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Under economic stress rational behavior may yield increased consumption of pricier goods

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Abstract: The response of economic actors to price changes is one of the elementary market forces. Consequently, the change in consumed quantity induced by price changes, measured as consumption price elasticity, is an important object of economic theory. Managing a given budget, consumers usually buy less of a product when it gets more expensive which corresponds to a negative consumer price elasticity. In particular, it depicts the willingness of an individual or a household to stretch their budget in high-price situations. Here, we show that a crisis can push an economy in an out-of-equilibrium state where positive price elasticities naturally arise from a self-stabilizing feedback mechanism, which moves the economy back into its equilibrium state. When rational consumers maximize their utility, the evolution of price elasticities in an out-of-equilibrium economy is driven by two factors, the relative price change of goods and their substitutability. In a heterogeneous price landscape among suppliers and goods, the budget-driven preference for products with the least relative price increase is competing with the utility-driven incentive to reduce consumption of more easily substitutable goods to form a stabilizing feedback loop. We illustrate this phenomenon in an agent-based model of myopically profit-optimizing producers and utility-optimizing consumers under weather-induced supply failures. The resulting elasticities are predominantly negative with a median comparable to macroscopically observed values, but positive elasticities emerge temporarily in crises situation due to the described mechanism. Thus, in a stressed economy pricier goods may be bought more even under rational consumer behavior with budget constraints.

Significance Statement: Consumption price elasticity determines the change of consumed quantity in response to price changes. In many cases, stable economic conditions justify the common assumption of constant negative price elasticity where higher prices yield reduced consumption. Here we show, however, that a more dynamic perspective is required for stressed economies, e.g., after natural disasters. We find that, if consumers maximize their utility, the distribution between goods may temporally yield higher consumption of pricier goods, during crises situations. Nevertheless, a self-stabilizing feedback restores the macroscopically observed behavior that corresponds to negative elasticities. This theoretical finding is demonstrated numerically in a global trade model of profit-optimizing producers and utility-optimizing consumers under weather-induced supply failures.

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RESEARCH REPORT

Under economic stress rational behavior may yield increased consumption of pricier goods

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Abstract

The response of economic actors to price changes is one of the elementary market forces. Consequently, the change in consumed quantity induced by price changes, measured as consumption price elasticity, is an important object of economic theory. Managing a given budget, consumers usually buy less of a product when it gets more expensive which corresponds to a negative consumer price elasticity. In particular, it depicts the willingness of an individual or a household to stretch their budget in high-price situations. Here, we show that a crisis can push an economy in an out-of-equilibrium state where positive price elasticities naturally arise from a self-stabilizing feedback mechanism, which moves the economy back into its equilibrium state. When rational consumers maximize their utility, the evolution of price elasticities in an out-of-equilibrium economy is driven by two factors, the relative price change of goods and their substitutability. In a heterogeneous price landscape among suppliers and goods, the budget-driven preference for products with the least relative price increase is competing with the utility-driven incentive to reduce consumption of more easily substitutable goods to form a stabilizing feedback loop. We illustrate this phenomenon in an agent-based model of myopically profit-optimizing producers and utility-optimizing consumers under weather-induced supply failures. The resulting elasticities are predominantly negative with a median comparable to macroscopically observed values, but positive elasticities emerge temporarily in crises situation due to the described mechanism. Thus, in a stressed economy pricier goods may be bought more even under rational consumer behavior with budget constraints.

Key words: Consumption price elasticity | Dynamic systems economics | Disequilibrium | Volatility clustering

Significance statement
Consumption price elasticity determines the change of consumed quantity in response to price changes. In many cases, stable economic conditions justify the common assumption of constant negative price elasticity where higher prices yield reduced consumption. Here we show, however, that a more dynamic perspective is required for stressed economies, e.g., after natural disasters. We find that, if consumers maximize their utility, the distribution between goods may temporally yield higher consumption of pricier goods, during crises situations. Nevertheless, a self-stabilizing feedback restores the macroscopically observed behavior that corresponds to negative elasticities. This theoretical finding is demonstrated numerically in a global trade model of profit-optimizing producers and utility-optimizing consumers under weather-induced supply failures.

Introduction

A major goal in economics is the bridging of the micro-macro gap by explaining macroeconomic observations based on microeconomic processes. Here, price elasticity as a determinant of consumer behavior is an important link connecting the microeconomic decisions of consumers with their macroeconomic outcomes.

Global economic stress situations like the financial crisis 2007–2009 [5, 25] or the global supply chain disruptions during the COVID-19 pandemic [9, 4] induce a complex response from the global economic system. But also more localized impact channels disrupt economic activity — e.g., local epidemic outbreaks [31, 3] or extreme weather events — and can have global repercussions [11, 36, 17, 24, 16].

Empirical studies are often hampered by ample confounding factors rendering the observation of time evolution in price elasticities difficult. This challenge can only be tackled by large-scale field experiments as, for instance, conducted by Jensen and Miller in their study showing evidence of Giffen good behavior in a real world setting [14] distributing vouchers for necessities in two Chinese provinces. Gaining a better theoretical understanding on the formation of price elasticities is, thus, an important factor to consider. However, there is little model-based research into price elasticity, one example being a study by He et al. on the case of electricity markets based on a CGE model [12].

In this study, we focus on analyzing the dynamic behavior of consumption price elasticity in response to economic stress, i.e., non-equilibrium situations induced by extreme weather events. To this end, we study the economic repercussions of extreme weather events as local events that can be regionally [15] or seasonally [28] synchronized and cause global economic repercussions [36]. Since under ongoing global warming, extreme weather events become more frequent and intense [23], a better understanding of their economic repercussions is quintessential to address adaptation and mitigation challenge [29]. Adding to more traditional approaches using Integrated Assessment models (IAMs) or econometrics, agent-based modeling of the economics of climate change is an important complementary approach. Examples of use include agent-based IAMs [20] or agent-based supply chain models [10] to analyze global effects under climate stress [11]. In the numerical experiments in this study, we use the global agent-based supply chain model *Acclimate* [27]. Allowing to describe the out-of-equilibrium dynamics in the aftermath of economic shocks, it has already been applied to analyze the propagation of indirect losses induced by extreme weather events in the global supply network [36, 18, 17, 24]. We here present a substantially extended version of the model. Going beyond the (rather strong but common) assumption of constant price elasticities, we introduce a utility maximization principle for consumers that allows for an endogenous description of time varying price elasticities emerging for the internal market dynamics. We show that, during the out-of-equilibrium transition phase in the aftermath of economic shocks, positive price elasticities can emerge entailing a self-stabilizing feedback mechanism that drives the economy back into equilibrium. We further provide an analytical description of this feedback mechanism in a simplified model for a rational utility maximizing consumer where the dynamics of price elasticities arises from the relative price changes of goods as well as from their substitutability. We finally show that the simplified analytical model can quantitatively reproduce the *market emerging elasticities* of the complex *Acclimate* model.

Results

Analytical description of price elasticity dynamics

A common way of modeling a consumer's decision is defining a utility function $U(x_1, \dots, x_N)$ depending on the consumption of N goods $x_i, i = 1, \dots, N$ and constrained by a budget B. The consumer's choice of a set of goods $(x_1, \dots, x_N)$ is now made by maximizing the utility given by $U(x_1, \dots, x_N)$. To align our analysis with the anomaly modeling of *Acclimate*, we refer — without loss of generality — to the undisturbed state of the economy as 'baseline' in the following analysis. We assume that the consumer's budget $B \equiv B^\star$ is constant at baseline level with

$$B^\star = \sum_{i=1}^{N} x_i^\star = \sum_{i=1}^{N} p_i x_i, \tag{1}$$

where p_i denotes prices relative to the baseline, $x_i^\star$ baseline consumption, and x_i current consumption of good i. Thus increased spending for one good necessitates reduced spending for all other goods and vice versa. Using Lagrangian multiplier optimization leads to the following set of equations for any utility function $U(x_1, \dots, x_N)$:

$$\frac{\partial U}{\partial x_i} = \lambda p_i x_i \forall i \in 1, \cdots, N \tag{2}$$

Defining $q_i := \frac{x_i}{x_i^\star}$ as the relative change of quantity compared to baseline and using the budget constraint eq. (1), we derive the following relation between relative quantities and relative prices,

$$q_i = \frac{\frac{\partial U}{\partial x_i} \sum_{j \neq i}^{N} \left(p_j q_j x_j^\star \right)}{p_i x_i^\star \sum_{j \neq i}^{N} \frac{\partial U}{\partial x_j}}, \tag{3}$$

and the optimal *market-emergent elasticity* is given by

$$\epsilon_i = \frac{q_i - 1}{p_i - 1} = \left(\frac{\frac{\partial U}{\partial x_i} \sum_{j \neq i}^{N} \left(p_j q_j x_j^\star \right)}{p_i x_i^\star \sum_{j \neq i}^{N} \frac{\partial U}{\partial x_j}} - 1 \right) / \left(p_i - 1 \right). \tag{4}$$

This market-emergent elasticity characterizes the re-balancing of budget-shares in response to price changes. If a good has a price elasticity of -1, its budget share is constant. For a positive price elasticity, the share of the budget is increased if prices rise and decreased if prices fall.

Feedback mechanism driving market emergence of elasticities

We analyze the elasticity emerging from utility maximization as derived in eq. (4). For that, we use a one-level constant elasticity of substitution (CES) utility function with elasticity of substitution σ as an explicit example:

$$U(x_1, \dots, x_N) = \left[\sum_{i=1}^{N} \left(a_i^{\star\,\frac{1}{\sigma}} x_i^{\frac{\sigma-1}{\sigma}} \right) \right]^{\frac{\sigma}{\sigma-1}} \tag{5}$$

Here, $a_i^\star$ denotes the baseline share of consumption of good i, defined as $a_i^\star := \frac{x_i^\star}{\sum_{j=1}^{N} x_j^\star}$. Its partial derivative with respect to x_i, the consumption of good i, reads

$$\frac{\partial U}{\partial x_i} = a_i^{\star\,\frac{1}{\sigma}} x_i^{-\frac{1}{\sigma}} \left[\sum_{j=1}^{N} \left(a_j^{\star\,\frac{1}{\sigma}} x_j^{\frac{\sigma-1}{\sigma}} \right) \right]^{\frac{1}{\sigma-1}}. \tag{6}$$

The following relation between the relative price change of good i, p_i, and relative quantity change q_i holds in each time step

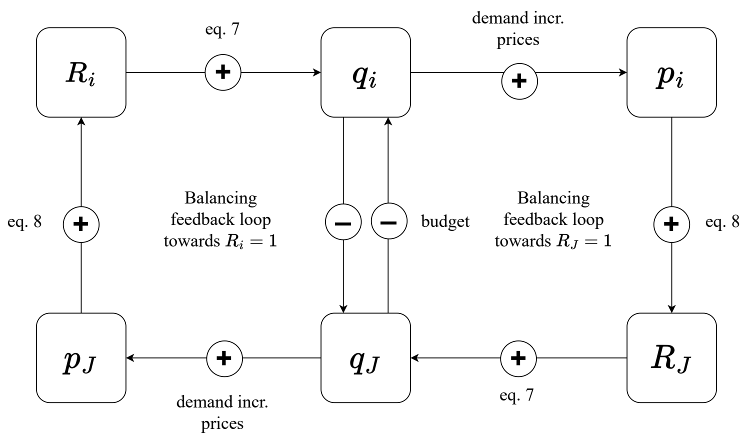

Fig. 1. Changes of R_i drive a self-regulating feedback loop. Schematic feedback loop with J defined as the combination of all other goods, i.e., $J := \{1, \dots, i-1, i+1, \dots, N\}$, resulting in two interconnected negative feedback loops.

(detailed calculation in the methods):

$$q_i = \left(R_i \cdot \frac{1}{p_i}\right)^{\frac{1}{1+\frac{1}{\sigma}}}, \tag{7}$$

where

$$R_i := \frac{\sum_{j\neq i}^{N}\left(p_j q_j x_j^\star\right)}{\sum_{j\neq i}^{N} q_j^{-\frac{1}{\sigma}}} \frac{1}{x_i^\star}. \tag{8}$$

measures the price landscape relative to good i, i.e., the substitution-weighted relative prices of all other goods. Relative prices favor consumption of good i if $R_i > 1$. For any utility function, we can derive a general expression for R_i – which might still depend on q_i – from eq. (3) as

$$R_i := \frac{\frac{\partial U}{\partial x_i}}{\sum_{j\neq i}^{N}\frac{\partial U}{\partial x_j}} \frac{\sum_{j\neq i}^{N}\left(p_j q_j x_j^\star\right)}{x_i^\star}. \tag{9}$$

While $\frac{\partial U}{\partial x_i}$ can depend on q_i, our following elaboration on the feedback processes driven by R_i are independent of the exact form of R_i. It is sufficient to assume $U(x_1, \dots, x_N)$ is strictly monotonous, i.e., $\frac{\partial U}{\partial x_i} > 0 \forall i \in 1, \dots, N$. This is satisfied as long as the standard assumption of non-saturation holds, i.e., that, all else being equal, marginally increasing consumption of one good always increases utility.

We identify R_i as central to the relation between p_i and q_i, such that a self-regulating feedback loop evolves as sketched in fig. 1. If relative prices favor good i (case $R_i > 1$), the increased consumption decreases this preference over the other goods, thus decreasing R_i and thereby the increased consumption is slowly pulled back to baseline state. In supplementary figure S1 we sketch a flow-chart of the feedback processes. Since this applies to all goods in parallel, complex patterns might still emerge, but the whole system relaxes back to baseline levels in the aftermath of a disturbance. This effect is symmetric for price decreases followed by demand reduction if a good is unfavorable, i.e., less important for utility than combined other goods (case $R_i < 1$).

Mechanisms resulting in positive price elasticities

Since shifts in R_i move the demand curve, the actually realized demand curve can deviate from the expected curve. An example is illustrated in fig. 2. Depending on the change in R_i, the resulting demand trajectory can yield positive or negative *market emergent price elasticities*. While these do not indicate the 1:1-dependency of price to quantity as in the case of classical constant price elasticity derived under ceteris paribus assumptions, the incorporation of the relative price effect gives a more complete, realistic picture of consumption behavior.

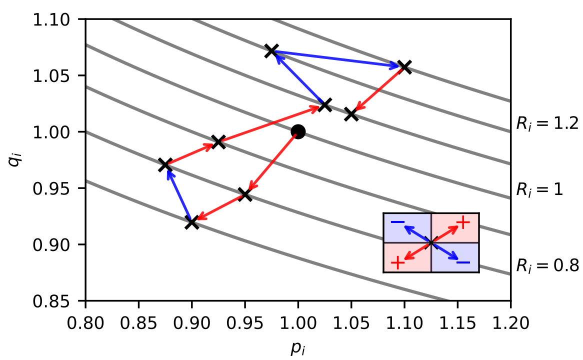

Fig. 2. Effect of the time dependence of R_i on the demand curve of good i. Illustrative projection of trajectory on (relative) price–quantity plane in the aftermath of a shock pushing the system out of the equilibrium point at $(1, 1)$. Arrows indicate the movement in price–quantity space induced by changes in R_i. The inset shows the sign of elasticity depending on the relative movement in price–quantity space; red and blue colors indicate positive and negative elasticities, respectively.

This implies a dynamic behavior driven by R_i, where the market interactions of relative prices can lead to counter-intuitive positive price elasticity for individual goods. The market forces are influenced by higher-order effects and yield results apparently contradicting the fundamental laws of the market — where increasing prices are assumed to cause decreasing demand. Importantly, the consumers in this framework do not use any further behavioral component to determine consumption, such that the resulting *market emerging elasticity* is solely driven by the standard economic assumption of utility maximization. Compared to the classical example of Giffen goods [14], positive price elasticities do not occur due to substitution of high-quality goods by lower-quality goods, but emerge from relative price effects in non-equilibrium states of the economy. The other classical case for positive price elasticities via Veblen goods [32, 2], which are luxury goods valued higher due to rising prices, also does not apply — the consumers only maximize utility under their budget constraint without any behavioral heuristic.

Utility maximization in *Acclimate*

To explore the described theoretical feedback processes in a numerical experiment, we use the agent-based global supply chain model *Acclimate* and extend its consumer module with the maximization of a two-layer CES utility function. In contrast to our simplified analytical framework, we use a two-level CES utility function since the 26 classes of goods are not equally substitutable for one another. For this, we define three consumption baskets to classify goods as 'necessary', 'relevant', and 'other goods', each with varying degrees of substitutability. We thereby follow the classification used previously to map consumption price elasticities from the Global Trade Analysis Project (GTAP) [13] to the Eora sectors. For details we refer to the methods.

Using a shock scenario for economic disturbances after extreme weather events, we can readily estimate the *market emergent price elasticity* — i.e., elasticity including market substitution effects, not using ceteris paribus assumptions — of consumption flows per region and income group based on our previous theoretical analysis.

With respect to our modeling results we focus on the data of consumer agents from the three biggest economic blocks: China, the USA, and the EU28. Since China and the USA are resolved on sub-national level and the EU28 is naturally partitioned into countries, we thus show data for an ensemble of 550 consumer agents (31 provinces of China, 51 states of the US, and 28 EU28 countries with 5 income groups each).

Comparing analytical expectations and modeling results

To compare analytical expected emerging elasticities and results from *Acclimate*, we generate a random distribution of substitution-weighted relative prices of all other goods R_i to plot corresponding distributions of theoretical emerging elasticity ϵ_i depending on price change p_i. For this, we draw a uniform sample of price change $p_i \in [-0.01, 0.01] \setminus (-0.0001, 0.0001)$, excluding values close to 0 as price elasticity is ill-defined there. We assume R_i to be normally distributed with mean $\mu = 1$. Further, we assume variance ν to be decreasing for an increasing inter-basket substitution coefficient in the utility function since a higher substitution between goods should lead to a less volatile R_i. The resulting distribution of price elasticity ϵ_i with respect to price change p_i shows that reduced substitutability, conventionally assumed for elementary goods, results in a price elasticity closer to 0 and thus also more frequent emergence of positive price elasticities (*(A,B,C)* in fig. 3). Comparing the numerical to the analytical results in fig. 3, we observe that the simulated two-level behavior follows the theoretical prediction. In particular, increases in sigma shift the elasticity for relevant and other goods to more negative values. Deviations in median price elasticity compared to the theoretical analysis are induced by the lack of two-level structure in the theoretical example, while they also might point to higher-order effects regulating the elasticity dynamics. These are likely driven by the network interactions and complexities not accounted for in the simplified, randomized parameter draw for (*(A,B,C)* in fig. 3).

Volatility clustering of consumption price elasticity

To analyze the temporal dynamics of the simulated processes, we show a 5-year time series sample from our 20 years of simulations in fig. 4. While the consumption price elasticity emerging from *Acclimate* is fluctuating around its median, the economic stress in the agents trade network is dominated by heat stress in the northern hemisphere summertime and, thus, induces a periodic clustering of volatility of elasticity. This link between external forcing and the reaction of the utility maximizing consumers shows the dynamic nature of price elasticity under economic stress. While in this specific example, we recover the seasonal pattern of heat stress on the Northern Hemisphere, the described feedback mechanisms might drive volatility clustering of consumption price elasticities in any type of clustered economic stress.

Discussion and conclusion

We show analytically that consumption price elasticities are dynamic in response to economic shocks and demonstrate this behavior extending a numerical agent-based model of the world economy.

Based on the analysis of market emergent price elasticities resulting from utility maximization under a constraint budget, we show that substitution effects and relative price changes introduce a self regulating feedback loop. This leads to positive price elasticities manifesting from increasing demand in spite of increasing prices driven by utility maximizing consumers without behavioral assumptions. Thus, our results are consistent with standard assumptions of rational decision making. These theoretical results are reproduced in a complex agent-based supply chain model and show the need to consider complexity additional to ceteris paribus analyses in economic modeling. The qualitative differences we observe between baskets of goods indicate the need for an extension of existing models of price elasticity by heterogeneous modeling approaches.

We also observe, that seasonal economic stress induces seasonality in the volatility of price elasticity. While periods of volatility clustering is well-explored for financial markets and numerous behavioral explanations are discussed using agent-based modeling [22, 6, 30], in our case the connection between high volatility and economic stress provides a direct explanation. Additionally, this direct mechanism is potentially reinforced by the agents' herding behavior in our model due to utility functions of the same form. This stresses the importance of the development of methods to model the dynamics of consumption price elasticity overcoming the assumption of static elasticity. While there are discussions about the exact effects of the COVID-19 pandemic on supply chains [9, 4, 33, 34], it clearly showed that global economic connections foster the transmission and synchronization of economic stress. Even if this motivates initiatives to decouple economies, a full decoupling — with uncertain benefits, would be economically costly, if not infeasible. Moreover, for the pandemic scenario, there is evidence that decoupling rather reinforces negative consequences of regional lock-downs [4]. Thus, the observation of increased complexity of consumption price elasticity in a state of synchronized economic stress should be considered when modeling the impacts of economic crisis scenarios. A more

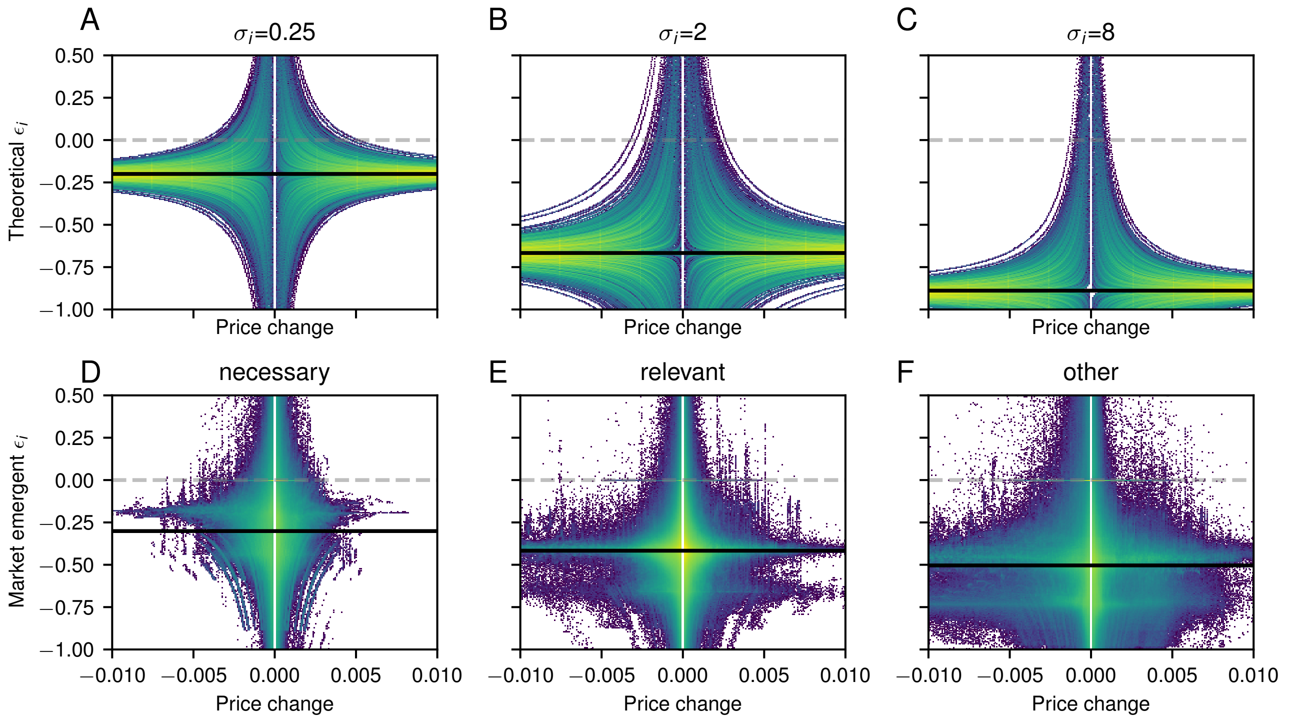

Fig. 3. Results of the full model are qualitatively in line with elasticity distributions randomly drawn from simplified theory. Analytical approximation in *(A,B,C)* shows the effect of σ_i corresponding to the baskets of 'necessary' (first column), 'relevant' (second column), and 'other' (third column) goods on the expected elasticity distribution for randomly fluctuating R_i. R_i is assumed to be normally distributed with mean 1 and variance ν that decreases with increasing σ_i to reflect the dampening effect of higher substitutability on R_i's volatility, i.e., *(A)* $\nu = 16 \cdot 10^{-4}$, *(B)* $\nu = 8 \cdot 10^{-4}$ and *(C)* $\nu = 4 \cdot 10^{-4}$. **Full model results** in *(D,E.F)* show the corresponding modeling results for *(A)* 'necessary' basket, *(B)* 'relevant' basket and *(C)* 'other' basket. Solid black line shows median elasticity. Distributions are plotted with log-scaling.

dynamic modeling of economic systems might reveal an overall tendency of economic systems to exhibit volatility clustering, which could be used as a potential early warning signal or a measure of economic stress.

We cannot provide a full assessment of potential inflationary pressure of economic shocks on the global economy due to a lack of a labor market and monetary policy agents in the current version of *Acclimate*. Nevertheless, our results might show one cause of such an inflationary pressure: Dynamic price elasticities inducing price increases due to the potential for positive price elasticity increasing demand in spite of increasing prices. Further, these dynamics suggest that any such exercise would need to consider the behavior of consumption agents carefully — assumptions about static price elasticities might underestimate the persistence of demand for elementary goods. Recent studies are so far unclear about whether climate change induced inflation is persistent [26] or decays after an initial shock [8]. Regarding supply chain disruptions during COVID-19, there is some evidence for the US [19] and Euro area [7] that bottlenecks in global supply chains contributed to the observed inflation, thus stressing the necessity for global trade sensitive modeling of economic activity.

While we present a theoretical mechanism and its manifestation in a complex numerical model of the world economy explaining dynamics of price elasticities, there are certain limitations of our study. First, we assume fixed substitution coefficients between different goods. While this is a reasonable assumption on short time scales, one could also investigate models with a more flexible substitutability between goods. Second, our analysis is based on a fixed consumption budget since our modeling approach does not consider wages driven by a labor market model. Third, our numerical modeling results are limited to one specific utility function due to constraints of computational effort, such that a wider comparison of different utility functions is omitted. While alternative forms might lead to slightly different behavior, we choose the nested CES structure since its limited number of parameters enables its application in our global modeling exercises.

In future research the presented methods for modeling consumption behavior in response to to economic shocks will be applied to analyze the inequalities of impacts of climate change on different income groups.

We conclude that the analytical description of the dynamics of price elasticity of utility maximizing consumers and their numerical modeling enables the exploration of the interactions of micro and macroeconomic processes driven by economic stress. The potential emergence of positive price elasticities shows that classic economic ceteris paribus analysis should be complemented by dynamic modeling to describe periods of economic stress.

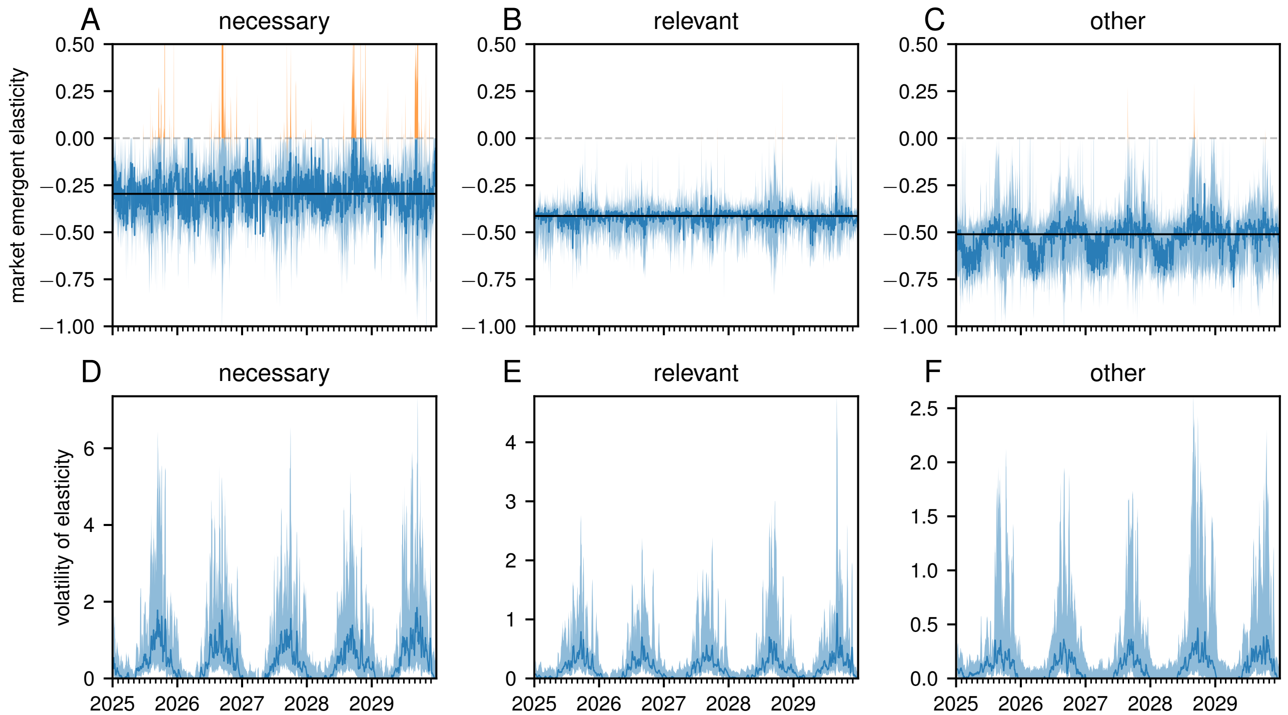

Fig. 4. Dynamics of price elasticity are stronger in periods of economic stress *(A,B,C)* show sample time-series of the market emerging elasticity for the respective consumption basket. Orange lines highlights positive elasticities. *(D,E.F)* show the corresponding 7-day volatility of market emerging elasticity. Solid blue lines show the median over the ensemble of all considered consumer agents, while shaded areas indicate the 16.66-83.33 percentile intervals. The solid black line in *(A,B,C)* shows the ensemble median over time. The definition of our volatility measure is given in the methods (eq. (18)).

Methods

Derivation of optimum conditions

Starting with eq. (1), it follows, that

$$\lambda\left(B^\star-\sum_{j\neq i}^{N} p_j x_j\right)=\frac{\partial U}{\partial x_i} \tag{10}$$

$$\Leftrightarrow \qquad \lambda=\frac{\sum_{i=1}^{N}\frac{\partial U}{\partial x_i}}{B^\star}, \tag{11}$$

and with the baseline relative change of quantity $q_i := \frac{x_i}{x_i^\star}$,

$$\frac{\partial U}{\partial x_i}\left(B^\star-p_i x_i\right)=p_i x_i\sum_{j\neq i}^{N}\frac{\partial U}{\partial x_j} \tag{12}$$

$$\Leftrightarrow \qquad \frac{\frac{\partial U}{\partial x_i}}{\sum_{j\neq i}^{N}\frac{\partial U}{\partial x_j}}=\frac{p_i q_i x_i^\star}{\sum_{j\neq i}^{N}\left(p_j q_j x_j^\star\right)}. \tag{13}$$

Hence, eq. (3) follows.

Derivation of $\mathbf{R_i}$

$$q_i=\frac{\frac{\partial U}{\partial x_i}}{\sum_{j\neq i}^{N}\frac{\partial U}{\partial x_j}}\frac{\sum_{j\neq i}^{N}p_j q_j x_j^\star}{p_i x_i^\star}$$

$$\Leftrightarrow \qquad q_i=\frac{{x_i^\star}^{\frac{1}{\sigma}}\,{x_i}^{-\frac{1}{\sigma}}}{\sum_{j\neq i}^{N}{x_j^\star}^{\frac{1}{\sigma}}\,{x_j}^{-\frac{1}{\sigma}}}\frac{\sum_{j\neq i}^{N}p_j q_j x_j^\star}{p_i x_i^\star}$$

$$\Leftrightarrow \qquad {q_i}^{1+\frac{1}{\sigma}}=\frac{\sum_{j\neq i}^{N}p_j q_j x_j^\star}{\sum_{j\neq i}^{N}{q_j}^{-\frac{1}{\sigma}}}\frac{1}{x_i^\star}\frac{1}{p_i}, \tag{14}$$

, thus eq. (7) and eq. (8) follow.

Acclimate

Acclimate is an agent-based model of the world economy using baseline data from the Eora [21] multi-regional input output (MRIO) tables. We provide a sketch of its general structure in the supplementary materials, figure S2. Since we dissaggregate China to province and the USA to state level resolution [35], we obtain a network with 264 regions (excluding regions with poor data quality). Dissaggregating consumption demand based on world bank development indicator income shares [1] and the assumption that all income quintiles consume equal amounts of food, we obtain 1320 individual consumption agents. These operate as consumers of final demand in a network with 6243 firm agents, which represent one of the 26 Eora sectors in each region. In total, our simulations are based on the modeling of 7563 individual agents under consecutive extreme event forcing of heat stress, river floods, and tropical cyclones as in [17] for a time-period of twenty years. For details about the *Acclimate* dynamics in the firm sector, we refer to the model description [27].

In the following, we present the new consumption decision dynamics and methods allowing to extract emerging price elasticity. Extending the existing *Acclimate* model by utility maximizing consumers enables us to evaluate differentiated trends in consumer behavior after economic shocks. For this, we endow each consumer agent with a nested CES utility function to maximize and observe the reaction to economic shocks. Noteworthy, there are no assumptions on behavioral drivers for the consumption decision, but pure *Homo oeconomicus* utility maximization. The two-level utility function considers goods in three broad baskets of *necessary*, *relevant* and *other* goods. The composition of the baskets based on the Eora sectors can be found in the supplementary materials, table S1. We use a plausible set of global parameters for the CES utility function to demonstrate the concept and its effects.

Utility function for *Acclimate* consumers

The utility function for a consumer in region r and income quintile q is given by

$$U_{rq}=\left(\sum_{i=1}^{G}\left({b_i}^{\frac{1}{\theta}}\left[\sum_{k=1}^{m_i}\left({a_k}^{\frac{1}{\sigma_i}}{x_{k\to rq}}^{\frac{\sigma_i-1}{\sigma_i}}\right)\right]^{\frac{\sigma_i}{\sigma_i-1}}\right)^{\frac{\theta-1}{\theta}}\right)^{\frac{\theta}{\theta-1}} \tag{15}$$

Each consumer optimizes their utility for G consumption baskets. Within each class of goods, the varying σ_i for $i \in 1,\ldots,B$ allows for a varying degree of intra-basket substitution, while θ controls inter-basket substitution. The share factors of good k in basket i for k $= 1, \ldots, m_i$ are chosen such that

$$a_k=\frac{x^\star_{k\to rq}}{\sum_{i=1}^{m_i}{x^\star}_{i\to rq}}, \tag{16}$$

while the basket share factors b_j for $j = 1, \ldots, G$ are chosen such that

$$b_j=\frac{\sum_{i=1}^{m_i}{x^\star}_{i\to rq}}{\sum_{i=1}^{M}{x^\star}_{i\to rq}}, \tag{17}$$

For the application of eqs. (15) to (17) in *Acclimate* we use $G = 3$ with three baskets classified as *necessary, relevant*, and *other* goods. We refer to the SI, supplementary table 1, for the exact basket specification, resulting in 5 'necessary', 12 'elevant', and 9 'other' goods. We choose $\sigma_{necessary} = 0.25$, $\sigma_{relevant} = 2$, $\sigma_{other} = 8$, and $\theta = 0.5$ for our trial simulations.

To summarize, the local utility optimization of each agent's consumption reacting to economic shocks and the calculation of market emergent price elasticities, as summarized in supplementary figure S3, enables to study changes of consumption price elasticity based on utility maximization.

Economic shock scenario

As a shock scenario for our trial simulation runs, we use one realization of the combined river flood, heat stress, and tropical cyclone shocks spanning the double decade 2020–2039 as presented in [17].

Definition of volatility measure

We measure volatility ν_w as the 7-day rolling standard deviation of relative changes of ϵ_i at time t. The latter are given by

$$\delta_{\epsilon_i}(t) := \frac{\epsilon_i(t-1) - \epsilon_i(t)}{\epsilon_i(t-1)}$$

for window size w. Then, the rolling mean reads

$$\bar{\delta}_{\epsilon_i}(t) := \frac{\sum_{k=t-w+1}^{t} \delta_{\epsilon_i}(k)}{w},$$

and the resulting volatility

$$\nu_w(t) := \sqrt{\frac{\sum_{k=t-w+1}^{t} \left(\delta_{\epsilon_i}(k) - \bar{\delta}_{\epsilon_i}(t)\right)^2}{w}}. \tag{18}$$

We choose $w = 7$ to analyze the small-scale dynamics of *market emergent price elasticity*.

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Supplementary Material

Supplementary material is available at PNAS Nexus online.

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Author contributions statement

L.Q. and A.L. designed the study and developed the theoretical feedback mechanism. L.Q. conducted the formal analysis. S.W., C.O. and A.L. developed the original Acclimate model. L.Q. developed the consumer extension with S.W. L.Q. handled the trial model simulations. All authors –L.Q., C.O., S.W., R.M. and A.L. – discussed the results. L.Q. wrote the first draft of the manuscript. All authors provided feedback and wrote the final manuscript.

Code Availability

The implementation of the *Acclimate* model is available as open source on `https://github.com/acclimate/acclimate`.

Analysis and plotting code will be made available on Github with publication.

Data availability

All data will be made available with publication in a public repository.

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