Hoarding, Stockouts, and Commodity Futures Prices During the Pandemic

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Abstract

During the pandemic, processed foods and other essential products frequently ran out at retail stores while disruptions in production and the supply chain lead to weakness in their underlying spot commodities markets causing negatively related consumer and producer price inflation. In addition, the correlation between retail stockouts of processed goods and the futures basis of the raw material input commodities was positive for most of 2020, while the theory of storage predicts a negative relationship. To understand these findings, we provide a theoretical model in which severe labor shortages lead to contango in the futures market for raw materials, which in turn, influences consumers' hoarding decisions. Our model exhibits an efficient 'no hoarding' equilibrium as well as an inefficient 'hoarding equilibrium', depending on the commodity futures' slope. The hoarding equilibrium can arise in a period of dropping wholesale prices, and exhibits rising consumer prices.

Key Words: Retail stockouts; commodity futures' basis; contango; hoarding; global games

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1 Introduction

The global COVID-19 pandemic had a profound economic impact, causing significant disruptions in the production and supply of goods to consumers. These disruptions escalated operational costs for businesses, making it challenging for retailers to effectively manage inventories. Consequently, consumers faced widespread stockouts and associated costs across various goods, ranging from essential items like toilet paper to electronics thereby exerting inflationary pressures. Amidst these disruptions, our empirical evidence reveals an unexpected positive relationship between the frequency of stockouts and the slope of futures curves for underlying commodities during the pandemic. This relationship is at odds with the theory of storage, the workhorse of futures pricing models for several decades now. Moreover, the pandemic-induced production disruptions led to a divergence between consumer and producer prices, contrary to historical trends where consumer prices typically lag increases in producer prices. To provide intuition for the emergence of both anomalous relationships, we provide a theoretical model in which the prices in the futures market for raw materials influences consumers hoarding decisions.

The commodity storage literature has always struggled to provide evidence of stockouts at a macro level. In a pioneering paper, Cavallo and Kryvtsov (2021) provides a direct, high-frequency measure of consumer product shortages during the pandemic by analyzing data from the websites of 70 major retailers across seven countries. In this paper, we examine the stockout data presented in their paper and establish correlations with futures prices in the commodities market.

We measure the slope of the commodities' futures curve as the weak relative basis, which is the proportional difference between the discounted value of the futures price and the current spot price (see e.g. Litzenberger and Rabinowitz (1995)). When this difference is positive (negative), we say the futures market is in weak contango (backwardation). The theory of storage (Kaldor (1939); Working (1948)) implies that the futures relative basis is negatively correlated to stockouts: in periods of strong demand, current inventory runs out, and spot prices rise above futures prices (backwardation). However, contrary to what the theory of storage predicts, we find that the correlation between the commodities futures basis and incidence of retail stockouts was positive for a large part of 2020 (after March). The correlation was negative prior to March 2020 and then again in

2021, suggesting that the pandemic period indeed displayed pathological aspects on the relationship between wholesale and retail markets.

Further, during the initial months of the COVID-19 pandemic, notably in May and June 2020, consumer food prices surged while producer prices declined, diverging from their typical relationship. This anomaly persisted throughout the sample period from November 2019 to May 2021, marking a significant departure from historical patterns. We show that the decline in producer food prices during the pandemic can be attributed to labor shortages precipitated by the crisis, disrupting both the production and transportation of processed goods, and resulting in decreased demand for commodities. At the same time, supply chain disruptions and increased demand due to hoarding behavior fuelled surging consumer prices.

Our paper aims to explain these anomalous relationships during the pandemic. We first note that the stockouts are in retail products whereas the futures basis pertains to the wholesale commodity markets. We argue that the futures relative basis contains information about inter-temporal resource prices, which has important implications for consumers' decisions about hoarding important commodities. During the pandemic, the retailers were constrained in sourcing inventory due to production and supply chain issues. The inventory outcomes were then largely decided by consumer behaviour, whose hoarding decisions were in turn influenced by information about future prices and the behaviour of other consumers around them.

To explain the behaviour of consumers during the pandemic, we develop a model of a hoarding game, where a continuum of consumers decide whether to hoard a commodity for future consumption. The model considers a retailer who carries a limited inventory the commodity. The retailer sources the commodity from the producer at a cost which is reflective of the wholesale commodity spot prices in the market (or equivalently, the producer prices). The consumers" choice to store the commodity or not, depends on their expectations of the future retail prices, which comprises both the future wholesale commodity price and the possible supply chain costs in sourcing the commodity.

Customers are served sequentially, and if the customers in aggregate demand more quantity of the commodity than the inventory carried by the retailer, the retailer faces a stockout and some customers remain unserved. In the event of a stockout, the retailer incurs stockout costs that represent supply chain costs for immediately replenishing inventory while carrying a backlog of unfilled orders (as in Arrow, Karlin, Scarf, Beckmann, Gessford, and Muth (1958), Kahn (1992) and Krane (1994)). Building on this, we assume that the stockout costs are a function of the number of customers that remain unserved. Retail prices are assumed sticky (see Clark et al. (1995), Nakamura (2008) and Eichenbaum, Jaimovich, Rebelo, and Smith (2014), among others), so that the retailer passes on the stockout costs to the consumer in the forthcoming period.

Our results describe the behaviour of agents depending on the difference between the expected price of the wholesale commodity, given their information and the current price (equivalently, the expected price increase)

(i) If the expected price increase is sufficiently negative, no agent hoards due to costly hoarding with insufficient future price benefits (ii) If the expected price increase is positive, all agents hoard to benefit from future price increases (iii) For an expected increase between zero and a negative threshold, both equilibria obtain based on agents' hoarding expectations. If all agents believe that others will hoard, then it is in their interest to hoard as well. Conversely, if all agents believe that others will not hoard, then it is in their interest not to hoard.

The no-hoarding equilibrium is efficient, as it avoids the additional cost of stockouts. However, the hoarding equilibrium can arise due to self-fulfilling higher-order beliefs, similar to the sunspot or bank run equilibrium in Diamond and Dybvig (1983). We argue that the futures basis provide the consumers a signal of the future prices of the wholesale commodity. Based on the expectation of the prices in the next period and his beliefs about other consumers' expectations, a consumer decides to whether to hoard a particular commodity or not. Using the global games equilibrium selection methodology (as in Morris and Shin (2001), Goldstein and Pauzner (2005)) we arrive at a unique threshold futures price of the commodity, such that beyond the threshold, consumers hoard and below the threshold they do not. We therefore provide a new link between the information in commodity futures' basis and the probability that a constrained retailer faces stockouts.

To understand fluctuation in the futures curve for commodities, we model the production by competitive wholesalers during normal times and pandemics. The wholesalers produce processed goods each period using labor and a raw material commodity. Labor supply is reduced during pandemics, due to stay-at-home workforce unavailability. We consider two states of the world: normal and pandemic, with a simple Markov chain that governs the transitions between these states. The firm minimizes production costs with fixed wages and a commodity price that exhibits an upward-sloping supply curve. Due to lower demand, commodity prices are lower during pandemics, and the commodity futures slope is positive (contango) as the market expects a recovery in commodity prices when normal production resumes. Conversely, the commodity futures curve is backwardated in normal times.

Retailers and consumers shape their expectations of future producer prices based on the commodity futures slope. Hindered by reduced production from supply chain disruptions and stay-at-home restrictions, retailers face challenges in fulfilling higher consumer demand. Simultaneously, consumers, anticipating rising production costs, hoard the retail commodity. This hoarding behavior, influenced by both future price expectations and the actions of other consumers, leads to retail stockouts and elevated retail prices.

We link our model to inflation in consumer prices. We break up consumer inflation has two components: an input cost inflation due to the cost of raw materials (or, producer price inflation), and a supply-chain led inflation due to stockouts, which in turn depends on the hoarding behavior of agents. When all agents hoard, this component of inflation is positive and adds to the input cost inflation, resulting in a higher total inflation (or, consumer price inflation). Thus, the hoarding behavior of consumers affects the retail price of the commodity in the second period through the potential for stockout costs. This leads to a sharp spike in consumer price inflation, despite constant demand and falling producer prices.While historically, consumer price changes occurred after producer price changes, and maintained the same sign, the first few months of the pandemic witnessed a divergence. Producer prices fell while consumer prices rose. Our model therefore describes the divergence between consumer price inflation and producer price inflation during the pandemic.

1.1 Relation to Literature

Our paper contributes to the literature on the economic effects of the Covid-19 pandemic in several ways. Firstly, it highlights the crucial role of supply chain costs, particularly stockout costs, in influencing hoarding behavior and inflation. Arrow, Karlin, Scarf, Beckmann, Gessford, and Muth (1958) distinguished between holding inventory costs and those incurred when a firm's supply falls short of meeting current demand, resulting in a stockout. Building on this, Kahn (1992) and Krane (1994) explain how these costs contribute to industry output variability surpassing that of sales or demand. Our paper studies the reverse impact: elevated stockout costs transferred to consumers in the subsequent period, drive hoarding that fuels consumer price inflation. This aligns with the findings of Cavallo and Kryvtsov (2023), who link unexpected product shortages during the Covid-19 pandemic to inflationary fears.

Closely related to our research, Acharya, Crosignani, Eisert, and Eufinger (2023) provide empirical evidence establishing connections among supply-chain pressures, firm pricing power, and consumer inflation expectations during the post-pandemic inflation surge in the Euro area (see also Alessandria, Khan, Khederlarian, Mix, and Ruhl (2023) and Kalemli-Ozcan, Silva, Yildirim, and di Giovanni (2022)). Their findings reveal that disruptions in the supply chain not only triggered inflation through a cost-push mechanism but also heightened consumer inflation expectations. Our paper goes further in developing the consumer price inflation that arises due to excess hoarding of processed goods by consumers.

This paper also addresses the delay in passing retail cost increases to consumers (or, "sticky prices"; e.g. .Clark et al. (1995), Nakamura (2008) , Eichenbaum, Jaimovich, Rebelo, and Smith (2014)). This delay has implications for hoarding, as demonstrated by Benabou (1989), illustrating how sticky prices induce anticipatory stockpiling following a cost shock. Our model reveals that hoarding behavior, even with fixed production costs, can trigger a self-fulfilling cascade of stockout costs due to 'sunspot behavior' among consumers. In this context, our work aligns closely with Hansman, Hong, De Paula, and Singh (2020) who quantify how sticky prices exacerbate hoarding for personal use by analyzing data from the 2008 Global Rice Crisis, driven by an Indian ban on raw rice exports.

Our study develops the concept of 'sunspot equilibria,' extensively explored in bank run scenarios (Diamond and Dybvig (1983); see Allen, Carletti, and Gu (2008) for a recent exposition), to encompass retail inventory and consumer dynamics. Retailer stockouts induce queuing among consumers, analogous to banks facing bankruptcy, incurring direct costs for retailers. Complementarity in actions drives the emergence of 'good' and

’bad’ equilibria: consumers queue if they expect others to, and vice versa. Anticipated producer price increases drive consumer actions, akin to the fundamental variable in Diamond and Dybvig (1983)’s model extended by Goldstein and Pauzner (2005). When futures markets are in contango, queuing dominates, whereas when they are sufficiently backwardated, consumers refrain from queuing and hoarding. Intermediate scenarios could result in both queuing and non-queuing as equilibria, determined by consumers’ beliefs. Using the global games approach (Carlsson and Van Damme (1993), Morris and Shin (2001) and Goldstein and Pauzner (2005)), we establish unique thresholds for commodity price increases that influence queuing and hoarding behavior.

More recently, Hakenes (2021) also models hoarding in items (e.g., drugs, face masks, etc.), where agents are unsure whether they will need the item at a future date (similar to ’patient’ and ’impatient’ depositors in Diamond and Dybvig (1983)). In contrast, in our model, consumers all consume the same amount of the product in each period, and hoarding behavior is due to cost pressures induced by stockouts rather than scarcity. Furthermore, we link wholesale prices in commodity markets to retail behavior and illustrate how hoarding can strain the supply chain, leading to higher retail prices. In this respect, our paper is related to the empirical literature that analyzes the impact of underlying commodity prices and supply chain constraints on retail prices.[1]

Our paper intersects with the literature on consumer inflation expectations. Consumers often derive signals about inflation from regularly observed “easy-to-collect“ input prices, notably oil and food prices (D’Acunto, Malmendier, Ospina, and Weber (2019); Cavallo, Cruces, and Perez-Truglia (2017); Coibion, Gorodnichenko, and Weber (2022); Harris, Kasman, Shapiro, and West (2009); Wong (2015)). Examining U.S. households

[1] Carrière-Swallow, Deb, Furceri, Jiménez, and Ostry (2023) and Jiménez-Rodríguez and Morales-Zumaquero (2022) examine the impact of global shipping costs and commodity prices on domestic prices and inflation expectations. Benigno, Di Giovanni, Groen, and Noble (2022) propose an index to measure global supply-chain pressures and their effects on inflation. U.S.-focused research by Isaacson and Rubinton (2023), Ball, Leigh, and Mishra (2022), Bernanke and Blanchard (2023) and Comin, Johnson, and Jones (2023) explore various factors, such as shipping costs, import prices, labor supply constraints, and capacity limitations, and their contribution to retail price increases. In the euro area, Finck and Tillmann (2022), Kuehl, Capolongo, and Skovorodov (2022), Celasun, Hansen, Mineshima, Spector, and Zhou (2022) and Binici, Centorrino, Cevik, and Gwon (2022) investigate the impact of global supply-chain shocks, supply bottlenecks, and global factors on inflation in Europe.

during the pandemic, Coibion, Gorodnichenko, and Weber (2022) suggests that supply-side frictions during the pandemic influenced both inflation experiences and expectations, particularly across demographics. Our paper establishes hoarding behavior driven by stockout costs as a self-fulfilling factor in inflation dynamics. Further, we provide a link between futures commodity prices and inflation expectations, as described below.

The most popular driver of the futures slope is inventory, as modeled in *theory of storage*, with important extensions by Deaton and Laroque (1992), Williams and Wright (1991), and Routledge, Seppi, and Spatt (2000). In our model, consumers use futures commodity prices as signals to determine whether to queue and store commodities. This behavior yields an unexpected result: while storage theory predicts stockouts to be associated with backwardation in commodity futures slope, we show that stockouts during the Covid-19 pandemic correlated with contangos in the futures market. Another explanation for the futures slope dynamics is frictions in the production process (see Carlson, Khokher, and Titman (2007) and Kogan, Livdan, and Yaron (2009)). David (2019) shows that in addition to these two channels, upstream investments by producing firms affects the futures slope for oil. This paper provides a new driver, which is a combination of supply disruptions and hoarding behavior by households in response to these disruptions.

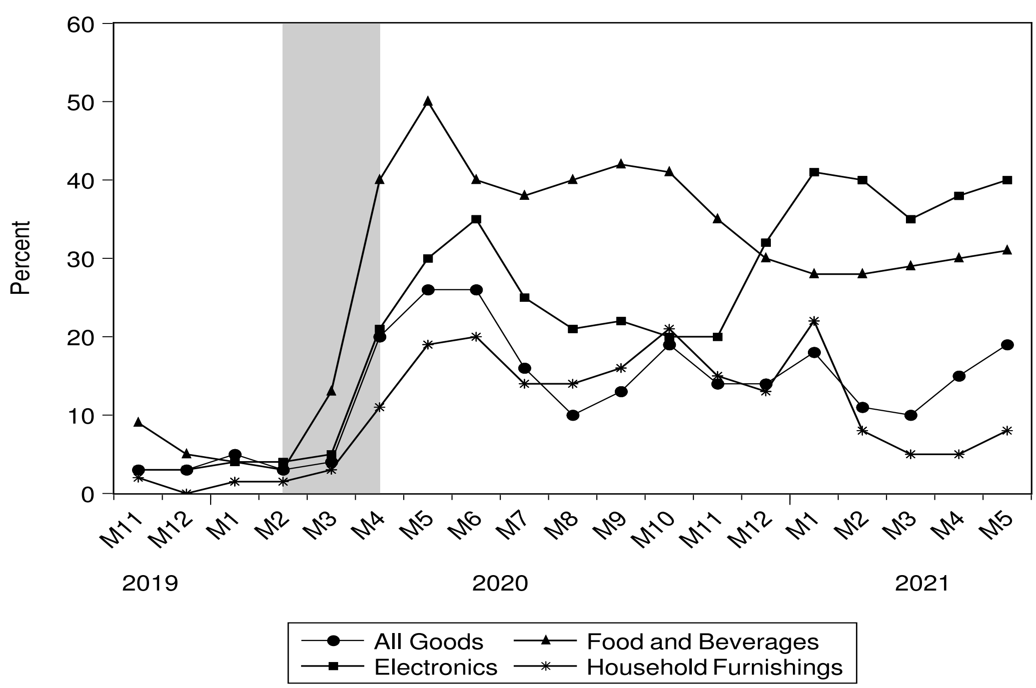
Finally, our paper complements studies on the empirical properties of bank runs (see, e.g. Iyer and Puri (2020) and Schmidt, Timmermann, and Wermers (2017)). Modeling runs on food and essential retail products, our paper draws attention to the essential fragility of these markets, akin to the financial system.

2 Empirical findings on retail stockouts and commodity prices during the pandemic

We will start by examining the occurrence of stockouts across various retail sectors, as depicted in Figure 1. The data presented in this figure is reconstructed from Cavallo and Kryvtsov (2021), who measured stockouts using the *PriceStats* database. PriceStats is a private firm associated with the *Billion Prices Project*, and their data cover stockouts in 70 retailers across seven countries, namely Canada, China, France, Germany, Japan, Spain, and the United States. The sample period is from November 2019 to May 2021.

Figure 1 visualizes the proportion of all products experiencing stockouts, as well as those in food and beverages, electronics, and household furnishings. Prior to the pandemic, around 5% of all products were affected by stockouts. However, this figure surged significantly, surpassing 25% in early May 2020. Although there was a partial recovery during the summer of 2020, stockouts climbed again, there were at least two more waves of stockouts in late 2020 and early 2021. Food and beverage products had the most stockouts (50 percent) in May 2020, and this proportion remained above 30 percent, when our series ended in May 2021. As stockouts for most products normalized into 2021, in electronics, stockouts kept increasing and in May 2021 were at their highest level at about 40 percent.

Figure 1: Stockouts in Retail Products (2019:11-2021:5)



This figure plots the timeseries of retail stockouts as measured by Cavallo and Kryvtsov (2021). The shaded area denotes the NBER-dated recession.

Next, we develop the relationship between the slope of commodity futures and stockouts. We use the weak relative basis (discounted futures price/spot price - 1) for various commodities. The stockouts that we consider are in the following retail products: food and beverages, electronics, and household furnishings. The retail products require multiple input commodities, and we attempt to provide a broad set of commodities for each retail product sector for which we can find futures prices. Appendix A provides a detailed description of the construction and sources for the series. In brief, food and beverages are linked to 21 commodity prices, twelve of which are agricultural, and eight are animal-based. Electronics are linked to ten commodities, which are mainly metals. Finally, household furnishings are linked to six commodities including cotton, lumber, and some metals like steel.

To parsimoniously capture the systematic component of the futures basis of the commodities for each retail product sector, we conduct a principal components analysis the futures basis, whose results are shown in Table 1. As seen, each sector has a major systematic component. The 1st PC accounts for 49 percent, 93 percent, and 73 percent of the variation in food and beverages, electronics, and household furnishings, respectively. To simplify our exposition, we focus on the relationship between the 1st PC of the basis of each retail products sector, and stockouts in that sector.

Table 1: Principal Components Analysis of Commodities Used for the Production of Household Products (2019:11 – 2021:5)

Product	Variance PC_1	Variance PC_2	Variance PC_3
Food and Beverages	0.490	0.252	0.115
Electronics	0.927	0.057	0.009
Household Furnishings	0.733	0.200	0.050

The input commodities for food (agricultural, and animal-based), electronics, and household furnishings are listed in Figures 5, 6, 7, and, 8, respectively (see Appendix 1). Food and beverage products are produced from both agricultural and animal-based commodities. The table shows the proportional variance explained by each principal component.

The 1st principal component of the basis of the three retail product sectors are shown in the top panels of Figure 2. As can be seen, in each sector, the 1st PC of the weak relative basis spiked upwards around May 2020, and then steadily declined until the end of the sample in May 2021. The middle panels show the proportional stockouts of each sector, which we have already commented on in our discussion of Figure 1. As mentioned, stockouts in each sector spiked rapidly in May 2020, and was followed by two other episodes of rising stockouts until early 2021. The bottom panels show the dynamic conditional correlation between the 1st PC of the futures basis and stockouts. The correlations are estimated using the Vech Garch (1,1) model of Bollerslev, Engle, and Woolridge (1988).[2] We discuss these next.

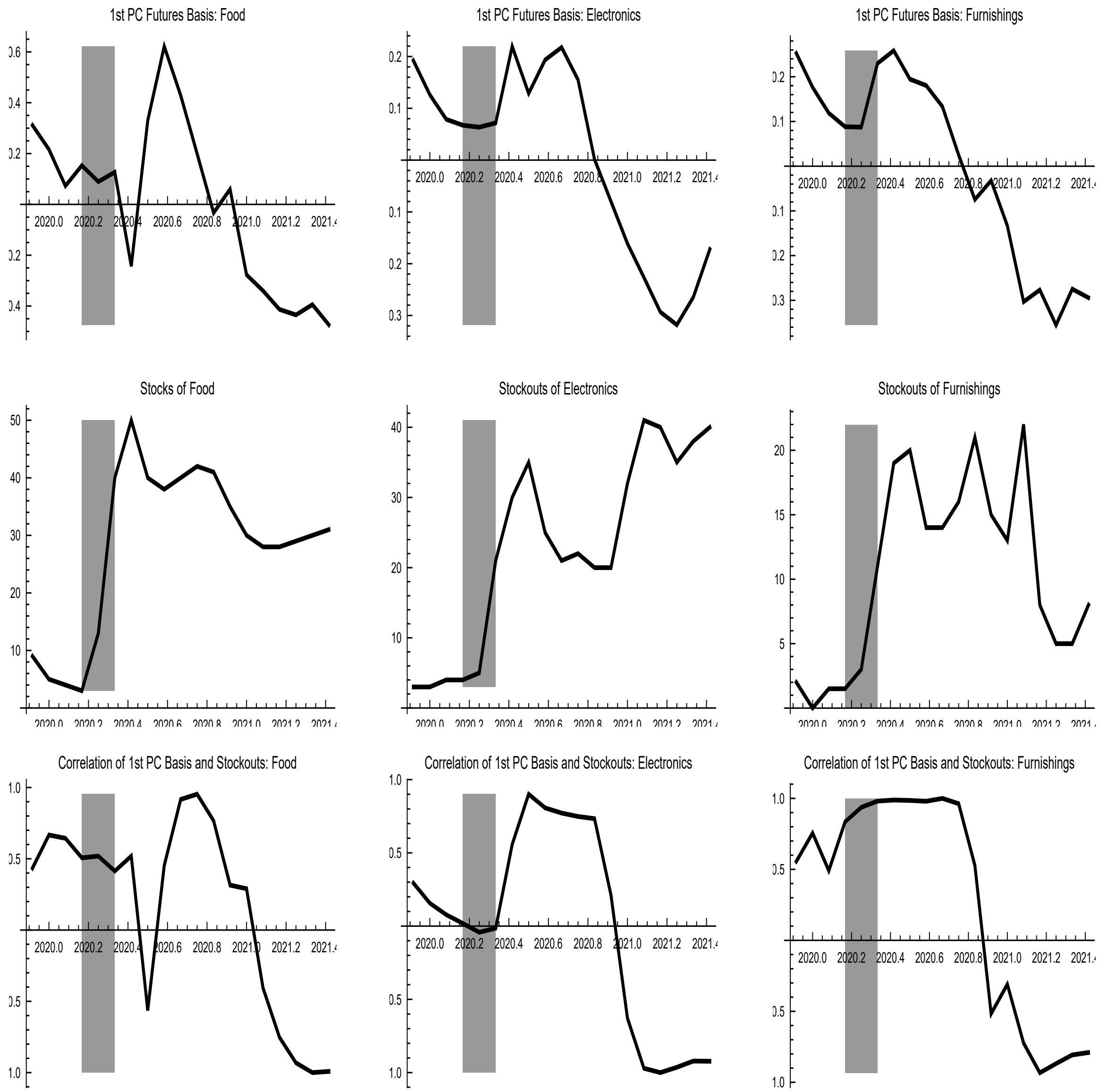
The correlation in each sector was positive during the recession, and rose around May 2020 although notably for food and beverages, it initially fell around May 2020, before climbing rapidly. In each sector, the correlation then declined and became negative by 2021. When the futures bases is positive, the theory of storage predicts that retailers would build up inventory to sell their products in the future. However, given the production and supply chain constraints during the pandemic, the retailers were unable to augment their inventory. The consumers, on the other hand, started hoarding inventory in fear of (i) higher prices or scarcity in the future, and (ii) other consumers beating them in the queue to obtain the limited retail stocks. In the following section, we describe this consumer behaviour in driving the association between stockouts and the futures basis in a theoretical model inspired by the bank run models of Diamond and Dybvig (1983) and Goldstein and Pauzner (2005).

In the top panel of Figure 3, we point towards the divergence in consumer and three-month lagged producer food prices. Consumer food prices increased significantly during the first few months of the pandemic, with a significant spike in inflation in May and June 2020. During this producer prices showed a notable decline. In general, consumer prices tend to lag increases in producer prices (see for e.g. Clark et al. (1995)), but this relationship reversed during the pandemic. For the sample from 2019:11 t0 2021:5, the correlation between the food CPI and three-month lagged PPI was -0.34. For comparison we also plot the CPI and the three-month lagged PPI for a longer sample from 1985:12 to 2024:2 in Figure 9 in the appendix. As seen, the relationship is generally positive, with a correlation of 0.64.

The decline in producer food prices can be attributed to labor shortages during the pandemic that disrupted the production and transportation of processed goods and consequently the decline in demand for commodities. Indeed, in the bottom panel of Figure

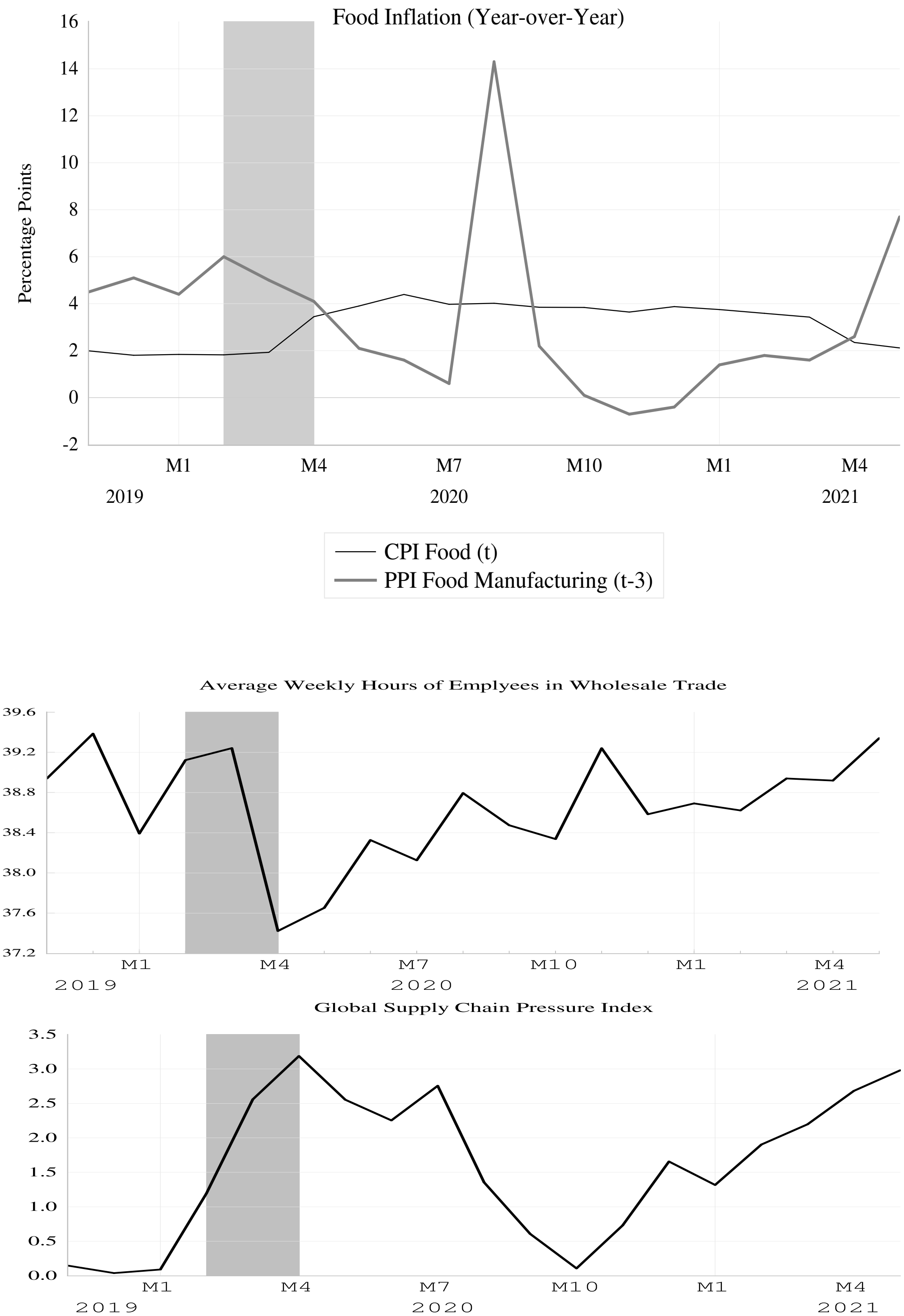
[2]We estimate the Vech Garch (1,1) model using the routine provided in EViews 12.

Figure 2: Dynamic Correlation Between the Futures Basis and Stockouts (2019:11 – 2021:5)



The **top panels** show the 1st principal components of the futures weak relative basis of each retail product sector. The **middle panels** show the proportion of retail products facing stockouts as measured by Cavallo and Kryvtsov (2021). The **bottom panels** show the dynamic conditional correlation between the series in the top and middle panels which are estimated using the Vech Garch (1,1) model of Bollerslev, Engle, and Woolridge (1988)

Figure 3: Food Prices, Hours Worked in Wholesale Trade, and Supply Chain Cost Index



Consumer (series CPIUFDSL) and Producer (series PCU311311) Food Price Index Data (top panel) are obtained from the St. Louis Fred database. Average Weekly Hours (series CEU4142000002) of Employees in Wholesale Trade (middle panel) is obtained from the St. Louis FRED database. The Global Supply Chain Pressure Index (bottom panel) is obtained from the Federal Reserve Bank of New York.

3, we see that the weekly hours of workers in wholesale trade plunged rapidly in April 2020 at the onset of the pandemic. At the same time the New York Fed's Global Supply Chain Pressure Index (GSCPI) rose sharply as the shortages at the retail level sparked an increase in demand due to hoarding behavior, which led to surging consumer prices.

In summary, the first few months of the pandemic witnessed anomalous price behaviour, first, between between producer and consumer basis, and second between stockouts and commodities' futures basis. We argue that this was primarily due to supply chain disruptions and consumers' hoarding behavior and set out to build a theoretical model which pins down these forces with greater clarity and rigour.

3 Model

There is a unit continuum of consumers $i \in [0, 1]$ each of whom has an inelastic consumption of 1 (divisible) unit of a finished product at date $t = 2$. A retailer carries an inventory of $0 \leq I_0 \leq 1$ units at date $t = 1$ to service the needs of the consumers. The retailer can source the products in advance at a cost of c_t in each period t, which represents the producer prices in the market. We refer to this cost variously as the wholesale price, producer price, the resource price or the raw material cost.

We assume that consumers, having met their consumption needs for date 1, decide whether to buy and store some extra finished product for future consumption. The retailer rations the finished product, by allowing a customer to buy no more than η units of the finished product at date 1 for storage purposes, where $0 \leq \eta \leq 1$. The customers are served sequentially and they arrive at random. If customers' aggregate demand exceeds the inventory, the retailer faces a stockout and some customers remain unserved. Each customer's demand is given by $D_i \geq 0$ which may or may not be fulfilled. The actual amount stored by consumer i is given by $H_i \geq 0$.

Hereon, we uniquely consider symmetric situations where each customer demands the same amount of the finished product, that is, $D_i = D_j$ for all $i, j \in [0, 1]$. The total demand is then given by $D = D_i$. If $D > \eta$, then each customer is served η, else they are served D. The number of customers remaining unserved is then given by $\gamma = \max(1 - \frac{I_0}{\min(\eta, D)}, 0)$. For such consumers, the storage $H_i = 0$. The stockout costs are given by $k(\gamma)$ with $k'(\gamma) > 0$ and $k(0) = 0$. The amount of finished product stored by the consumer who is served by the retailer is given by $H_i = \min(D_i, \eta)$.

We consider two components of increases in retail prices of processed goods. First, the stockout costs represent supply chain costs incurred while carrying a backlog of unfilled orders (Kahn (1992) and Krane (1994)) or immediate costs for replenishing the inventory that are over and above the manufacturing cost of the finished product, as well as customer goodwill lost when demand is unmet immediately. In our model, both the retailer and the consumer face zero storage costs. We normalize the supply chain cost of delivering the finished product to the customers in the first period as equal to zero. We assume that retail prices are "sticky", i.e., the retailer passes on the stockout costs to the consumer in the forthcoming period ($t = 2$).

The second component of retail costs arises when the aggregate demand of the customers is less than the inventory position (that is, $D < I_0$). In this case, the retailer passes on the cost or benefits associated with carrying inventory at historical prices to the consumer. More specifically, let $I_0^{rem} = \max(I_0 - H, 0)$ be the remaining inventory carried by the retailer at the end of the first date. This inventory is sourced at a cost of c_1 before date 1. Let $Q_2 = 1 - I_0^{rem} - H$ be the incremental quantity ordered by the retailer at date 2 at the wholesaler's price c_2. Then, the benefit or cost passed on to consumers in the next period is given by $b(c_1 - c_2)$ where $b = \frac{I_0^{rem}}{Q_2 + I_0^{rem}}$ is the proportion of the remaining inventory to overall sales in period 2.[3]

Overall, the retail price (or equivalently, the consumer price) at date 1 equals the wholesaler's cost:

$$P_1 = c_1 \tag{1}$$

However, the retail price of the finished product at date 2 comprises manufacturing costs, stockout costs and realized historical inventory-related costs or benefits:

$$P_2 = c_2 + k(\gamma) + b(c_1 - c_2) \tag{2}$$

Thus, we divide the prices, and the associated inflation, into three components:

[3] Notice that the weighted average price at date 2, not accounting for stockout costs, is given by:

$$P_2 = \frac{Q_2 c_2 + I_0^{rem} c_1}{Q_2 + I_0^{rem}} = \frac{Q_2 c_2 + I_0^{rem} c_1 + I_0^{rem} c_2 - I_0^{rem} c_2}{Q_2 + I_0^{rem}} = c_2 + b(c_1 - c_2)$$

where $b = \frac{I_0^{rem}}{Q_2 + I_0^{rem}}$.

(i) wholesale costs, c_t, which represent the per unit manufacturing or raw material costs of producing/delivering the good. The associated producer price inflation in absolute terms is given by $\left[\mathbb{E}[c_2] - c_1\right]$

(ii) stockout costs due to hoarding behavior, $k(\gamma)$, which represent the costs associated with ordering, inventory management, supply re-routing etc. Shifts in demand across time are therefore endogenous in our model, and depend on how all agents behave collectively in the market. We will clarify the link in the following discussion.

(iii) excess inventory costs, $b(c_1 - c_2)$, which potentially represents higher costs or savings associated with carrying inventory at historical prices.

The consumers' strategy at $t = 1$ is to choose the optimal amount of personal inventory to carry at date 1, $H_i \geq 0$, based on current prices, expectation of the future price and given the other agent's consumption choice H_{-i}. The demand that he submits to the retailer is then $D_i = H_i$. The demand of the customer may or may not be fulfilled depending on the customer's random position in queue. Given the other agent's storage choice H_{-i}, agent i's strategy choice minimizes the amount V that he expects to spend on the finished product:

$$\min_{0 \leq H_i \leq \eta} V_i = P_1(1 + H_i) + \mathbb{E}_1[P_2(1 - H_i)|H_{-i}] \tag{3}$$

We consider a set of 2 equilibria: one where the consumer does not stock any finished product at all, and the other where he tries to stock as much of the finished product as possible (subject to the rationing constraint η). We present the occurrence of the two equilibrium outcomes in the retail market as a function of the expected increase in wholesale commodity prices.

Proposition 1 *We characterize the equilibrium in the hoarding game described above as follows:*

(i) When the expected increase in the wholesale commodity price is $\left[\mathbb{E}_1[c_2] - c_1\right] < -k(\gamma)$*, then, for all* $i \in [0, 1]$*,* $D_i = 0$ *is the unique equilibrium in retail markets. Neither agent hoards.*

(ii) When the expected increase in the wholesale commodity price is $\left[\mathbb{E}_1[c_2] - c_1\right] > 0$*, then, for all* $i \in [0, 1]$*,* $D_i = \min(1, \eta)$ *is the unique equilibrium in retail markets. All agents hoard and the retailer faces a stockout.*

(iii) When the expected increase in wholesale commodity prices lies in the range: $-k(\gamma) < \left[\mathbb{E}_1[c_2] - c_1\right] < 0$*, then both* $D_i = 0$ *and* $D_i = \min(1, \eta)$ *are equilibria where* $\gamma = \max(1 - \frac{I_0}{\min(\eta,1)}, 0)$.

The proof is in Appendix 2.

When the expected price increase in producer prices falls within the range of 0 to $-k(\gamma)$, the decision of each agent to hoard or not depends on the behavior of other agents. If all other consumers hoard, then it is in the best interest of an agent to hoard as well, while if all others refrain from hoarding, the agent will also choose not to store the finished product. It is worth noting that the no hoarding equilibrium is the most efficient one, as it avoids adding unnecessary stockout costs to prices. If a consumer believes that all other agents will hoard anyway, then it is rational for them to try their luck with the queue, since they will end up paying the price for hoarding behavior regardless of whether they hoard or not. Similarly, if all other consumers do not hoard, then in the expected producer price increase rate of 0 to $-\frac{k(\gamma)}{c_1}$, the agent will miss out on the benefits of lower commodity prices in the future if they also refrain from hoarding. Therefore, the equilibrium decision in this expected price increase range is dependent on the higher order beliefs of the consumers. The hoarding equilibrium is similar in some respects to the sunspot and bank run equilibrium described by Diamond and Dybvig (1983).

The phenomenon of 'sunspot equilibria' is extensively examined in bank run scenarios (Diamond and Dybvig (1983); see Allen, Carletti, and Gu (2008) for a more recent exposition), is adapted in our study to encompass retail inventory and consumer dynamics. Analogous to banks facing bankruptcy, the occurrence of retailer stockouts in our model induces queuing behavior among consumers, leading to direct costs for retailers. Both depositors (as evident in bank run models) and consumers (as per our model) engage in queuing, anticipating that failure to do so might result in non-service when others are ahead in the queue. However, our model's adverse equilibrium differs from bank run models, especially avoiding the patient/impatient depositor categorization. [4]

[4] In the bank run framework, impatient depositors seek short-term returns, with banks committing to this by penalizing patient depositors in the long term. While serving as upfront insurance, this arrangement risks an adverse equilibrium where patient depositors might demand their deposits back if they foresee a similar action by others. Costs to depositors manifest when banks are compelled to liquidate long-term assets at a discount, and are unable to pay the promised higher rate of return to all depositors.

Even in the absence of expected price hikes, consumers might opt to store the commodity if they foresee a similar behavior among others. When customer demand surpasses retail inventory, resulting in stockouts, retailers face direct costs in the form of supply chain expenses. These costs are then passed on to the next period, impacting consumers who were not served initially. In contrast, those served earlier are spared the cost increase since they stored the goods in the preceding period. This complementarity in actions is crucial to the emergence of 'good' and 'bad' equilibria in our model: consumers queue if they believe others will, and vice versa.

Deriving the prices in retail markets, the price at date 2 without hoarding is given by:

$$P_2 = c_2 + I_0(c_1 - c_2) \tag{4}$$

With hoarding, the retail price at date 2 is given by:

$$P_2 = c_2 + k(\gamma) \tag{5}$$

The total price increase in such scenario is given by:

$$\underbrace{\mathbb{E}_1\big[P_2\big] - P_1}_{\text{consumer price increase}} \quad = \quad \underbrace{\mathbb{E}_1\big[c_2\big] - c_1}_{\text{producer price increase}} \quad + \quad \underbrace{k(\gamma)}_{\text{price increase due to hoarding/stockouts}}$$

Our model thus shows that the expected consumer price increase has two components: an input cost increase due to the cost of raw materials (or, producer price inflation) ordered over and above the inventory and a price increase due to hoarding/stockouts, which could depend on the hoarding behavior of agents. The additional price increase caused by hoarding, which results from stockout costs, is given by the expression $k(\gamma)$. When all agents hoard, this component of price increase is positive and adds to the input cost increase, resulting in a higher total price increase (or, consumer price inflation).

We denote the expected producer price increase $\big[\mathbb{E}_1[c_2] - c_1\big]$ as Δc and the expected consumer price increase $\mathbb{E}_1\big[P_2\big] - P_1$ as ΔP and describe the sensitivity of consumer prices changes to that of producer price changes, $\frac{\Delta P}{\Delta c}$, for different regions of Δc in the following proposition.

In the context of retail stockouts, all consumers are treated uniformly, without being divided into patient or impatient types. Their decision to store the commodity is influenced by factors such as the anticipation of producer prices increasing in the next period and potential stockout costs.

Proposition 2 *The price sensitivity $\frac{\Delta P}{\Delta c}$, as a function of Δc is as follows*

(i) when $\Delta c < -k(\gamma)$, then $0 \leq \frac{\Delta P}{\Delta c} \leq 1$ (consumers uniquely do not hoard)

(ii) when $-k(\gamma)) \leq \Delta c < 0$, then $\frac{\Delta P}{\Delta c} < 0$ if consumers hoard and $0 \leq \frac{\Delta P}{\Delta c} \leq 1$ if consumers do not hoard

(iii) when $\Delta c > 0$, then $\frac{\Delta P}{\Delta c} > 1$ (consumers uniquely hoard)

The proof is in Appendix 2.

We note that the consumer price response to increase in producer prices could be negative in the region $-k(\gamma)) < \Delta c < 0$ when agents choose to hoard. In such scenario, despite falling producer prices (and constant overall demand), consumer prices could increase and this component of hoarding is attributable to self fulfilling higher order beliefs, as in the bank run literature. Our theoretical finding also aligns with empirical data. Figure 3, points towards the divergence in consumer and three-month lagged producer food prices, where consumer food prices increased significantly during the first few months of the pandemic, despite a notable decline in producer prices. At the same time the New York Fed's Global Supply Chain Pressure Index (GSCPI) rose sharply, pointing to the role of supply chain costs in reversing the usual trend.

3.1 The Wholesale Market

We assume that processed goods, which are sold at the retail level, are produced by competitive wholesalers. The representative wholesaler produces 1 unit of output each period during normal times using labor and a raw material commodity. To simplify our analysis, we assume the Leontief production function for the wholesaler:

$$Y_t = \min(L_t, X_t), \tag{6}$$

where L_t and X_t are the quantities of labor and commodity used.[5] We assume that the supply of labor has an upper bound each period, $\bar{L}_t$, which can take on the values $\bar{L}^N$, or, $\bar{L}^P$, the upper bounds in normal times or during a pandemic. The upper bounds satisfy: $\bar{L}^N \geq 1 > \bar{L}^P > 0$, i.e. during the pandemic period, the required unit of the processed good cannot be produced. We assume a simple Markov chain for transitions between the

[5]Alternative production functions can be used without changing the main results of our paper.

two states:

$$P = \begin{bmatrix} p & 1-p \\ 1-q & q \end{bmatrix}.$$

In the above matrix, the transition probability from the normal state to a normal state is given by p and a pandemic state to a pandemic state is given by q. The firm minimizes costs of production. We assume that wages are fixed at w, while the price of the raw material $S = s(X)$, with $s'(X) > 0$, i.e., there is an upward sloping supply curve for the commodity. For example David (2019) provides evidence that the marginal cost of drilling oil wells increases over time. Therefore, the average cost of production in normal times, $c^N = w + s(1)$ is greater than the cost during the pandemic, given by $c^P = w + s(\bar{L}^P)$.

The futures slope and expected change in production costs are straightforward in this model. Assuming there is adequate inventory of the commodity in each period, risk-neutrality of all agents assumed in our model implies that the futures price of the commodity equals the expected spot price. Therefore, spot prices of the commodity equal $S^N = s(1)$ and $S^P = s(\bar{L}^P)$ in the two states, while the futures prices are $F^N = (1-p)\,S^P + p\,S^N$, and $F^P = (1-q)\,S^N + q\,S^P$.[6] Under our assumption of $s'(.) > 0$, the futures slope is negative (backwardation) in normal times and positive (contango) during pandemics. In addition, future production costs are expected to decrease in normal times, and increase during pandemics.

3.2 Interaction of the wholesale market with the retail market during the pandemic:

In our model, both retailers and consumers form expectations of future producer prices by observing the futures slope for commodity prices. In normal times, futures markets are in backwardation and retailers carry low inventory as they expect prices to decline in the future. The consumers also expect prices to decline and hence postpone their purchases.

During the pandemic, futures markets are in contango. The retailer wishes to carry a large inventory position anticipating price increases in the future. However, the retailer

[6] Note that the futures slope (or basis) is given by futures price/spot price -1.

is unable to do so because of reduced production resulting from supply chain disruptions and stay-at-home restrictions affecting the workforce

At the same time, consumers expect future production costs to increase during the pandemic, and start hoarding the retail commodity. The hoarding behaviour is influenced not just by future price expectations of the commodity, but also the hoarding behaviour of other consumers around them. This could lead to spiral of self-fulfilling beliefs, to the extent that consumers may hoard even when the pandemic situation ameliorates and futures prices are expected to decrease (up to a certain threshold). This hoarding behaviour leads the retail markets to experience stockouts during the pandemic, and this shortage may persist even when the on-ground situation improves. Additionally, hoarding contributes to elevated retail prices due to the costs associated with stockouts.

In the next section, we derive a link between the information content in the futures basis and the probability that a retailer faces stockouts.

3.3 Global games: agents with private signals

Utilizing the global games approach (inspired by Carlsson and Van Damme (1993)) we now extend the model to obtain the probability of retailers facing stockouts by assuming that at $t = 1$ each agent receives a private signal regarding the inflation in producer prices. These signals lead agents to coordinate their actions. They will hoard when the inflation in producer prices is in one range, and select the good, 'no hoarding' equilibrium in another range. $<$ Specifically, we assume that the agents get a signal of the producer prices, as $x_i = c_2 + \epsilon_i$. We assume that ϵ_i is an error term that is distributed uniformly over the interval $[-B, +B]$. The effect of the signal is twofold: (i) the signal provides information concerning the expected producer prices in the second period: the higher the signal, the higher is the posterior distribution attributed by the agent to the true value of producer prices in the second period, and the higher the incentive to hoard (ii) an agent's signal provides information about other agents' signals, which allows agents to make an inference regarding their actions. Observing a high signal makes the agent believe that other agents obtained high signals as well. Consequently, the agent attributes a high likelihood to the possibility that the other agents will hoard as well. Since strategies are complementary, this makes the agents incentive to hoard even bigger.

Table 2: Ex-Post Amount Spent by Agents

	$l < \frac{I_0}{\eta}$	$l > \frac{I_0}{\eta}$
$H_i = 0$	$c_2 + b(l)(c_1 - c_2)$	$c_2 + k(\gamma)$
$H_i = \eta$	$c_1\eta + \big(c_2 + b(l)(c_1 - c_2)\big)(1-\eta)\big]$	$(1-\gamma)\Bigg(c_1\eta + \big(c_2 + k(\gamma)\big)\big(1-\eta\big)\Bigg) + \gamma\big(c_2 + k(\gamma)\big)$

We note that our model has 2 dominant regions (as in Morris and Shin (2001) and Goldstein and Pauzner (2005)) so that whenever the signal is large(small) enough, it is dominant action for the agents to (not) hoard, irrespective of what the other agents do. However, for intermediate values of the signal, we show the existence of a unique threshold such that agents hoard when the signal they receive is above that particular threshold and do not hoard when the signal is below the threshold.

Let l be the proportion of agents who hoard. We have already established that whenever the agents hoard, they will demand the maximum possible quantity of storage allowed by the retailer: η. We have also noted in Section 3.1 that when $\eta < I_0$ the retailer does not face stockouts. In this section, we consider the more interesting problem when $\eta > I_0$ so that we can solve for the probability of stockouts. In this situation, whenever the proportion of the consumers hoarding is greater than $\lambda = \frac{I_0}{\eta}$, then the retailer faces a stockout. The payoffs for the agents are given in Table 2. Since, $I_0 < \eta \leq 1$, we note than the probability that the agent faces stockouts $\gamma = \max(1 - \frac{I_0}{\min(\eta,1)}, 0) = 1 - \frac{I_0}{\eta}$.

Further, when $l < \lambda$, proportion l of the agents demand η units, the remaining inventory is $I_0 - l\eta$. The amount ordered at date 2 is $Q_2 = 1 - I_0^{rem} - H = 1 - (I_0 - l\eta) - l\eta = 1 - I_0$. Therefore, the proportion of historical inventory to overall demand in period 2 is given by $b(l) = \frac{I_0 - l\eta}{I_0 - l\eta + 1 - I_0} = \frac{I_0 - l\eta}{1 - l\eta}$ when $l < \lambda$, else $b(l) = 0$.

An agent who receives signal $c_2^* = c_2 + \epsilon_i$ must be indifferent between hoarding and not hoarding at date 1. That agent's posterior distribution of c_2 is uniform over the interval $[c_2^* - B, c_2^* + B]$. Given c_2, she believes that the proportion of agents withdrawing in period 1 is l. Thus, her posterior distribution of l is uniform over $[0, 1]$.

As per Table 2, when $l < \lambda$, the difference in the amount spent by the agents when agents choose to hoard vs. not hoard is given by:

$$\Delta V(l, c_2) = \eta\Big(c_1 - \big(c_2 + b(l)(c_1 - c_2)\big)\Big) \tag{7}$$

Similarly, when $l > \lambda$, the difference in the amount spent by the agents when agents choose to hoard vs. not hoard is given by:

$$\Delta V(l, c_2) = (1-\gamma)\eta\Bigg(c_1 - \big(c_2 + k(\gamma)\big)\Bigg) \tag{8}$$

Following Morris and Shin, 2003, there is an implicit threshold $\Delta c^* = c_2^* - c_1$ such that agents hoard if their signal $x_i \geq c_2^*$ (and do not hoard otherwise). The threshold is given by the solution of Δc^* to the following equation:

$$\int_{l=0}^{l=\lambda=\frac{I_0}{1+\eta}} \Big(\Delta c^* - b(l)\Delta c^*\Big) dl + \int_{l=\lambda=\frac{I_0}{1+\eta}}^{l=1} (1-\gamma)\Bigg(\Delta c^* + k(\gamma)\Bigg) dl = 0 \tag{9}$$

Equation (9) represents the equilibrium condition where agents are indifferent between hoarding and not hoarding at date 1, given their private signal x_i regarding the inflation in producer prices. It determines the threshold Δc^* that separates the regions where agents choose to hoard or not hoard based on their signals. The equation balances the expected change in Δc^* due to hoarding and not hoarding behavior, ensuring that agents make optimal decisions regarding storage of the commodity.

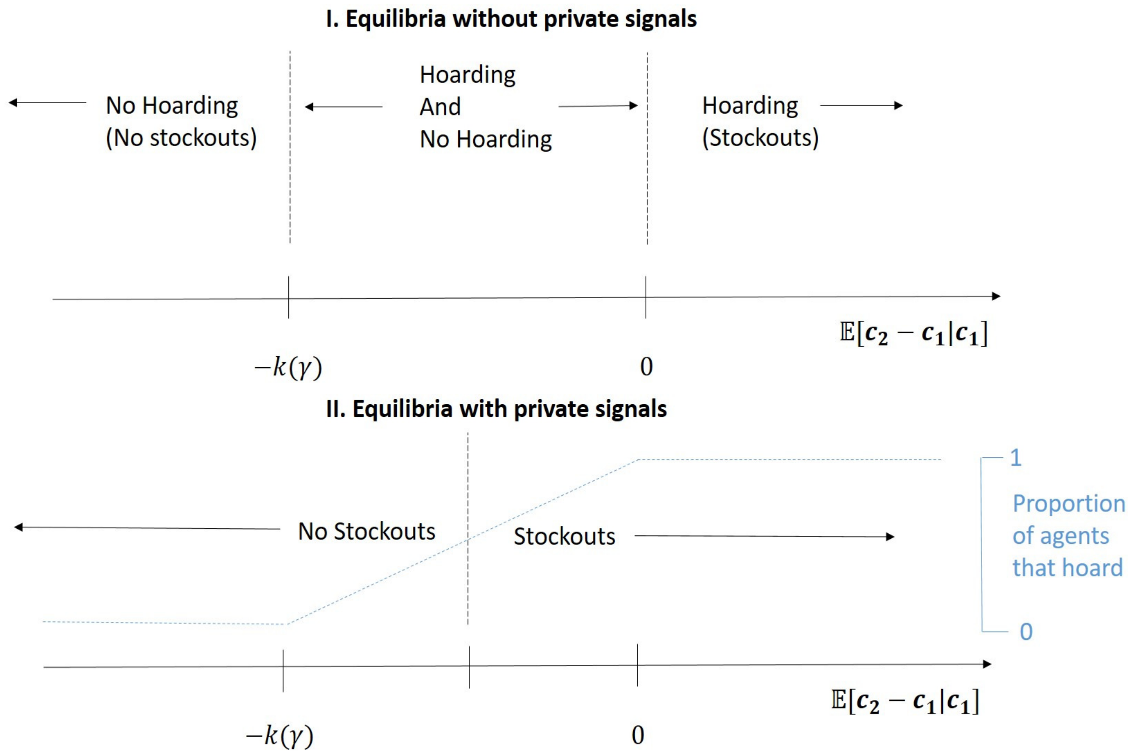
To find an explicit solution to Equation (9) we assume that the stockout cost function is linear, that is, $k(\gamma) = k\gamma$. We then solve for the optimal threshold in the Appendix as $B \to 0$ and summarize the result above in the following proposition:

Proposition 3 *Suppose the stockout cost function is given by $k(\gamma) = k\gamma$. Then $\Delta c^* = \frac{kI_0(1-\ln(\frac{\eta}{I_0})+\frac{I_0}{\eta})}{(1-I_0)\ln(1-\frac{I_0}{\eta})+I_0\ln(\frac{\eta}{I_0})}$ and the hoarding game has a unique equilibrium such that agent i hoards if they observe a signal of the absolute inflation $x_i - c_1 \geq \Delta c^*$ and do not hoard otherwise. Further, the threshold Δc^* is less than zero.*

We note that Δc^* serves a proxy for the futures basis. We can use Proposition 3 to calculate the proportion l of agents that choose to hoard when they are in the multiple equilibrium region that arose in the situation without private signals. It is interesting to note that the hoarding episodes in the multiple equilibrium region occur even when consumers expect the producer prices to fall. The reason consumers hoard in this region is because they believe that others will do so.

The proportion of agents that demand the commodity is given by:

Figure 4: Equilibria in the hoarding game: I. Without private signals and II. With private signals



$$l(\Delta c, \Delta c^*) = \begin{cases} 0 & \text{if } \Delta c < \Delta c^* - \epsilon \\ \frac{1}{2} + \frac{\Delta c - \Delta c^*}{2B} & \text{if } \Delta c^* - B < \Delta c < \Delta c^* + B \\ 1 & \text{if } \Delta c > \Delta c^* + \epsilon \end{cases}$$

An illustration of the hoarding behaviour of agents under private signals is shown using the blue dotted line in Figure 4.

Further, when $l(\Delta c, \Delta c^*) \geq \frac{I_0}{\eta}$, then the retailer faces a stockout. The threshold increase in consumer prices at which the retailer faces a stockout is given by:

$$\Delta c \geq \Delta c^* + B(\frac{2I_0}{\eta} - 1) \tag{10}$$

When the variance of the signal $B \to 0$, we note that this threshold converges to Δc^*. Beyond this threshold, the consumer prices set by the retailer incorporate the effects of stockout costs while below this threshold, they do not.

Proposition 4 *Let $B \to 0$, then the price sensitivity $\frac{\Delta P}{\Delta c}$, as a function of Δc is as follows:*

(i) when $\Delta c < \Delta c^*$*, then* $0 \leq \frac{\Delta P}{\Delta c} \leq 1$ *(consumers uniquely do not hoard)*

(ii) when $\Delta c^* \leq \Delta c < 0$*, then* $\frac{\Delta P}{\Delta c} < 0$ *(consumers uniquely hoard)*

(iii) when $\Delta c > 0$*, then* $\frac{\Delta P}{\Delta c} > 1$ *(consumers uniquely hoard)*

The proof is in Appendix 2.

The above Proposition implies that consumer price sensitivity to producer prices remain between zero and one as long as sufficient consumers do not hoard, but once the signal received by agent crosses Δc^*, sufficient consumers hoard even though $\Delta c^* < 0$. That is, even though producer prices are expected to fall next period, consumers panic and start hoarding as they expect other agents to behave in a similar manner. There is a sharp spike in the consumer prices, and the consumer price sensitivity to producer prices turns from positive to negative in this particular region ($\Delta c^* \leq \Delta c < 0$). This section helps us determine the unique threshold at which this divergence between producer and consumer prices occur, as a function of stockout costs, inventory and rationing.

4 Conclusion

In conclusion, the global COVID-19 pandemic had a profound impact on supply chains, leading to stockouts and increased costs for retailers. The observed relationship between stockouts and the futures basis during the pandemic deviated from theoretical expectations, with stockouts coinciding with a positive futures basis initially and then reverting to the expected negative correlation. This study highlights the influence of the futures basis on consumer hoarding decisions and retail stockouts, emphasizing the role of expectations of future commodity prices and social influences. The existence of both efficient and inefficient hoarding equilibria, even when consumers anticipate falling commodity prices, demonstrates the presence of self-fulfilling higher-order beliefs during the pandemic. Furthermore, our findings emphasize that consumer hoarding, despite declining wholesale commodity prices, can result in significant spikes in consumer price inflation. These insights provide valuable implications for understanding the dynamics of stockouts, hoarding behavior, and price inflation during times of supply disruptions.

Appendix 1

Data Description

Futures prices for raw material commodities are obtained from *Barchart*. Barchart, collects and diseminates data from different futures exchanges. In Table 3, we provide a list of all the contracts used in our paper along with their symbols and exchanges.

Table 3: Futures Data Description

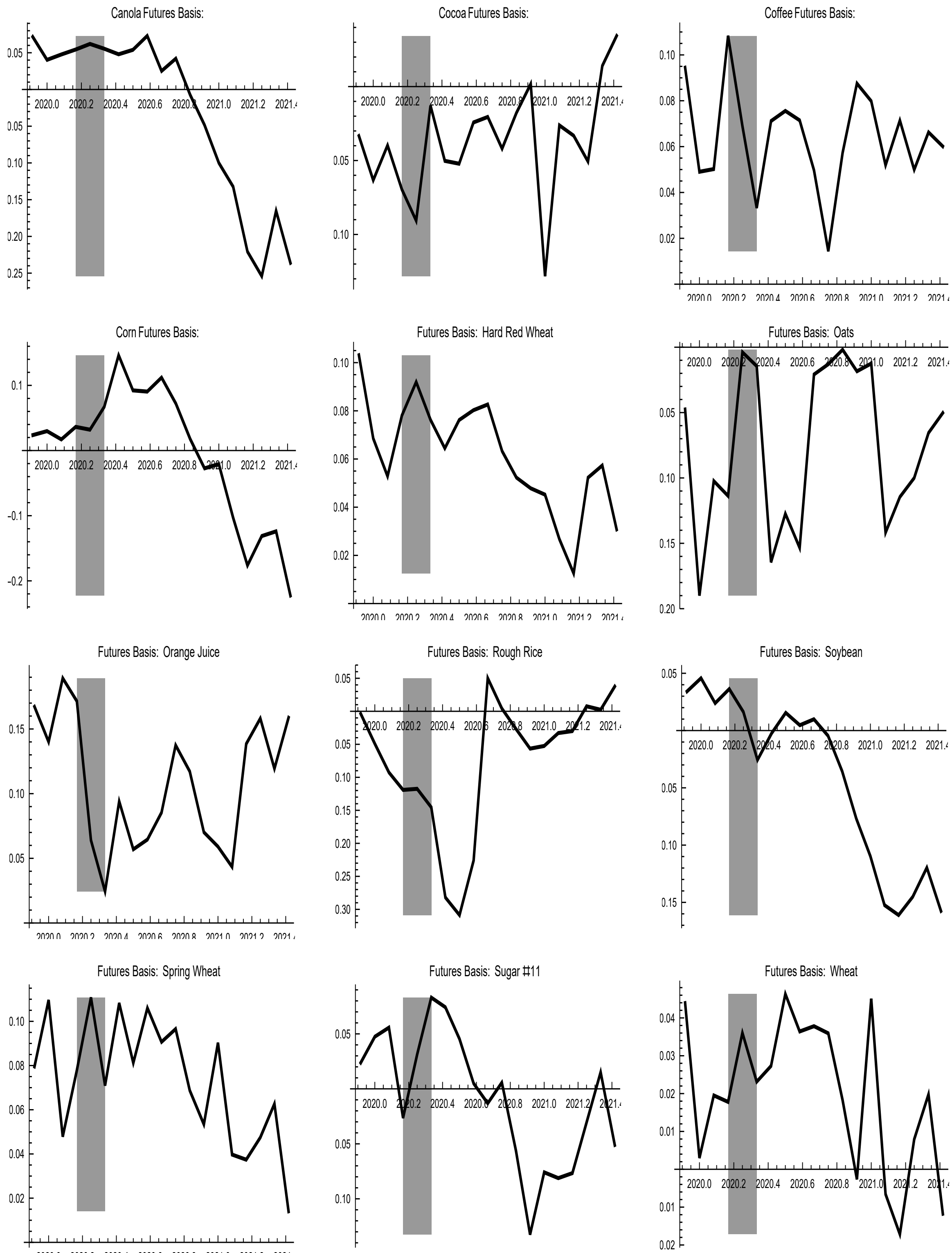
	Agricultural Commodities				Animal-Based Commodities		
No.	Commodity	Symbol	Exchange	No.	Commodity	Symbol	Exchange
1	Canola	RS	ICE US	13	Butter Cash Settled	BD	CME GLOBEX
2	Cocoa	CC	ICE US	14	Cheese Cash Settled	BJ	CME GLOBEX
3	Coffee	KC	ICE US	15	Class III Milk	DL	CME GLOBEX
4	Corn	ZC	CME GLOBEX	16	Dry Whey	DG	CME GLOBEX
5	Hard Red Wheat	KE	CME GLOBEX	17	Feeder Cattle	GF	CME GLOBEX
6	Oats	ZO	CME GLOBEX	18	Lean Hogs	HE	CME GLOBEX
7	Orange Juice	OJ	ICE US	19	Live Cattle	LE	CME GLOBEX
8	Rough Rice	ZR	CME GLOBEX	20	Nonfat Dry Milk	DF	CME GLOBEX
9	Soybean	ZS	CME GLOBEX				
10	Spring Wheat	MW	MGEX		Electronics Commodities		
11	Sugar # 11	SB	ICE US				
12	Wheat	ZW	CBOT	27	Aluminum	AL	COMEX
				28	Cobalt	U8	CME GLOBEX
	Household Furnishing Commodities			29	High Grade Copper	HG	COMEX
21	Cobalt	U8	CME GLOBEX	30	Nickel	Q0	LME
22	Cotton #2	CT	ICE US	31	Paladium	PA	NYMEX
23	SGX TSi Iron Ore 62%	TR	COMEX	32	Platinum	PL	NYMEX
24	Lumber Random Length	LS	CME GLOBEX	33	SGX TSi Iron Ore 62%	TR	COMEX
25	Nickel	Q0	LME	34	Silver	SI	CME GLOBEX
26	US Midwest Steel	CR	CME GLOBEX	35	Steel HRC	HRC	NYMEX

For each chosen contract, we focus on the spot price (the futures prices for the same month of settlement) and the 12-months ahead futures price at the beginning of the month. We picked commodities from these exchanges that would be used as inputs for food and beverages, electronics, and household furnshings. For each contract, i at each trading date, t, we construct the weak relative basis for the contract expiring at date T, as

$$\text{WRB}^i(t,T) = \frac{e^{-r\,(T-t)}F^i(t,T)}{S^i(t)} - 1, \tag{11}$$

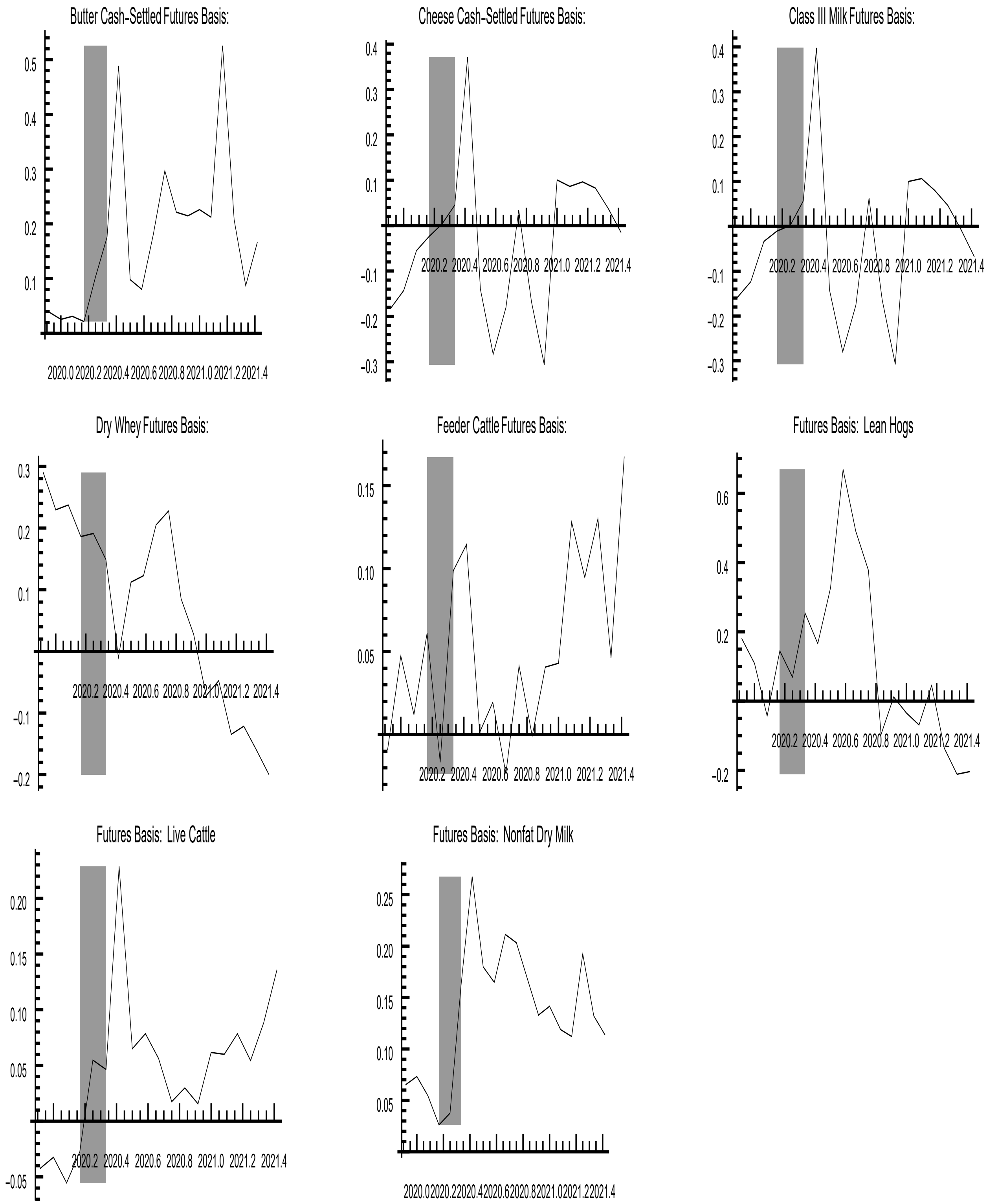
where r is the riskless rate of interest. We used interest rates that would be used by derivatives dealers from *Optionmetrics*, which uses the interest rate determined by put-call parity for options. Since rates are provided for a discrete set of maturities, we interpolate these rates for the exact maturity.

Figure 5: The Weak Relative Basis of Various Agricultural Commodities (2019:11 – 2021:5)



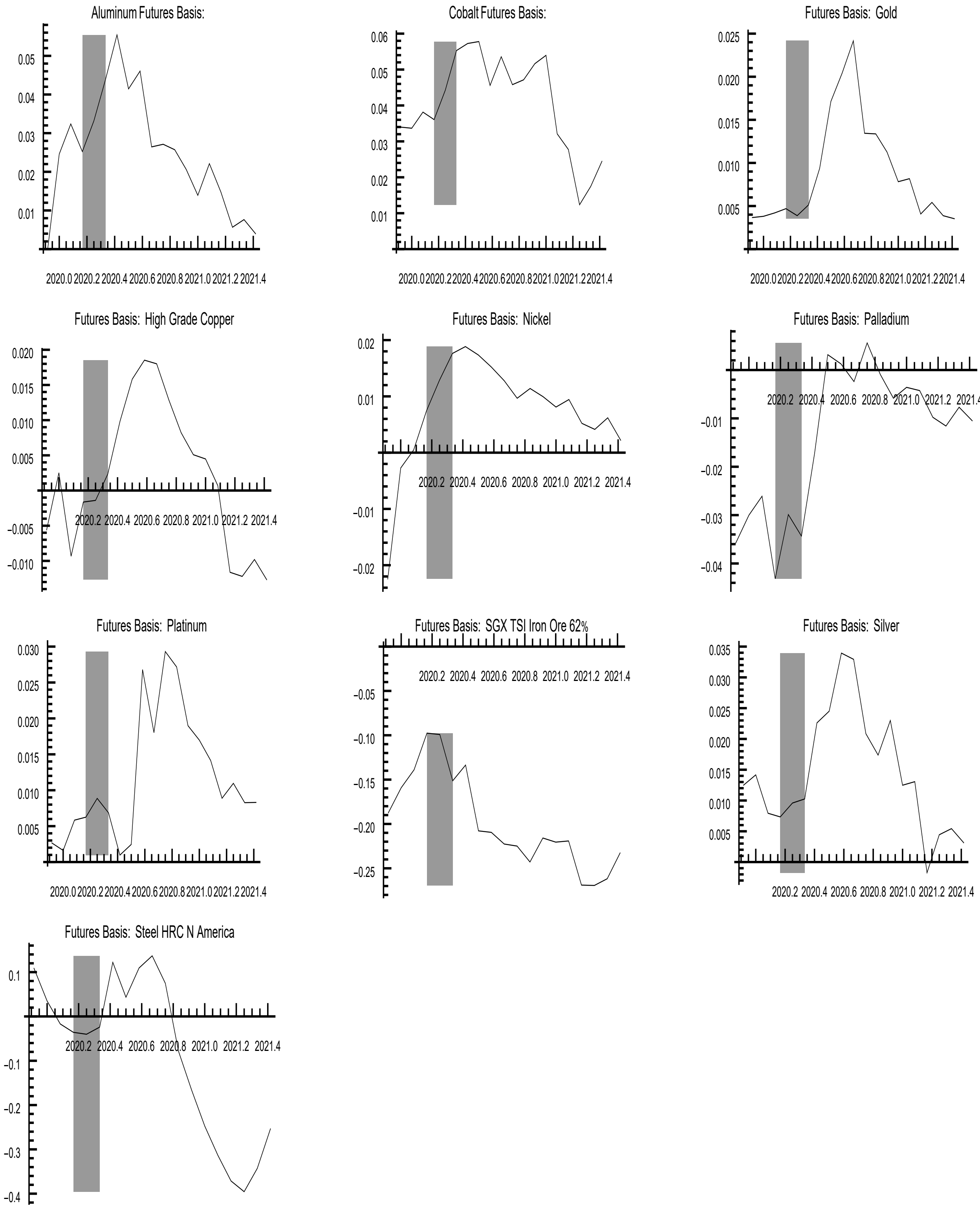
Futures prices are obtained from Barchart. For each contract, i at each trading date, t, we construct the weak relative basis for the contract expiring at date T, as $\text{WRB}^i(t,T) = (e^{-r\,(T-t)}F^i(t,T))/S^i(t) - 1$, where r is the riskless rate of interest. We used interest rates that would be used by derivatives dealers from *Optionmetrics*, which uses the interest rate determined by put-call parity for options.

Figure 6: The Weak Relative Basis of Various Animal-Based Commodities (2019:11 – 2021:5)



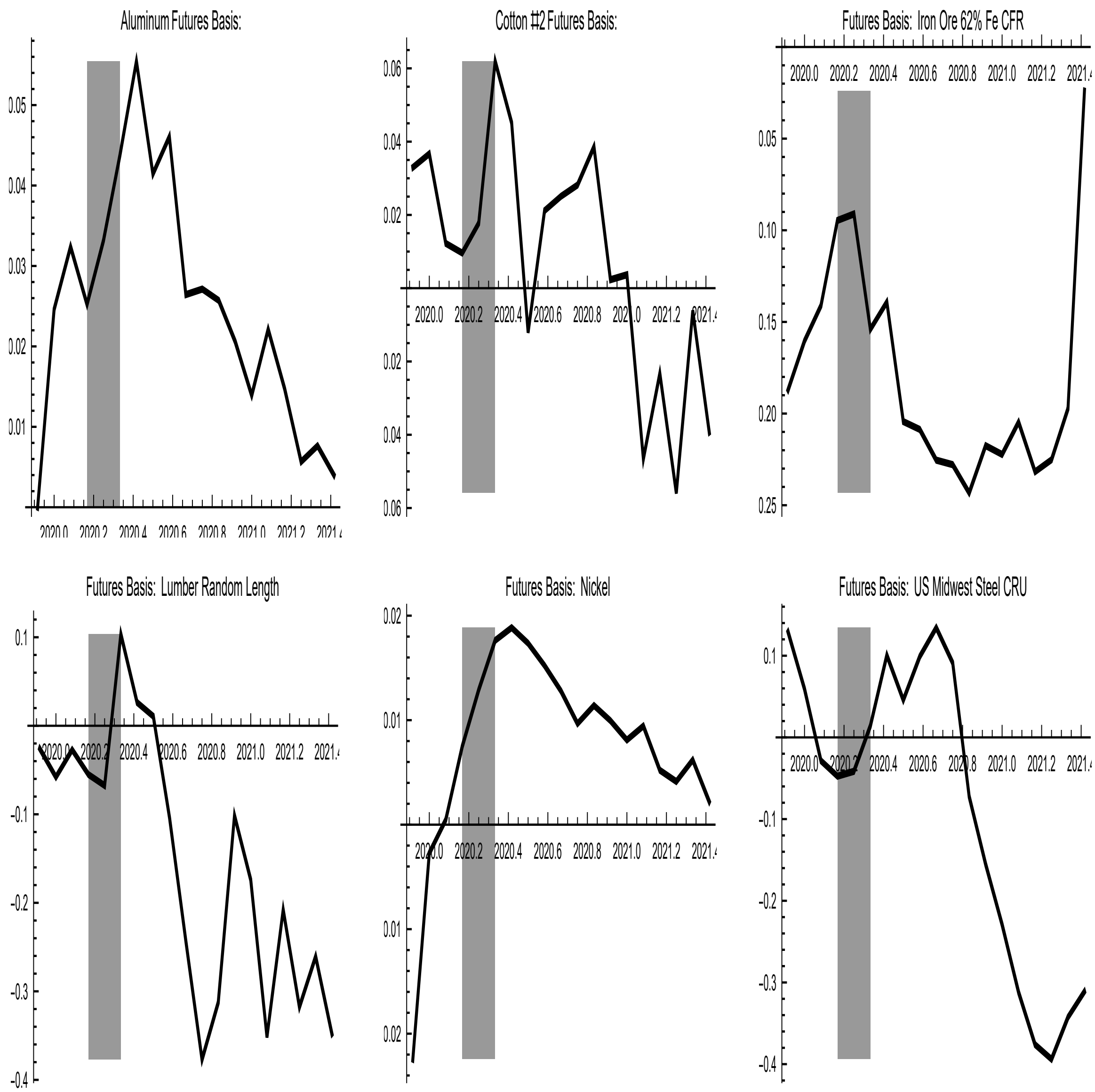
Futures prices are obtained from Barchart. For each contract, i at each trading date, t, we construct the weak relative basis for the contract expiring at date T, as $\text{WRB}^i(t,T) = (e^{-r\,(T-t)}F^i(t,T))/S^i(t) - 1$, where r is the riskless rate of interest. We used interest rates that would be used by derivatives dealers from *Optionmetrics*, which uses the interest rate determined by put-call parity for options.

Figure 7: The Weak Relative Basis of Various Commodities Used as Inputs for Electronics Products (2019:11 – 2021:5)



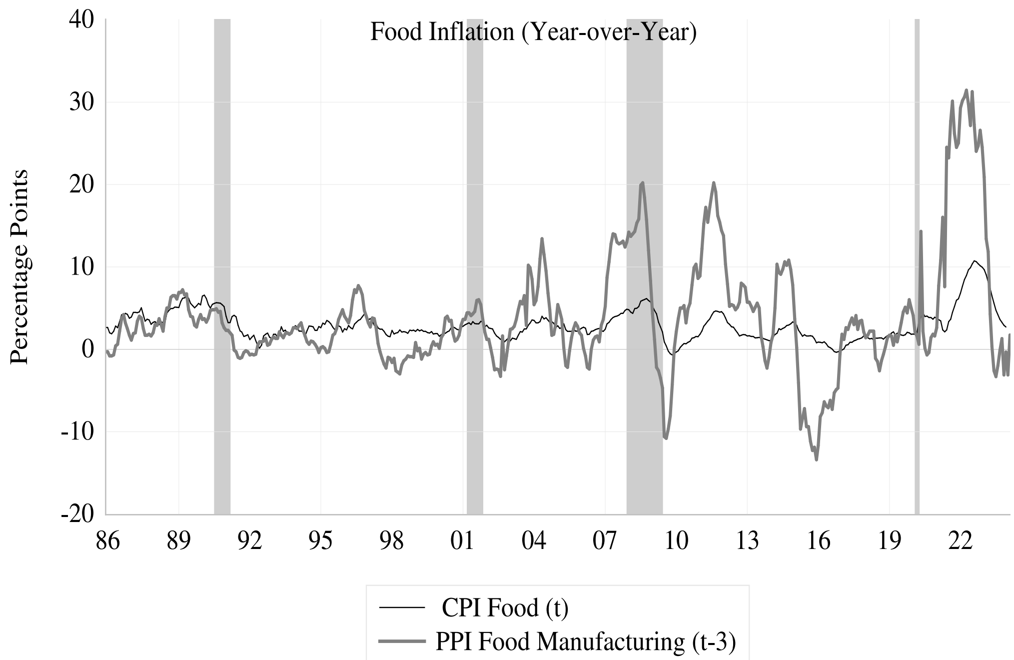
Futures prices are obtained from Barchart. For each contract, i at each trading date, t, we construct the weak relative basis for the contract expiring at date T, as $\text{WRB}^i(t,T) = (e^{-r\,(T-t)}F^i(t,T))/S^i(t) - 1$, where r is the riskless rate of interest. We used interest rates that would be used by derivatives dealers from *Optionmetrics*, which uses the interest rate determined by put-call parity for options.

Figure 8: The Weak Relative Basis of Various Commodities Used as Inputs for Household Furnishing Products (2019:11 – 2021:5)



Futures prices are obtained from Barchart. For each contract, i at each trading date, t, we construct the weak relative basis for the contract expiring at date T, as $\text{WRB}^i(t,T) = (e^{-r\,(T-t)}F^i(t,T))/S^i(t) - 1$, where r is the riskless rate of interest. We used interest rates that would be used by derivatives dealers from *Optionmetrics*, which uses the interest rate determined by put-call parity for options.

Figure 9: Food Prices (1985:12 – 2024:2)



Consumer (series CPIUFDSL) and Producer (series PCU311311) Food Price Index Data (top panel) are obtained from the St. Louis Fred database.

Appendix 2

Proof of Proposition 1

We derive conditions for the existence of two types of equilibria. Case (a) No agents hoard, that is, $D_i = 0$ and $H_i = 0$ and Case (b) All agents hoard, $D_i = \min(1, \eta)$ and $H_i = \min(1, \eta)$ with probability $1 - \gamma$ and $H_i = 0$ with probability γ. Case (a) is an equilibrium outcome when given the strategy of other agents $D_{-i} = 0$, we have that $D_i = 0$ is a best response. Or, equivalently, $H_i = 0$ is an optimum to equation (3). Replacing $H_{-i} = 0$ in equation (3) and noting that $k(\gamma) = 0$, it must be that $H_i = 0$ is a solution to the problem below.

$$\min_{H_i} c_1 H_i + \mathbb{E}_1\big[\big(c_2 + b(c_1 - c_2)\big)(1 - H_i)\big] \tag{12}$$

Further, since agent i is infinitesimal, if follows that $b = I_0$ whenever $H_{-i} = 0$. Expanding the above expression, yields

$$\min_{H_i} c_1 H_i + \mathbb{E}_1\big[c_2\big](1 - I_0)(1 - H_i) + I_0 c_1 (1 - H_i) \tag{13}$$

Notice that the above expression is linear in H_i and the coefficient of H_i in this expression is given by $-\mathbb{E}\big[c_2\big](1 - I_0) + (1 - I_0)c_1$. Whenever the coefficient of H_i is greater than 0, then the agent chooses $H_i = 0$ to minimize the value of the above expression. Given that $0 \leq I_0 \leq 1$, it follows that whenever $(\mathbb{E}\big[c_2\big] - c_1) < 0$, then $H_i = 0$ (no hoarding) is an optimal response to $H_{-i} = 0$.

Next, we have that in case (b), $D_i = \min(1, \eta)$ is an equilibrium strategy. We consider two separate sub-cases. First, whenever $\eta < I_0$, then all agents are served η units of the product and there are no stockouts. The retailer orders an additional $1 - I_0$ units of the product for purchase and consumption at date 2 and passes on the cost benefits associated with carrying $I_0 - \eta$ units of the product to the customers. If all agents demand $D_{-i} = \eta$, agent i's optimization problem is

$$\min_{D_i} c_1 H_i + \mathbb{E}_1\big[\big(c_2 + b(c_1 - c_2)\big)(1 - H_i)\big] \tag{14}$$

where $b = \frac{I_0^{rem}}{Q_2 + I_0^{rem}} = \frac{I_0 - \eta}{I_0 - \eta + 1 - I_0} = \frac{I_0 - \eta}{1 - \eta}$. Expanding the above expression, yields

$$\min_{D_i} c_1 D_i + \mathbb{E}_1\big[\big(c_2 + \frac{I_0 - \eta}{1 - \eta}(c_1 - c_2)\big)(1 - D_i)\big] \tag{15}$$

Expanding further,

$$\min_{D_i}(c_1 - \mathbb{E}_1\big[c_2\big])D_i(1 - \frac{I_0 - \eta}{1 - \eta}) + \mathbb{E}_1\big[c_2\big] + (c_1 - \mathbb{E}_1\big[c_2\big])\frac{I_0 - \eta}{1 - \eta} \tag{16}$$

Since $\eta < I_0$, the coefficient of D_i is negative whenever $\big[\mathbb{E}_1[c_2] - c_1\big] \leq 0$. Hence, the agent will choose $D_i = \eta$ to minimize his expenditure. It follows that $H_i = \eta$ in this sub-case.

Second, when $\eta > I_0$ the storage outcome for agent i is given by $H_i = \min(1, \eta)$ with probability $1 - \gamma$ and $H_i = 0$ with probability γ, where $\gamma = 1 - \frac{I_0}{\min(\eta, 1)}$. This storage outcome must be a solution to the problem below.

$$\min_{H_i}(1 - \gamma)\big(c_1 H_i + \mathbb{E}_1\big[\big(c_2 + k(\gamma)\big)\big(1 - H_i\big)\big]\big) + \gamma\big(\mathbb{E}_1\big[\big(c_2 + k(\gamma)\big)\big]\big) \tag{17}$$

Rearranging terms, the expression above simplifies to:

$$\min_{H_i}(1 - \gamma)\big(c_1 - \mathbb{E}_1\big[\big(c_2 + k(\gamma)\big)\big]\big)H_i + \mathbb{E}_1\big[\big(c_2 + k(\gamma)\big)\big] \tag{18}$$

Again, since the expression is linear in H_i, the agents will choose $D_i = \min(1, \eta)$ whenever the slope of the equation is less than zero. Considering the coefficients of H_i, it follows that the agent hoards when $\mathbb{E}_1\big[c_2\big] - c_1 > -k(\gamma)$. Summarizing the two sub-cases of (b) yields the region where agents hoard. Now, noting that $-k(\gamma) < 0$, we have an overlapping region for expected price inrease $-k(\gamma) < \big[\mathbb{E}_1[c_2] - c_1\big] < 0$ where both the hoarding and no hoarding equilibria are possible (Part (iii) of the proposition). Outside this region, either the hoarding equilibrium (Case (ii): $\big[\mathbb{E}_1[c_2] - c_1\big] > 0$) or no-hoarding equilibrium (Case (i): $\big[\mathbb{E}_1[c_2] - c_1\big] < -k(\gamma)$) obtains uniquely. ■

Proof of Proposition 2

Whenever consumers hoard, uniquely or not, $\Delta c > -k(\gamma)$. Then, in this region,

$$\Delta P = \Delta c + k(\gamma)$$

The sensitivity of $\frac{\Delta P}{\Delta c}$ is given by

$$\frac{\Delta P}{\Delta c} = 1 + \frac{k(\gamma)}{\Delta c}$$

The equation above implies that $\frac{\Delta P}{\Delta c} < 0$ when $-k(\gamma)) \leq \Delta c < 0$. When $\Delta c > 0$, $\frac{\Delta P}{\Delta c} > 1$.

On the other hand, when consumers do not hoard, uniquely or not (that is, $\Delta c < -k(\gamma)$), the change in consumer prices is given by

$$\Delta P = \Delta c - I_0 \Delta c$$

The sensitivity is given by

$$\frac{\Delta P}{\Delta c} = 1 - I_0$$

Since $0 \leq I_0 \leq 1$, we have that $0 \leq \frac{\Delta P}{\Delta c} \leq 1$.

Now segregating the regions where consumers hoarding or not hoarding is a unique equilibrium, and the region where both equilibria are possible (as in Proposition 1) gives us the result.

■

Proof of Proposition 3

We aim to solve the following equation for Δc^* from the main text.

Solving Equation (16):

$$\int_{l=0}^{l=\lambda=\frac{I_0}{\eta}} \Big(1 - \frac{I_0 - l\eta}{1 - l\eta}\Big)\Delta c^* dl + \int_{l=\lambda=\frac{I_0}{\eta}}^{l=1} (1-\gamma)\Bigg(\Delta c^* + k(\gamma)\Bigg) dl = 0$$

Rewriting the terms:

$$\int_{l=0}^{l=\frac{I_0}{\eta}} \Big(\frac{1 - I_0}{1 - l\eta}\Big)\Delta c^* dl + \int_{l=\frac{I_0}{\eta}}^{l=1} \Big(\frac{I_0}{l\eta}\Big)\Bigg(\Delta c^* + k(1 - \frac{I_0}{l\eta})\Bigg) dl = 0$$

Solving for the first integral:

$$\int_{l=0}^{l=\frac{I_0}{\eta}} \Bigg(\frac{1 - I_0}{1 - l\eta}\Bigg)\Delta c^* dl$$

Now, integrating:

$$= (1 - I_0)\Bigg[\Delta c^* \ln|1 - l\eta|\Bigg]_{l=0}^{l=\frac{I_0}{\eta}}$$

$$= (1 - I_0)\Delta c^* \ln\left|1 - \frac{I_0}{\eta}\right|$$

Solving for the second integral:

$$\int_{l=\frac{I_0}{\eta}}^{l=1} \left(\frac{I_0}{l\eta}\right)\left(\Delta c^* + k\left(1 - \frac{I_0}{l\eta}\right)\right) dl$$

Simplifying the second integrand:

$$\frac{I_0}{l\eta}\left(\Delta c^* + k\left(1 - \frac{I_0}{l\eta}\right)\right) = \frac{I_0}{l\eta}\left(\Delta c^* + k - k\frac{I_0}{l\eta}\right)$$

$$= \frac{I_0}{l\eta}\Delta c^* + \frac{kI_0}{l\eta} - \frac{kI_0^2}{(l\eta)^2}$$

Now, integrating:

$$I_0\left[\Delta c^* \ln|l\eta| + k\ln|l\eta| + \frac{kI_0}{l\eta}\right]_{l=\frac{I_0}{\eta}}^{l=1}$$

$$= I_0 \Delta c^* \ln\left[\frac{\eta}{I_0}\right] + kI_0 \ln\left[\frac{\eta}{I_0}\right] + \frac{kI_0^2}{\eta} - kI_0$$

Adding the first and second integral terms together

$$(1 - I_0)\Delta c^* \ln\left[1 - \frac{I_0}{\eta}\right] + I_0 \Delta c^* \ln\left[\frac{\eta}{I_0}\right] + kI_0 \ln\left[\frac{\eta}{I_0}\right] + \frac{kI_0^2}{\eta} - kI_0 = 0$$

which gives us

$$\Delta c^* = \frac{kI_0(1 - \ln\left[\frac{\eta}{I_0}\right] + \frac{I_0}{\eta})}{(1 - I_0)\ln\left[1 - \frac{I_0}{\eta}\right] + I_0 \ln\left[\frac{\eta}{I_0}\right]}$$

Since $\eta > I_0$, we note that the denominator is negative while the numerator is positive. Hence, $\Delta c^* < 0$.

■

Proof of Proposition 4

When sufficient consumers hoard, that is, when $\Delta c \geq \Delta c^*$, then

$$\Delta P = \Delta c + k(\gamma)$$

Then the sensitivity of $\frac{\Delta P}{\Delta c}$ is given by

$$\frac{\Delta P}{\Delta c} = 1 + \frac{k(\gamma)}{\Delta c}$$

The equation above implies that $\frac{\Delta P}{\Delta c} < 0$ when $\Delta c^* \leq \Delta c < 0$ (recall that $k(\gamma) \leq \Delta c^* < 0$). When $\Delta c > 0$, $\frac{\Delta P}{\Delta c} > 1$.

On the other hand, when sufficient consumers do not hoard (that is, $\Delta c < \Delta c^*$), the change in consumer prices is given by

$$\Delta P = \Delta c - b(l)\Delta c$$

where $b(l) = \frac{I_0 - l\eta}{1 - l\eta}$. The sensitivity is given by

$$\frac{\Delta P}{\Delta c} = 1 - b(l)$$

Since $0 \leq I_0 \leq 1$ and $0 \leq b(l) \leq 1$ we have that $0 \leq \frac{\Delta P}{\Delta c} \leq 1$.

■

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