constraints (land availability)

The results in the solid line (without biophysical constraints) show that the decrease in land productivity directly leads to higher land use and hence to higher land prices, which are then passed on to agriculture producers and then to food processors that rely heavily on agricultural goods as intermediate inputs. This intersectoral cost transmission induces a secondary increase in the price of food products, illustrating the structural interconnectedness embedded in the production network. These cost increases are not absorbed entirely by producers; rather, they are partially shifted to consumers via higher final goods prices. land-rent responses to scarcity differ by context (sector/region), as the rent sensitivity and scarcity weights can vary. This allows stronger pass-through in land-intensive or tighter markets, and milder responses where institutional or biophysical conditions dampen rent changes.

This scarcity-induced price increase also has a dual effect. On one hand, it allows sectors to preserve or expand their profit margins in the face of rising input costs. On the other hand, the resulting increase in consumer prices dampens aggregate demand, particularly in price-sensitive sectors. As demand contracts, production slows, inventories accumulate, and the economy experiences a general decline in output and growth.

Moreover, the behaviour of inventories reinforces these dynamics. As food producers reduce output in response to weaker demand, agricultural input demand also contracts, causing inventories in agriculture to accumulate. This inventory build-up acts as a temporary buffer but also signals excess capacity, contributing to a deceleration in production and moderating further price increases.

The alternative results, shown by the dot-dashed line, illustrate how resource constraints on production can lead to fundamentally different adjustment processes. In the scenario of land productivity losses, aspirational production falls short of demand because the required resources are unavailable. In a general equilibrium framework, prices would rise to either reduce demand or induce the substitution of land with other forms of capital, effectively eliminating resource scarcity as a binding constraint.

In contrast, within the traverse model developed here, actual production fails to meet intended levels, and real constraints emerge, giving rise to a distinct dynamic adjustment. This aligns with the strong sustainability approach, which posits that natural, physical, and human capital are not a priori substitutes (Yilmaz and Godin, 2024). Consequently, environmental services play a definitive role in shaping economic dynamics.

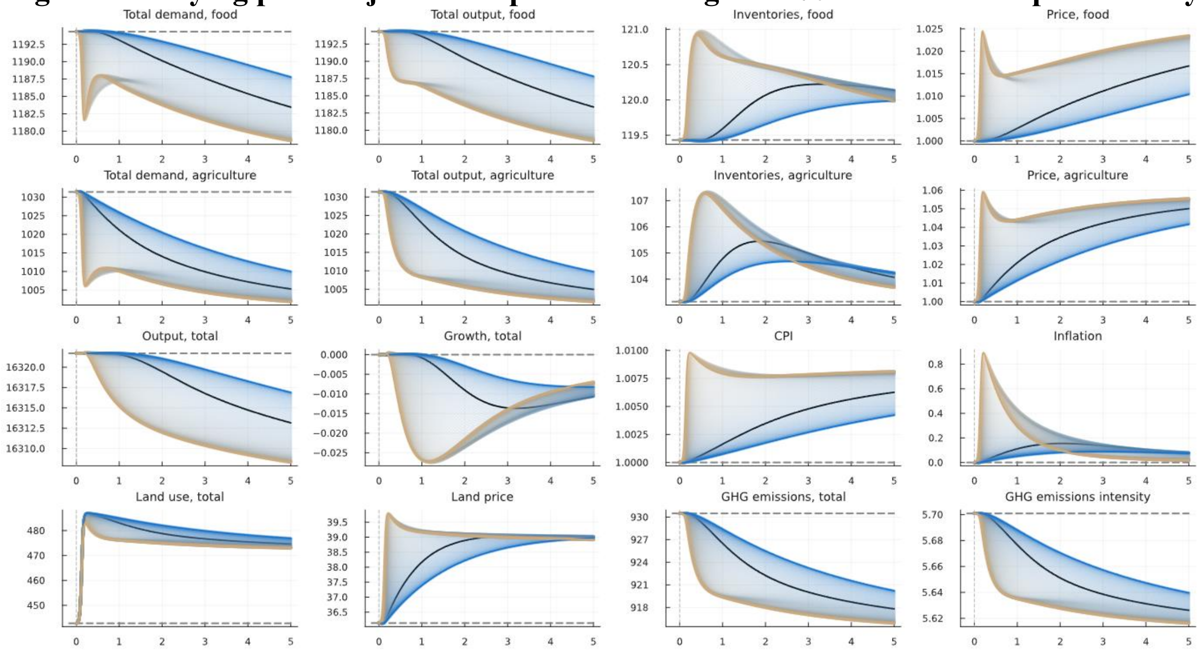
As illustrated by the dot-dashed line, the land productivity shock initially increases land use, but this expansion is constrained by biophysical limits. Without supply constraints, inventories would accumulate as prices rise and demand falls. However, in this scenario, despite a faster increase in prices, inventories deplete because production is constrained and unable to meet demand. The resulting inventory shortage feeds back into prices through markup dynamics, gradually reducing demand. This adjustment process does not occur immediately. Over time, demand declines sufficiently to fall below production levels, allowing inventories to begin recovering. As shown in the figure, however, this recovery may take many months – or even years – to materialise. Importantly, context-specific rent dynamics shape the magnitude and timing of price hikes and downstream effects – an empirical channel the model makes explicit.

The rapid increase in agricultural prices leads to higher food prices due to their close sectoral interlinkages. This mechanism reinforces the adjustment dynamics, as processed food is primarily destined for final demand, where substitution occurs. As a result, the overall economic dynamics become significantly more unstable. Initially, the frustration of aspirational production causes a decline in total output. However, as demand shifts from food to other goods and services – driven by changes in relative prices – other industries experience a positive shock. Total output then begins to recover in an inflationary environment. Depending on which sectors absorb this demand and their sectoral linkages, they may offset the decline in food demand.

Scenario 2b: Testing different price adjustment speeds

To deepen our understanding of cost-push inflation and the traverse dynamics after a negative shock on resource productivity, we examine how the speed of price adjustment (β^p) influences the transmission and macroeconomic effects. Figure 5 presents these results for the scenario without constraint in resource availability. Interpreting β^p behaviourally, higher values represent faster attention and repricing under bounded rationality (lower menu/coordination costs), whereas lower values represent stickiness and partial adjustment.

Figure 5. Varying price adjustment speeds following a –10% shock on land productivity



Dashed line: baseline scenario; solid line: shock in the land productivity; from blue to yellow: very low to very high price adjustment speed (β^p_{blue} = 0.5; β^p_{yellow} = 365)

When price adjustments are highly flexible (e.g., $\beta^p = 365$, in yellow), firms in both the agricultural and food sectors pass on cost increases to consumers almost immediately. This leads to rapid and pronounced inflation, as final goods prices rise sharply in response to higher input costs. Although this quick response allows firms to maintain margins, it significantly suppresses consumer demand, particularly in the food sector. The combination of rising prices and falling demand results in an abrupt contraction in output, and inventories accumulate as unsold goods build up along the supply chain. These dynamics can trigger further reductions in production and induce inflationary-recessionary cycles, where the economy simultaneously faces higher prices and lower activity.

In contrast, when price adjustments are more rigid (e.g., $\beta^p = 0.5$, in blue), the inflationary impact of the markup shock unfolds more gradually. In these scenarios, the characteristic time of price adjustment is two years ($\beta^p = 0.5$) or one year ($\beta^p = 1$, solid line), which is consistent with many findings in the literature on sticky prices, despite the substantial heterogeneity across goods (Klenow and Malin, 2010). Firms initially absorb part of the increased costs through reduced margins or temporary inventory drawdowns. As a result, price increases are more subdued, and the contraction in demand is less severe. While the economy still experiences a decline in output, the process is more controlled and less volatile, allowing for a smoother adjustment path and reducing the risk of overcorrection.

These findings underscore the critical role of price-setting behaviour in shaping macroeconomic responses to supply-side shocks. High pricing flexibility accelerates inflation transmission but can destabilise demand and output, whereas more gradual price adjustments moderate inflation at the cost of short-term margin compression. The value of β^p thus has significant implications for the persistence and intensity of inflationary episodes, particularly in economies where key sectors such as agriculture serve as foundational suppliers of inputs to broader production systems. Moreover, heterogeneous land-pricing contexts imply that identical β^p values can yield different inflation paths depending on local scarcity intensity and rent pass-through (Eqs. 11, 16).

Taken together, Scenarios 2 and 2b highlight the importance of mark-up dynamics and behavioural adjustment speeds in the emergence and propagation of cost-push inflation. The results demonstrate that shocks originating in key upstream sectors can cascade through the economy, amplifying inflationary pressures and undermining output stability. These insights contribute to a broader understanding of how pricing behaviour and sectoral interdependencies interact to shape the macroeconomic impact of supply shocks.

Table 4: Summary of Simulation Scenarios

Scenario	Description	Key Mechanisms Analysed
Scenario 1	10% decrease in final demand for the food sector.	Examines how demand shocks propagate through input-output linkages, affecting total production, inventories, and prices in both food and agriculture.
Scenario 1b	From $\beta^y = 0.5$ (low adjustment in production) to $\beta^y = 365$: (quasi-instantaneous adjustment in production)	Evaluates how different output adjustment speeds impact economic equilibrium convergence, contrasting slow, inventory-driven responses with different production shifts.
Scenario 2	10% decrease in land productivity with and without resource constraints	Investigates how cost-push inflation (both through land price and inventory depletion) spreads through higher agricultural prices, affecting food prices, total output, and inflationary pressures.
Scenario 2b	From $\beta^p = 0.5$ (slow adjustment in actual prices) to $\beta^y = 365$: (quasi-instantaneous adjustment in actual prices)	Evaluates how different pricing regimes mediate the inflationary impact of cost shocks. Fast price adjustments transmit inflation rapidly but increase volatility.

5. Conclusion

This paper develops a traverse extension of the traditional Input–Output (I-O) framework by incorporating endogenous price and quantity adjustment mechanisms in response to economic shocks. Departing from standard equilibrium-based approaches, the model introduces out-of-equilibrium dynamics driven by inventory fluctuations, behavioural pricing rules, biophysical constraints and sectoral interdependencies. Calibrated to Brazil's 2021 I-O data, the simulation results offer new insights into how demand disturbances, pricing rigidities, and cost-push shocks propagate across interconnected production networks.

A key contribution of this study lies in its explicit modelling of transition dynamics. By allowing for time-varying responses in prices, production and use of biophysical resources, the framework captures adjustment trajectories that static I-O models typically overlook. The findings show that the speed of adjustment – in both prices and quantities – plays a critical role in shaping macroeconomic outcomes.

Price rigidity delays inflationary pressures, whereas high price flexibility accelerates cost pass-through but increases output volatility. Similarly, slow production adjustments hinder recovery and prolong disequilibrium, while excessively rapid responses may lead to fast-reaching quantity equilibrium (close to the Leontief quantity model). These dynamics underscore important trade-offs between stability and responsiveness, with direct implications for inflation management, production planning, and sectoral or resource use policy coordination. A central innovation is to embed ecological constraints – most notably land scarcity – directly into both production and pricing equations (via resource/land services, rents, and scarcity-sensitive mark-ups). Scarcity thus affects behavioural adjustments (quantities, prices, and their speeds), not merely technical capacities.

Importantly, this model bridges the classical divide in Leontief's framework by integrating the quantity and price models into a unified, dynamic structure. In doing so, it enables a more realistic representation of economic behaviour under disequilibrium, where both production and prices adjust gradually in response to shocks. This joint modelling approach allows for the examination of feedback loops between inventory cycles, mark-up dynamics, environmental pressures and dependence, and demand elasticities, offering a more comprehensive understanding of how shocks unfold over time and how different behavioural parameters affect the trajectory of adjustment. In this sense, the model serves as a powerful analytical tool for studying *traverse disequilibrium*, helping to reveal the diverse paths economies may follow depending on their structural characteristics and behavioural flexibilities. The framework builds a bridge between environmental economics and behavioural/evolutionary economics, showing how ecological scarcity transmits through cost-plus–mark-up pricing and boundedly rational adjustment, and how heterogeneous land-pricing contexts generate diverse inflation paths.

Nonetheless, the framework has several limitations. It adopts simplified behavioural assumptions, particularly in relation to expectation formation and inventory targets. The model does not yet include financial frictions, labour market dynamics, or capital accumulation – key elements for analysing long-term growth and structural transformation. Instead, its focus is on short- to medium-term dynamics, making it less suited for studying technological changes. Moreover, the analysis is conducted at the sectoral level, abstracting from firm-level heterogeneity and micro-level adjustment mechanisms that shape price-setting power, investment behaviour, and competitive dynamics.

Future research should address these limitations by integrating financial and labour market modules, introducing endogenous investment and capacity constraints, and modelling heterogeneous agents within sectors. The inclusion of credit channels, wage dynamics, and capital formation would significantly improve the model's capacity to simulate more complex macro-financial interactions. Furthermore, extending the framework to include country comparisons would offer a broader understanding of how structural characteristics, such as openness, supply chain complexity, and institutional context, influence economic resilience and adjustment speed.

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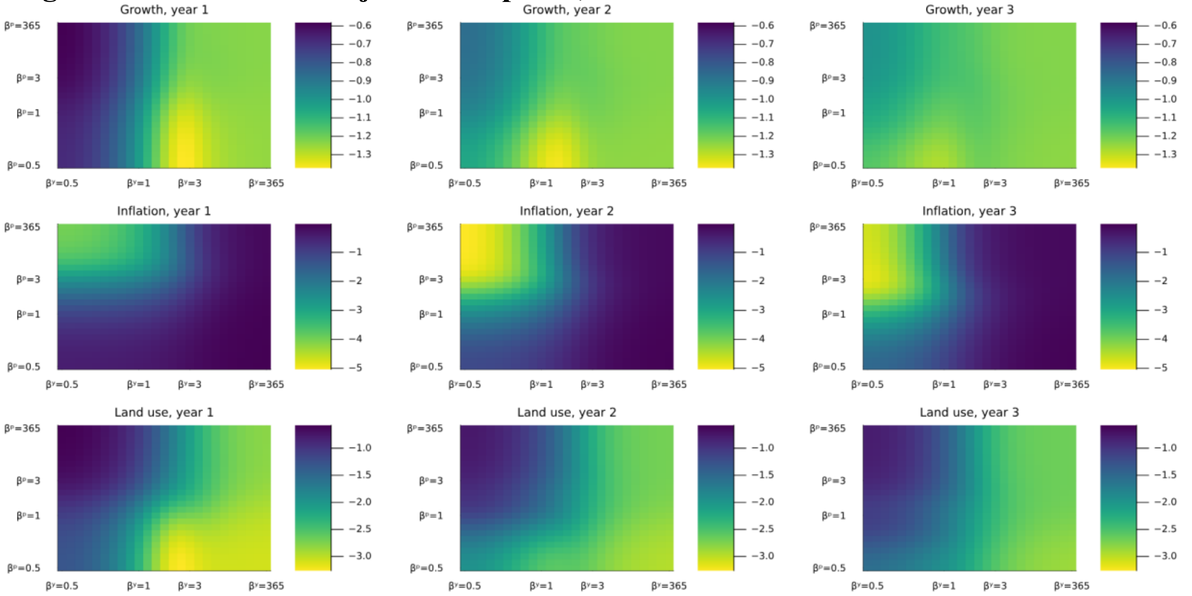
Table A.1: Parameters for Model Calibration

Variable	Symbol	Description	Value/Source
		Initial Conditions	
Sectoral Output	$\mathbf{y}$	Observed production levels across economic sectors	IO Matrix
Final Demand	$\mathbf{y^f}$	Disaggregated into household consumption, government spending, investment, and trade	IO Matrix
Inventories	$\mathbf{v}$	Estimated based on observed stock variations relative to output	IO Matrix
Land price	p^l	Based on Simet/Incra and S&P Global Commodity Insights	R$ 2500/ha/y
		Parameters	
Technical Coefficients	$\mathbf{A}$	Input requirements per unit of output (from I-O matrix)	IO Matrix
Wage Costs	$\mathbf{w}$	Extracted from sectoral value-added data, used in production cost calculations	IO Matrix
Production Adjustment Speed	β^y	Speed at which sectors revise expected production levels	3
Price Adjustment Speed	β^p	Speed at which sectors revise prices in response to cost changes	1
Price Elasticity	η	Sensitivity of demand to price changes	−1
GHG emission intensity	$\mathbf{q^c}$	Extracted from sectoral emission database by energy, waste, agriculture and industrial use	IPEA
Land use intensity	$\mathbf{q^l}$	Extracted from GLORIA database and adjusted based on total land use (IBGE)	GLORIA
Land price elasticity	λ_1	Land price sensitivity to demand	1
Markup sensitivity	μ_1	Responsiveness of markups to inventory deviations from desired level	0.65
Consumer Price Index	p^c	Weighted average of sectoral base prices, aligning with aggregate inflation trends	1 (base year)

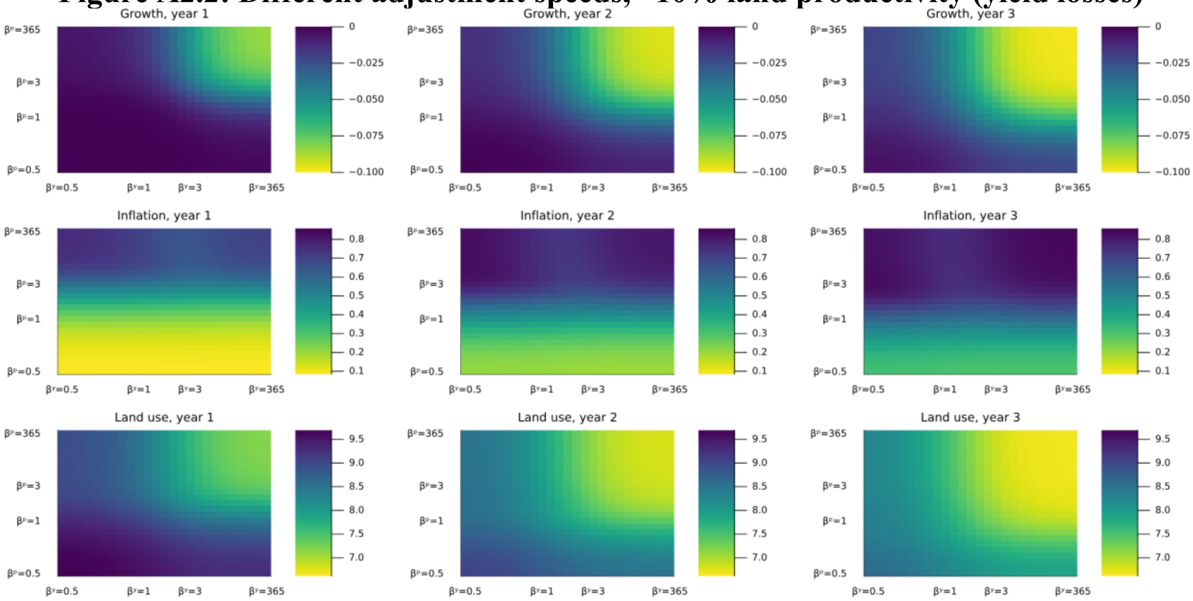
Annex A2. Testing for different price and quantity adjustment speeds

Figure A2.1: Different adjustment speeds, –10% final demand shock in the food sector



Authors' elaboration; the figure shows that after a demand shock, growth and land use are not very sensitive to price adjustment speed, but inflation is – a low adjustment speed prevents inflation.

Figure A2.2: Different adjustment speeds, –10% land productivity (yield losses)



Authors' elaboration; the figure shows that after a yield loss shock, inflation is not very sensitive to quantity adjustment speed, but growth and land use are – a low adjustment speed prevents a reduction in output and leads to higher land use.