Accurate market price formation model with both supply-demand and trend-following for global food prices providing policy recommendations

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Recent increases in basic food prices are severely affecting vulnerable populations worldwide. Proposed causes such as shortages of grain due to adverse weather, increasing meat consumption in China and India, conversion of corn to ethanol in the United States, and investor speculation on commodity markets lead to widely differing implications for policy. A lack of clarity about which factors are responsible reinforces policy inaction. Here, for the first time to our knowledge, we construct a dynamic model that quantitatively agrees with food prices. The results show that the dominant causes of price increases are investor speculation and ethanol conversion. Models that just treat supply and demand are not consistent with the actual price dynamics. The two sharp peaks in 2007/2008 and 2010/2011 are specifically due to investor speculation, whereas an underlying upward trend is due to increasing demand from ethanol conversion. The model includes investor trend following as well as shifting between commodities, equities, and bonds to take advantage of increased expected returns. Claims that speculators cannot influence grain prices are shown to be invalid by direct analysis of price-setting practices of granaries. Both causes of price increase, speculative investment and ethanol conversion, are promoted by recent regulatory changes—deregulation of the commodity markets, and policies promoting the conversion of corn to ethanol. Rapid action is needed to reduce the impacts of the price increases on global hunger.

behavioral economics | agricultural commodities | food prices | nonequilibrium markets | global crisis

In 2007 and early 2008 the prices of grain, including wheat, corn, and rice, rose by over 100%, then fell back to prior levels by late 2008. A similar rapid increase occurred again in the fall of 2010. These dramatic price changes (1) have resulted in severe impacts on vulnerable populations worldwide and prompted analyses of their causes (2–57). Among the causes discussed are (*i*) weather, particularly droughts in Australia, (*ii*) increasing demand for meat in the developing world, especially in China and India, (*iii*) biofuels, especially corn ethanol in the United States and biodiesel in Europe, (*iv*) speculation by investors seeking financial gain on the commodities markets, (*v*) currency exchange rates, and (*vi*) linkage between oil and food prices. Many conceptual characterizations and qualitative discussions of the causes suggest that multiple factors are important. However, quantitative analysis is necessary to determine which factors are actually important. Although various efforts have been made, no analysis thus far has provided a direct description of the price dynamics. Here we provide a quantitative model of price dynamics demonstrating that only two factors are central: speculators and corn ethanol. We introduce and analyze a model of speculators describing bubbles and crashes. We further show that the increase in corn-to-ethanol conversion can account for the underlying price trends when we exclude speculative bubbles. A model combining both increasing ethanol conversion and speculators quantitatively matches food price dynamics. Our results imply that changes in regulations of commodity markets that eliminated restrictions on investments (58–62), and government support for ethanol production (63–66), have played a direct role in global food price increases.

The analysis of food price changes immediately encounters one of the central controversies of economics: whether prices are controlled by actual supply and demand or are affected by speculators who can cause "artificial" bubbles and panics. Commodity futures markets were developed to reduce uncertainty by enabling prebuying or selling at known contract prices. In recent years "index funds" that enable investors (speculators) to place bets on the increase of commodity prices across a range of commodities were made possible by market deregulation (58). The question arises whether such investors, who do not receive delivery of the commodity, can affect market prices. One thread in the literature claims that speculators cannot affect prices (67, 68). Others affirm a role for speculators in prices (2–5, 11–17, 45–47, 59, 69, 70), but there has been no quantitative description of their effect. The rapid drop in prices in 2008, consistent with bubble/crash dynamics, increased the conviction that speculation is playing an important role. Still, previous analyses have been limited by an inability to directly model the role of speculators. This limitation has also been present in historical studies of commodity prices. For example, analysis of sharp commodity price increases in the 1970s (71) found that they could not be due to actual supply and demand. The discrepancy between actual prices and the expected price changes due to consumption and production was attributed to speculation, but no quantitative model was provided for its effects. More recently, statistical (Granger) causality tests were used to determine whether any part of the price increases in 2008 could be attributed to speculative activity (15, 72, 73). The results found statistical support for a causal effect,

Significance

Recent increases in food prices are linked to widespread hunger and social unrest. The causes of high food prices have been debated. Here we rule out explanations that are not consistent with the data and construct a dynamic model of food prices using two factors determined to have the largest impact: corn-to-ethanol conversion and investor speculation. We overcome limitations of equilibrium theories that are unable to quantify the impact of speculation by using a dynamic model of trend following. The model accurately fits the data. Ethanol conversion results in a smooth price increase, whereas speculation results in bubbles and crashes. These findings significantly inform the discussion about food prices and market equilibrium and have immediate policy implications.

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but the magnitude of the effect cannot be estimated using this technique.

The controversy about commodity price dynamics parallels discussions of market dynamics more generally. Traditional economics assumes market prices are determined by events that affect fundamental value (i.e., news). The statistical properties of news then map onto price behaviors. A distinct approach considers the price dynamics as a result of market trader (agent) behaviors (74–83). Diverse assumptions, especially about trader strategies that change over time, lead to intrinsic market price dynamical behaviors, which are distinct from the traditional assumptions about news behavior. Models of the role of information delays in the beef commodity market have also been motivated by considering hetrogeneous agents (84, 85).

Here we construct a behavioral model guided by the concepts of universality and renormalization group applied to dynamical processes (86–88), which motivates including only lowest-order (largest-scale) terms. Because many traders are involved in market dynamics, renormalization group implies that observed behavior results only from "relevant" parameters (i.e., those external and internal factors that affect behavior at largest aggregate scales). This strategy is particularly pertinent to analysis of the large food price changes discussed here. In this approach the incremental change in price is given by

$$P(t+1)-P(t)=-k_{sd}(P(t)-P_e(t))+k_{sp}[P(t)-P(t-1)] + \sum_{i=1}^{N} k_i[P_i(t)-P_i(t-1)], \quad [1]$$

which is an expansion to first order in variables describing the system and can be converted to a recursive iterative map by adding $P(t)$ to both sides. Although not constructed as an agent model, the individual terms can be interpreted as arising from agent behaviors. The first term can be identified with Walrasian buy-low sell-high investors with a fundamental price $P_e(t)$. The second term can be identified with trend following speculators, who buy when the price goes up and sell when the price goes down. The absence of any reference to a fundamental price in the second term is distinct from more typical agent models, although it follows from the construction of the model. The final sum incorporates the influence of traders switching to N other markets with prices $P_i(t)$ indexed by i. This approach may be considered as a new way to bridge between traditional and agent-based concepts. The first-order approximation gives a dynamical version of the traditional equilibrium market and is extended to include relevant terms that lead to intrinsic self-generated dynamical price behaviors.

Given Eq. **1** we (*i*) identify the characteristic behaviors of this model to build intuition about how it relates to price behavior, (*ii*) identify the external factors that should be included in P_e for food prices, and (*iii*) motivate economically the inclusion of trend following in commodity futures markets. Armed with the external factors, the ultimate objective is a validation of Eq. **1** by direct comparison with empirical data. The validation is reduced to a few-parameter fit. We then address the important topic of inventory dynamics for out-of-equilibrium prices and infer policy implications. Given the multiple steps involved, we summarize the key findings here. We defer the building of mathematical intuition to *SI Appendix* and use *Results* for the discussion of external factors, the motivation of including trend following, and validation tests. The topics of inventory dynamics and policy implications are in *Discussion*.

The behavior of the model can be understood as follows. The first term results in exponential convergence to equilibrium—if investors believe supply and demand do not match, there is a countering (Walrasian) force toward equilibrium prices. The incorporation of trend following manifests in bubble and crash dynamics. When prices increase, trend following leads speculators to buy, contributing to further price increases. If prices decrease speculators sell, contributing to further price declines. The interplay of trend following and equilibrium-restoring transactions leads to a variety of behaviors depending on their relative and absolute strengths. For a sufficiently large speculator volume, trend following causes prices to depart significantly from equilibrium. Even so, as prices further depart from equilibrium the supply-and-demand restoring forces strengthen and eventually reverse the trend, which is then accelerated by the trend following back toward and even beyond the equilibrium price. The resulting oscillatory behavior, consisting of departures from equilibrium values and their restoration, matches the phenomenon of bubble and crash dynamics. The model clarifies that there are regimes in which traders have distinct effects on the market behavior, including both stabilizing and destabilizing the supply-and-demand equilibrium.

To apply Eq. **1** to food prices we systematically consider proposed factors that may contribute to $P_e(t)$. We provide quantitative evidence that justifies excluding all of those proposed from playing a major role in recent price changes except corn-to-ethanol conversion. We therefore use ethanol demand as the driver of equilibrium prices $P_e(t)$. In addition to trend following, we include market switching to equities (using the S&P 500 Index time series) and bonds (using the US 10-y treasury note price time series) in the last term, so that $N=2$. We fit the output of the entire model by adjusting four constants (k_{sd}, k_{sp}, k_{equity}, and k_{bonds}) in Eq. **1**, with the additional condition that the speculator term starts at the time of the fall of the mortgage market in early 2007. Results are shown in Fig. 1 for a fit until March 2011, an out-of-sample continuation until January 2012, and a fit until January 2012. The fits were originally performed contemporaneously with the data in 2011 and 2012 (89, 90). We note that the out-of-sample data change direction as does the theory without change of parameters. The results demonstrate remarkably good quantitative agreement. The model does not include stochastic variation, which could be included, for example in $P_e(t)$, but is not found to be needed—the time series is generated deterministically with only a few parameters, without

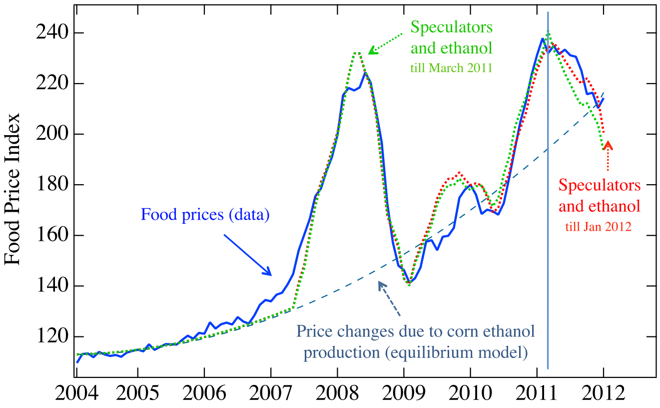

Fig. 1. Food prices and model simulations. The FAO Food Price Index (blue solid line) (1); the ethanol supply-and-demand model (blue dashed line), where dominant supply shocks are due to the conversion of corn to ethanol so that price changes are proportional to ethanol production; and the results of the speculator and ethanol model (green and red dotted lines), which adds speculator trend following and switching among investment markets, including commodities, equities, and bonds. The green curve is fit until March 2011 (vertical blue bar) and the red curve is fit until January 2012. Thus, the matching of the former to data after March 2011 is an out-of-sample fit. Green curve parameters: $k_{sd}=0.098$, $k_{sp}=1.29$, $k_{equity}=-0.095$, and $k_{bonds}=-67.9$. Red curve parameters: $k_{sd}=0.093$, $k_{sp}=1.27$, $k_{equity}=-0.085$, and $k_{bonds}=-48.2$.

additional parameters at every time step. Nevertheless, the corresponding statistical validation of both fits has $P < 10^{-60}$, and there is no difference between the statistical validation for the last 10 mo of the out-of-sample continuation and the complete fit for that period; both have $P < 0.001$. Efforts to fit the data using either just a supply-and-demand model or just a speculator model were not successful. The results are a validation of the approach of eliminating all but the most relevant external factors and internal behaviors.

Our results also provide a strong validation for the role of nontraditional behavioral agents in market dynamics. Systematically considering and including only the largest external factor provides evidence to counter the criticism that external factors might be identified that could account for behavioral results. Explicitly modeling external factors is generally difficult to do in most markets. We note other analyses often consider changing trader behavior leading to market statistical properties; our analysis is done in the limit of no change in the amounts of each type of trader, (k_{sd}, k_{sp}), once the speculative behavior starts in 2007. The variation of trader strategies does not seem to be relevant over this time frame for this market at the largest scale.

Our results have direct implications for understanding the complex dependencies of global economics and the societal effects of food prices. The flows of capital in global markets can be traced from the financial crisis through our speculator model. Owing to the collapse of the mortgage market and the stock market crash, investors moved money to the commodities market. This resulted in boom–bust cycles, including in food and other commodities. In a separate paper we describe the connection between food prices and the recent social unrest, violence, and government changes in North Africa and the Middle East (91). Our analysis extends the dominoes of global interdependence from housing to the stock market, to the commodities market, and to social unrest. Policy discussions should recognize the extent of such links.

Results

We divide our results into three parts: considering and mostly excluding potential factors that might contribute to fundamental shifts of food prices, providing various economic motivations for inclusion of speculator investment in commodity markets, and validation tests of the quantitative model.

Fundamental External Factors. Candidates for factors affecting fundamental value include weather, increasing consumption of meat and other livestock products in developing nations, the use of corn for ethanol production, changes in exchange rates, and energy costs.

Weather. The most common explanation provided by news interpreters for the 2008 food price increases was the drought in Australia (92–94). However, the production of grains in Australia does not correlate with global production (Fig. 2*A*). The Pearson correlation coefficient of the two time series over the last 20 y is only $\rho = 0.17$. Other countries have increases and decreases based upon variable conditions and therefore the changes in global production are not well described by Australia's production. The fraction of global grain production from Australia [circa 1.8% by weight in 2010 (95)] is therefore not sufficient to be a significant causal factor at the magnitude of influence of recent price changes, even if it might be at smaller scales and shorter time frames. In particular, the low production in Australia in 2006 did not coincide with a global production decrease, and in 2007 both Australia and the world had increases in production (Fig. 2*A*). Droughts in Australia, and global weather conditions more generally, are therefore unable to explain the recent food price changes.

Diet. A widely cited potential longer-term cause of increasing prices is a change of diet from grains to meat and other livestock products, as a result of economic development (99, 100). Development of China, India, and other countries, comprising more than one-third of the world population, has created higher food demands as the diet of these countries changes. Changes in diet might have a large impact on the consumption of feed grains, because the ratio of animal feed to meat energy content has been estimated to be as high as 4:1, 17:1, and 50:1 for chicken, pork, and beef, respectively (101). However, the increasing demand for grain in China and India has been met by internal production and these countries have not, in recent years, been major participants in the global grain markets (95). Indeed, demand growth in these countries slowed in the years leading up to the food price spike in 2008 (4, 12), and the countries combined remained net exporters (12, 22). As shown in Fig. 2*B*, their combined net international export of grains has decreased by 5 million metric tons (mmt), from 7 mmt in 2004 to 2 mmt in 2010 (95). In contrast, the increase in the amount of corn used for ethanol production is 20 times larger, 95 mmt [if we subtract a feed byproduct of ethanol production (96) it is 13 times larger, 67 mmt]. The increase in demand due to corn feed in China, for all purposes but primarily for hogs (the dominant source of meat), from 2004 to 2010 is 22 mmt, less than one-quarter of the ethanol demand (one-third after feed byproduct). Even this amount was mostly met by internal production increases. Import and export policies isolate the Chinese domestic grain market and domestic prices of feed grains do not track global prices, so only the reduction of net export affects the global market. The impact on global food prices of changes in feed grain demand due to economic development is therefore negligible with respect to US demand for corn for ethanol.

Ethanol. Only a small fraction of the production of corn before 2000, corn ethanol consumed a remarkable 40% of US corn crops in 2011 (95), promoted by US government subsidies based upon the objective of energy independence (63–66) and advocacy by industry groups (66, 102, 103). Corn serves a wide variety of purposes in the food supply system and therefore has impact across the food market (104–106). Corn prices also affect the price of other crops due to substitutability at the consumer end and competition for land at the production end (2). There have been multiple warnings of the impact of this conversion on global food prices and world hunger (107–115) and defensive statements on the part of industry advocates (116, 117). Among quantitative studies, ethanol conversion is most often considered to have been the largest factor in supply-and-demand models. Absent a model of speculators, ethanol conversion is sometimes considered the primary cause of price increases overall. However, ethanol conversion itself cannot describe the dynamics of prices because ethanol production has been increasing smoothly since 2004. Therefore, it cannot explain the sharp decline of prices in 2008. We show that ethanol can account for the smoothly rising prices once the high peaks are accounted for by speculation. Fig. 2*C* compares annual corn ethanol production and food prices. During the period 1999–2010, ignoring the 2007–2008 peak, the two time series can be well fitted by the same quadratic growth (no linear term is needed). The quadratic coefficients are 0.0083 ± 0.0003 for corn ethanol and 0.0081 ± 0.0003 for food prices, which are the same within fitting uncertainty. The quality of the fits is outstanding, with R^2 values of 0.986 and 0.989, respectively. The Pearson correlation coefficient of the food price and ethanol annual time series is $\rho = 0.98$. The parallel increase of the two time series since 2004 suggests that corn ethanol is likely to be responsible for the underlying increase in the cost of food during this period. The relationship between food prices and corn-to-ethanol conversion can be obtained by modeling the impact of corn ethanol production as a dominant shock to the agricultural system. According to this model, other supply-and-demand factors would leave the prices mostly unchanged. Before 1999 corn ethanol production and prices are not correlated because of the

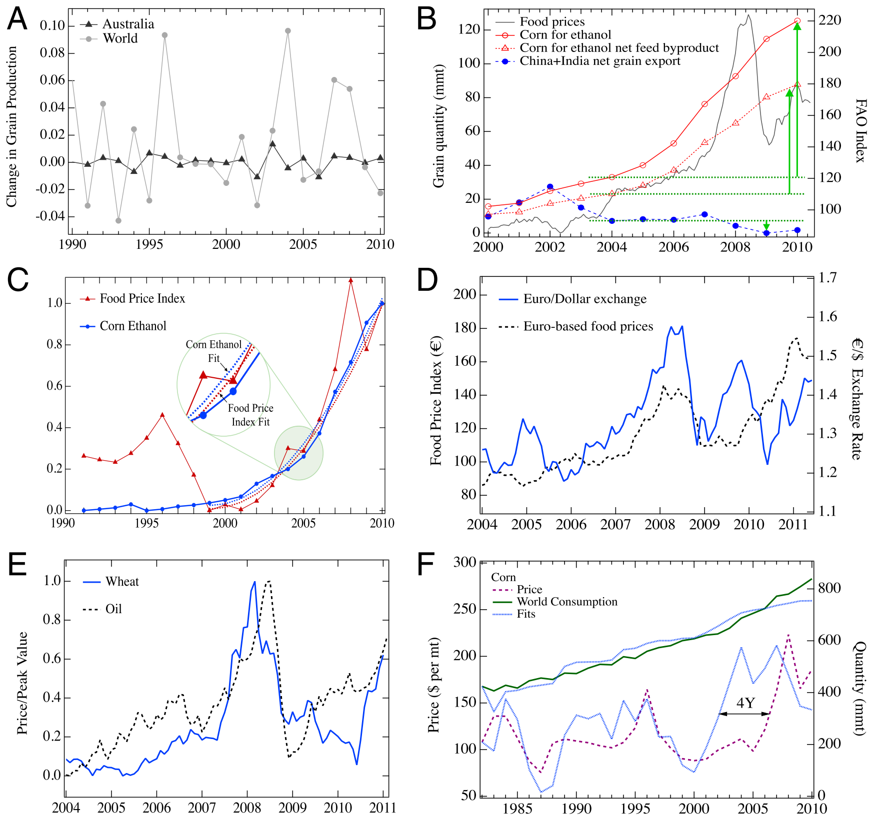

Fig. 2. Analysis of possible causes of food price increases. (*A*) Weather, specifically droughts in Australia. Comparison of change in world (gray) and Australian (black) grain production relative to total world production by weight (95). The correlation is small. (*B*): Changing diets in emerging countries, specifically meat consumption in China. Comparison of China and India net grain export (dashed blue) to the US corn–ethanol conversion demand (solid red) and net demand after feed byproduct (dotted red) (96), and FAO food price index (solid black). Arrows show the maximum difference from their respective values in 2004. The impact of changes in China and India is much smaller. (*C*) Ethanol production. US corn used for ethanol production (blue circles) and FAO Food Price Index (red triangles). Values are normalized to range from 0 to 1 (minimum to maximum) during the period 1990–2010. Dotted lines are best fits for quadratic growth, with coefficients of 0.0083 ± 0.0003 and 0.0081 ± 0.0003, respectively. The 2007/8 bubble was not included in the fit or normalization of prices (95). (*D*) Currency conversion. Euro-based FAO Food Price Index (dashed black), euro/dollar exchange (solid blue) (97). Both have peaks at the same times as the food prices in dollars. However, food price increases in dollars should result from decreasing exchanges rates. (*E*) Oil prices. Wheat price (solid blue) and Brent crude oil price (dashed black). The peak in oil prices follows the peak in wheat prices and so does not cause it (98). (*F*) Supply and demand. Corn price (dashed purple) and global consumption (solid green) along with best fits of the supply-and-demand model (blue) (95). Price is not well described after 2000.

small amount of ethanol production. Price variation during that period must be due to other causes.

Exchange rates. Dollar-to-euro conversion rates are, at times, correlated to commodity prices (2, 118). During these periods an increase in commodity prices coincides with an increase in euro value relative to the dollar. It has been suggested that the reason that food prices increased in dollars is because commodities might be priced primarily in euros, which would cause prices to rise in dollars. This has been challenged on a mechanistic level due to the dominance of dollars as a common currency around the world and the importance of the Chicago futures market (Chicago Board Options Exchange) (119). However, more directly, such a causal explanation is not sufficient, because the prices of commodities in euros have peaks at the same times as those in dollars, as shown in Fig. 2*D*. Because the United States is a major grain exporter, a decline in the dollar would give rise to a decrease in global grain prices. (The effect is augmented by non-US grain exports that are tied to the dollar, and moderated by supply-and-demand corrections, but these effects leave the direction of price changes the same.) The opposite is observed. Moreover, the exchange rate also experienced a third peak in 2009, between the two food price peaks in 2008 and 2011. There is no food price peak either in euros or dollars in 2009. This suggests that the correlation between food prices and exchange rates is not fundamental but instead may result from similar causal factors.

Energy costs. Some researchers have suggested that increasing energy prices might have contributed to the food prices (5, 22, 108, 119). This perspective is motivated by three observations: the similarity of oil price peaks to the food price peaks, the direct role of energy costs in food production and transportation, and the possibility that higher energy prices might increase demand for ethanol. Careful scrutiny, however, suggests that energy costs cannot account for food price changes. First, the peak of oil prices occurred after the peak in wheat prices in 2008, as shown in Fig. 2*F*. Second, US wheat farm operating costs, including direct energy costs and indirect energy costs in fertilizer, increased from $1.78 per bushel in 2004 to $3.04 per bushel in 2008 (120). The increase of $1.26, although substantial, does not account for the $4.42 change in farmer sales price. More specifically, the cost of fertilizers was about 5% the total value of wheat [the value of the global fertilizer market was $46 billion in 2007 (121), 15% of which was used for wheat (122); the value of the global wheat market was $125 billion (95, 98)]. Third, the demand from ethanol conversion (Fig. 2*D*) has increased smoothly over this period and does not track the oil price (Figs. 2*E* and 3). The connection between oil prices and food prices is therefore not the primary cause of the increase in food prices. Indeed, the increased costs of energy for producers can be seen to be an additional effect of speculators on commodity prices. As shown in Fig. 3, a large number of unrelated commodities, including silver and other metals, have a sharp peak in 2008. Given that some of the commodities displayed cannot be linked to each other by supply-and-demand consideration (i.e., they are not complements or substitutes, and do not have supply chain overlaps), the similarity in price behavior can be explained by the impact of speculators on all commodities. Metal and agricultural commodity prices behave similarly to the energy commodities with which they are indexed (123). It might be supposed that the increased cost of energy should be considered responsible for a portion of the increase in food prices. However, because the increases in production cost are not as large as the increases in sales price, the increase in producer profits eliminates the necessity for cost pass-through. The impact of these cost increases would not be so much directly on prices, but rather would moderate the tendency of producers to increase production in view of the increased profits.

Speculation. The role of speculation in commodity prices has been considered for many years by highly regarded economists (70, 71). There is a long history of speculative activity on

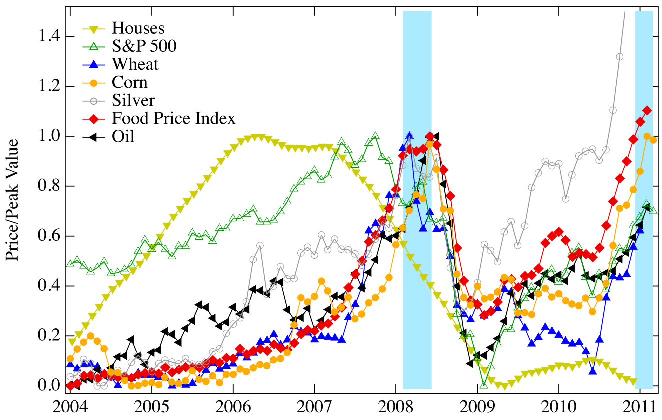

Fig. 3. Time dependence of different investment markets. Markets that experienced rapid declines, "the bursting of a bubble," between 2004 and 2011: houses (yellow) (135), stocks (green) (136), agricultural products (wheat in blue, corn in orange) (95), silver (gray) (98), food (red) (1), and oil (black) (98). Vertical bands correspond to periods of food riots and the major social protests called the "Arab Spring" (91). Values are normalized from 0 to 1, minimum and maximum values, respectively, during the period up to 2010.

commodity markets and regulations were developed to limit its effects (124–126). Recently claims have been made that there is no possibility of speculator influence on commodity prices because investors in the futures market do not receive commodities (67, 68). However, this claim is not supported by price-setting practices of granaries, which set spot (cash) market prices according to the Chicago Board of Trade futures exchange, with standard or special increments to incorporate transportation costs, profits, and, when circumstances warrant, slight changes for over- or undersupply at a particular time (127). The conceptual temporal paradox of assigning current prices based upon futures is not considered a problem, and this makes sense because grains can be stored for extended periods.

If commodities futures investors determine their trading based upon supply-and-demand news, the use of the futures market to determine spot market prices, discounting storage costs, would be a self-consistent way of setting equilibrium prices (128–130). However, if investors are ineffective in considering news or are not motivated by supply-and-demand considerations, deviations from equilibrium and speculative bubbles are possible. When prices depart from equilibrium, accumulation or depletion of inventories may result in an equilibrium-restoring force. This impact is, however, delayed by market mechanisms. Because producers and consumers generally hedge their sales and purchases through the futures market, transactions at a particular date may immediately affect food prices and decisions to sell and buy but affect delivery of grains at a later time when contracts mature. The primary financial consequences of a deviation of prices from equilibrium do not lead to equilibrium-restoring forces. Producers, consumers, and speculators each have gains and losses relative to the equilibrium price, depending on the timing of their transactions, but the equilibrium price is not identified by the market. Profits (losses) are made by speculators who own futures contracts as long as futures prices are increasing (decreasing), and by producers as long as the prices are above (below) equilibrium. When prices are above equilibrium consumers incur higher costs, which may reduce demand. Producers may increase production due to higher expected sales prices. The result of this reduction and increase is an expected increase in inventories when futures contracts mature after a time delay of 6 to 12 mo, an agricultural or financial planning cycle. Finally, the feedback between increased inventories and price corrections requires investors to change their purchases. First the information about increased inventories must become available. Even with information about increasing inventories, the existence of high futures prices can be interpreted as a signal of increased future demand, further delaying market equilibration. Speculatively driven bubbles can thus be expected to have a natural duration of a year or longer (Fig. 3). [We note that it is possible to relate trend following speculators to the "supply of storage" concept in which current inventories increase due to higher expected future prices (131, 132). However, in doing so we encounter paradoxes of recursive logic; see *SI Appendix* for more details.]

We review the empirical evidence for the role of speculation in food prices, which includes the timing of the food price spikes relative to the global financial crisis, the synchrony of food price spikes with other commodities that do not share supply-and-demand factors, the existence of large upward and downward movement of prices consistent with the expectations of a bubble and bust cycle, statistical causality analysis of food prices increasing with commodity speculator activity, and an inability to account for the dynamics of prices with supply-and-demand equations despite many economic analyses. We add to these an explicit model of speculator dynamics that quantitatively fits the price dynamics.

The mechanisms of speculator-driven food price increases can be understood from an analysis of the global consequences of the financial crisis. This analysis connects the bursting of the US real-estate market bubble and the financial crisis of 2007–2008 to the global food price increases (133, 134). Fig. 3 shows the behavior of the mortgage market (housing prices), stock market (S&P 500), and several commodities: wheat, corn, silver, oil, and the FAO food price index. The increase in food prices coincided with the financial crisis and followed the decline of the housing and stock markets. An economic crisis would be expected to result in a decrease in commodity prices due to a drop in demand from lower overall economic activity. The observed counterintuitive increase in commodity prices can be understood from the behavior expected of investors in the aftermath of the collapse of the mortgage and stock markets: shifting assets to alternative investments, particularly the commodity futures market (137–139). This creates a context for intermittent bubbles, where the prices increase due to the artificial demand of investment, and then crash due to their inconsistency with actual supply and demand, only to be followed by another increase at the next upward fluctuation. The absence of learning behavior can be explained either by the "greater fool theory," whereby professionals assume they can move their assets before the crash and leave losses to less-skilled investors, or by the hypothesis that traders are active for just one price cycle, and that the next cycle will see new traders in the market. Even without a quantitative analysis, it is common to attribute rapid drops in prices to bubble-and-crash dynamics because the rapid upward and downward movements are difficult to reconcile with normal fundamental supply-and-demand factors (2, 140, 141).

In addition to the timing of the peak in food prices after the stock market crash, the coincidence of peaks in unrelated commodities including food, precious and base metals, and oil indicates that speculation played a major role in the overall increase (142). An explanation of the food price peaks in 2008 and 2011 based upon supply and demand must not only include an explanation of the rise in prices of multiple grains, including wheat, corn, and rice, but must separately account for the rise in silver, oil, and other prices. In contrast, speculator-driven commodity bubbles would coincide after the financial crisis because of the synchronous movement of capital from the housing and stock markets to the commodity markets. Moreover, the current dominant form of speculator investment in commodity markets is in index funds (69), which do not differentiate the behavior of different commodities, because they are aggregate bets on the overall commodity market price behavior. Such investor activity acts in the same direction across all commodities, without regard to their distinct supply-and-demand conditions. The relative extent to which each type of commodity is affected depends on the weighting factors of its representation in index fund investing activity compared with the inherent supply-and-demand-related market activity.

Recently, the growth of commodity investment activity has been studied in relation to commodity prices (2, 15, 70, 72). Because index fund investments are almost exclusively bets on price increases (i.e., "long" rather than "short" investments), the investment activity is an indication of pressure for price increases. Increases in measures of investment have been found to precede the increases in prices in a time series (Granger) causality analysis (15, 72). [An Organisation for Economic Co-operation and Development study claiming that speculation played no role (143, 144) has been discounted due to invalid statistical methods (123).] Granger causality tests also show the influence of futures prices on spot market prices (73). The causality analysis results provide statistical evidence of a role of speculative activity in commodity prices. However, they do not provide quantitative estimates of the magnitude of the influence.

For many analyses, the absence of a manifest change in supply and demand that can account for the large changes in prices is considered strong evidence of the role of speculators. As we described in the previous section, supply-and-demand analyses of grain prices do not account for the observed dynamics of price behavior. None of the causes considered, individually or in combination, has been found to be sufficient. *SI Appendix*, section A reviews multiple efforts that have not been able to fit the changes in food prices to fundamental causes. *SI Appendix*, Fig. S1 shows explicit quantitative supply and demand models do not match prices for corn, wheat, and rice. As with analyses of commodity price changes in relation to supply and demand in the 1970s, such an absence is evidence of the role of speculators (71).

Validation Tests. We constructed a model of price dynamics including fundamental causes and speculator trend following (Eq. **1**, see *SI Appendix* for more details). Trend following results in an increase in investment when prices are rising and a decrease when prices are declining. Our results describe bubble-and-crash dynamics when certain relationships hold between the amount of speculative investment activity and the elasticity of supply and demand. The resulting price oscillations can be modified by investors switching between markets to seek the largest investment gains. When we include trend following, market switching behaviors, and the supply-and-demand changes only for corn-to-ethanol conversion, the results, shown in Fig. 1, provide a remarkably good fit of the food price dynamics. We find the time scale of speculative bubbles to be 11.8 mo, consistent with annual financial planning cycles and the maturation of futures contracts for delivery. Although there have been no such direct models that match observed price dynamics, trend following has been analyzed theoretically as a mechanism that can undermine fundamental price equilibrium (145, 146) and is a central component of actual investing: Advisors to commodity investors provide trend-following software and market investment advice based upon "technical analysis" of time series (147). Such market investment advice does not consider weather or other fundamental causes. Instead, it evaluates trends of market prices and their prediction using time series pattern analysis. Trend following is also at the core of agent-based market models (74–83).

We performed additional tests to see whether models could be fitted to the data that include either just speculation or just supply and demand, alternative null hypotheses.

We tested the possibility of a speculator model without external supply-and-demand factors. We find that without ethanol demand the speculative oscillations are unable to fit the dynamics of food prices for any value of the parameters (*SI Appendix*, section F).

Although ethanol alone cannot account for the peaks (Fig. 2*C*), we considered whether discrepancies of supply and demand for individual grains could describe them. The many reasons for changes in supply and demand can be considered together if they result in a surplus or deficit that is the primary reason for changes in grain inventories. Inventories can then be used as an indicator of supply-and-demand shocks to construct a quantitative model of prices (118). However, estimates provided by the US Department of Agriculture (95) of supply and demand are not consistent with global food prices when considered within such a model. The example of corn is shown in Fig. 2*F* (see also *SI Appendix*, Fig. S1). Prices shift upward if there is a deficit and downward if there is a surplus. In principle, the model allows a fit of both the observed price of the commodity and its consumption (or production). Before 2000 the main features of price dynamics can be fit by the model, consistent with earlier studies on the role of supply and demand (148, 149). However, since 2000, both the price and consumption values, including the recent large price increases, are not well described. There are reductions in the inventories around the year 2000, which give rise to significant price increases according to the model. However, the timing of these model-derived price increases precedes by 3 to 4 y the actual price increases. Also, the model implies an increase in consumption at that time that does not exist in the consumption data. Among the reasons for a reduction in reserves in 2000 is a policy change in China to decrease inventories (8, 150). Such a policy change would affect reserves but would not describe market supply and demand. Another reason for the inability for the supply-and-demand model to describe prices is the role of speculation as discussed above, and shown in Fig. 1. The high peaks of recent price behavior have also suggested to some that the mechanism is a decline of supply-and-demand elasticities, that is, high sensitivity of prices to small variations in supply-and-demand quantities (8). However, for this explanation to be valid, supply-and-demand shocks must still correspond to price dynamics, and this connection is not supported in general by Granger causality analysis (2, 15).

We note that our analysis of the effect of commodity investments on the food price index aggregates the impact of speculator investment across multiple grains. However, it is enlightening to consider the impact on the rice price dynamics in particular. The direct impact of speculators on rice is small because rice is not included in the primary commodity index funds, because it is not much traded on the US exchanges. Instead, the price of rice is indirectly affected by the prices of wheat and corn, especially in India, where wheat and rice can be substituted for each other. A sharp price peak in rice occurred only in 2008 (there is no peak in 2010) and this peak can be directly attributed to the global reaction to India's decision, in the face of rising wheat prices, to stop rice exports (2, 13, 151). The observation that rice did not have the behavior of other grains is consistent with and reinforces our conclusions about the importance of speculators in the price of corn and wheat, and thus food overall.

Discussion

Inventory Dynamics. Prices above equilibrium reduce demand and increase supply, leading to accumulation of grain inventories. Accumulation or depletion of inventory is often cited as the reason for rapid adjustment of prices toward equilibrium. However, whereas prices affect decisions immediately, delivery occurs after futures contract maturation. Futures contracts may be bought with maturity horizons at intervals of 3, 6, 9, and 12 mo, or more. The expected time delay is the characteristic time over which producers and consumers choose to contract for delivery, reflecting their hedging and planning activities, and can be reasonably estimated to be 6 mo to a year due to both agricultural cycles and financial planning. Thus, our model predicts that price deviations from equilibrium will be accompanied after such a time delay by changes in grain inventories. Fig. 4 shows that this prediction is consistent with empirical data (95). World grain inventories increased most rapidly between September 2008 and 2009, 1 y after the first speculative bubble. [Claims of decreasing inventories refer to the period before 2008 (152).] Inventories continued to increase, but less rapidly, 1 y after the near-equilibrium prices of 2009. According to the model, this period involved a rapid increase in corn use for ethanol production and shifting of food consumption to other grains, which was a major shock to the agriculture and food system. The increasing inventories are not consistent with supply-and-demand reasons for the price increases in 2010 but are consistent with our model in which the rising prices in 2010 are due to speculation.

As inventories increase, inventory information becomes available after an additional time delay. This information could influence investors, leading to the kind of Walrasian selling and buying that would reverse trends and restore equilibrium prices (i.e., cause a crash). The market reaction for pricing might be delayed further by the time participants take to react to these signals. Still, this provides an estimate of the duration of speculative bubbles. Indeed, the time until the peak of the bubbles of ~12 mo in both 2007–8 and 2010–11 provides a better estimate of time frames than the coarser inventory data do and is consistent with the financial planning time frames of producers and consumers. This suggests that investors may only be informed after actual supply-and-demand discrepancies are manifest in changing inventories. The existence of a second speculator bubble in 2010 raises the question of why speculators did not learn from the first crash to avoid such investing. Speculators, however, profited from the increase as well as lost from the decline and they may have an expectation that they can successfully time market directional changes, leaving others with losses (the greater fool theory).

The recent increasing inventories also raise humanitarian questions about the current global food crisis and efforts to address hunger in vulnerable populations in the face of increasing world prices (153–156). The amount of the increase in inventories—140 mmt from September 2007 to September 2010—is the amount consumed by 440 million individuals in 1 y. According to our model, the reason much of this grain was not purchased and eaten is the increase in food prices above equilibrium values due to speculation. This unconsumed surplus along with the 580 mmt of grain that was used for ethanol conversion since 2004 totals 720 mmt of grain, which could otherwise have been eaten by many hungry individuals. These outcomes are not only ethically disturbing, they

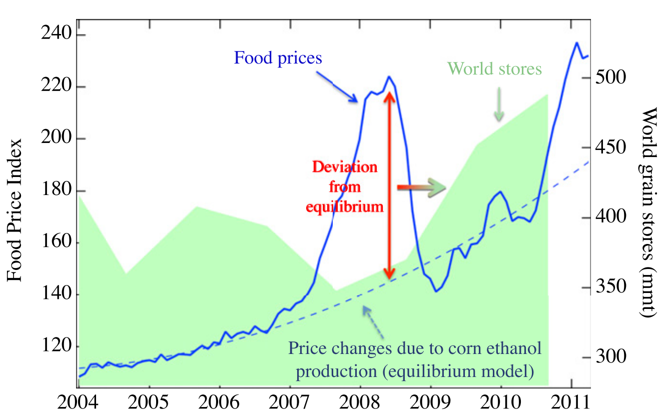

Fig. 4. Impact of food prices on grain inventories. A deviation of actual prices (solid blue curve) from equilibrium (dashed blue curve) indicated by the red arrow leads to an increase in grain inventories (green shaded area) delayed by approximately a year (red to green arrow). This prediction of the theory is consistent with data for 2008/2009. Increasing inventories are counter to supply-and-demand explanations of the reasons for increasing food prices in 2010. Restoring equilibrium would enable vulnerable populations to afford the accumulating grain inventories.

are also failures of optimal allocation according to economic principles. The deregulation of commodity markets resulted in nonequilibrium prices that caused a supply-and-demand disruption/disequilibrium driving lower consumption and higher production—inventories accumulated while people who could have afforded the equilibrium prices went hungry. Regulation of markets and government subsidies to promote corn-to-ethanol conversion have distorted the existing economic allocation by diverting food to energy use. This raised equilibrium prices, increased energy supply by a small fraction [US corn ethanol accounted for less than 1% of US energy consumption in 2009 (157)] and reduced grain for food by a much larger one [US corn used for ethanol production is 4.3% of the total world grain production, even after allowing for the feed byproduct (95, 96)]. The failures of both deregulation and regulation ably demonstrate that the central issue for policy is not whether to regulate, but how to choose the right regulations.

Policy Implications. A parsimonious explanation that accounts for food price change dynamics over the past 7 y can be based upon only two factors: speculation and corn-to-ethanol conversion. We can attribute the sharp peaks in 2007/2008 and 2010/2011 to speculation and the underlying upward trend to biofuels. The impact of changes in all other factors is small enough to be neglected in comparison with these effects. Our analysis reinforces the conclusions of some economic studies that suggest that these factors have the largest influence (2, 158). Our model provides a direct way to represent speculators, test if they can indeed be responsible for price effects, and determine the magnitude of those effects. The pricing mechanisms of the spot food price market confirm that futures prices are the primary price-setting mechanism, and that the duration of commodity bubbles is consistent with the delay in supply-and-demand restoring forces. Despite the artificial nature of speculation-driven price increases, the commodities futures market is coupled to actual food prices, and therefore to the ability of vulnerable populations—especially in poor countries—to buy food (139, 159–162).

Addressing the global food price problem in the short and long term is likely to require intentional changes in personal and societal actions. Over the longer term many factors and actions can play a role. Our concern here is for the dramatic price increases in recent years and the changes in supply and demand and investment activity that drove these price increases. The immediate implications of our analysis are policy recommendations for changes in regulations of commodity markets and ethanol production.

The function of commodity futures markets is benefitted by the participation of traders who increase liquidity and stabilize prices (163, 164). Just as merchants improve the distribution of commodities in space, traders do so over time. Yet, the existence of traders has been found to cause market behaviors that are counter to market function, resulting in regulations including the Commodity Exchange Act of 1936 (165). Arguments in favor of deregulation have cited the benefits that traders provide and denied other consequences, eventually resulting in deregulation by the Commodity Futures Modernization Act of 2000 (58). Our results demonstrate the nonlinear effects of increased trader participation (166). Higher-than-optimal numbers of traders are susceptible to bandwagon effects due to trend following that increase volatility and cause speculative bubbles (167), exactly counter to the beneficial stabilizing effects of small numbers of traders. Because intermediate levels of traders are optimal, regulations are needed and should be guided by an understanding of market dynamics. These regulations may limit the amount of trading or more directly inhibit bandwagon effects by a variety of means. Until a more complete understanding is available, policymakers concerned with the global food supply should restore traditional regulations, including the Commodity Exchange Act. Similar issues arise in the behavior of other markets, including the recent repeal of transaction rules (the uptick rule) that inhibited bandwagon effects in the stock market (168).

Today, the economics of food production is directly affected by nationally focused programs subsidizing agricultural production in the United States and other developed countries to replace fossil fuels. These policies affect global supply and demand and reflect local and national priorities rather than global concerns. Our analysis suggests that there has been a direct relationship between the amount of ethanol produced and (equilibrium) food price increases. Moderating these increases can be achieved by intermediate levels of ethanol production. Under current conditions, there is a tradeoff between ethanol production and the price of food for vulnerable populations. Because the ethanol market has been promoted by government regulation and subsidy, deregulation may be part of the solution. Alternative solutions may be considered, but in the short term a significant decrease in the conversion of corn to ethanol is warranted.

These policy options run counter to large potential profits for speculators and agricultural interests and the appealing cases that have been made for the deregulation of commodity markets and for the production of ethanol. In the former case, the misleading arguments in favor of deregulation are not supported by the evidence and our analysis. Similarly, the influence of economic interests associated with the agricultural industry is reinforced by since-debunked claims of the role of ethanol conversion in energy security and the environment (66). Thus, a very strong social and political effort is necessary to counter the deregulation of commodities and reverse the growth of ethanol production. A concern for the distress of vulnerable populations around the world requires actions either of policymakers or directly of the public and other social and economic institutions.

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