Supporting Information Appendix

In the Supporting Information, Section A provides a review of literature on causes of food prices, Sections C through F construct the mathematical model which we use to fit food prices. More specifically:

- Section A: Literature review of discussions of the causes of food price increases,
- Section B: A supply and demand model of commodity price formation,
- Section C: Corn ethanol demand model for food prices,
- Section D: Dynamic model of speculators and its behaviors,
- Section E: Combining ethanol demand and speculators, and comparison with data,
- Section F: Reduced model tests with only demand or only speculation.

Section A: Literature Review. The literature on the mechanisms of food price volatility is extensive. In this section we summarize a sample of the literature on the causes of the food price crisis of 2007-2008. For each paper, we note in Tables S1 and S2 which of several potential factors the authors examine: the change of diet in developing countries, biofuel conversion, financial speculation in the commodity futures market, the price of crude oil, and variation in currency exchange rates. We also list other possible causes addressed in each paper, and specify the timeframe in question, in particular whether it addresses just the rising prices in 2007/08, includes the subsequent decline and if it also includes the increase in 2010/11. For each potential factor, we indicate whether the the paper suggests or determines it to be a cause ("yes" or "no"). We also specify whether the analysis presented in the paper is quantitative (with an asterisk "*"), qualitative (with a "#"), or only a passing mention (normal). If the paper does not consider a particular factor, that column is left blank.

Section B: Commodity Prices: A Supply and Demand Model. In this section we present a simple model of commodity price formation based on supply and demand and show that, while the model is in general able to capture trends in prices before the year 2000, after this date other factors play a central role in determining prices.

Studies of supply-demand relationships for commodities have used two functional forms to characterize the price-quantity dependence [64]: a linear (constant slope) form [65] and a log-linear (constant elasticity) form [66,67]. If quantity demanded (Q_d) for a given commodity is determined by its price (P), the linear relationship is written as:

$$Q_d(t) = \alpha_d - \beta_d P(t) \qquad \textbf{[2]}$$

while the log-linear relationship is written as:

$$\ln Q_d(t) = \ln \alpha_d - \beta_d \ln P(t) \qquad \textbf{[3]}$$

Even though in empirical studies the choice of functional form is an important decision, it is generally assumed that there is no *a priori* reason for selecting either one [68]. A more general approach is given by the Box-Cox transformation [69],

$$Q_d(t,\lambda) = \alpha_d - \beta_d P(t,\lambda) \qquad \textbf{[4]}$$

where λ is the parameter of transformation, such that

$$Q_d(t,\lambda) = \frac{Q_d(t)^\lambda - 1}{\lambda} \qquad \textbf{[5]}$$

$$P(t,\lambda) = \frac{P(t)^\lambda - 1}{\lambda} \qquad \textbf{[6]}$$

As $\lambda \to 1$, Eq. 4 becomes Eq. 2, while as $\lambda \to 0$, Eq. 4 becomes Eq. 3. Similar equations hold for supply.

We assume that, at each time step, $P(t)$ changes due to either a supply shock or a demand shock. In order to identify what kind of shock occurs, we define the surplus, $S(t)$, as the difference between production and consumption of the commodity at time t. We assume there is a positive demand shock at time t if the surplus $S(t-1)$ is negative (shortage), so that the intercept of the demand curve shifts according to:

$$\alpha_d(t) = \alpha_d(t-1) - S(t-1) \qquad \textbf{[7]}$$

An analogous argument can be made for a supply shock, with appropriate signs. At each time step we can therefore estimate both price and quantity at equilibrium:

$$P_e(t,\lambda) = \frac{\alpha_d(t) - \alpha_s(t)}{\beta_d + \beta_s} \qquad \textbf{[8]}$$

$$Q_e(t,\lambda) = \frac{\alpha_d(t)\beta_s + \alpha_s(t)\beta_d}{\beta_d + \beta_s} \qquad \textbf{[9]}$$

where $\alpha_s(t)$ and β_s are the intercept and slope of the supply curve, respectively.

Best fits of Eq. 8 and Eq. 9 for wheat, corn, rice and sugar are shown in Fig. 1.

Section C: Corn Ethanol and Food Prices. Currently, the two main uses of corn are livestock feed (consuming 41.4% of the US supply in 2010), and ethanol production (40.1%) [73]. Other uses include direct human consumption and the production of oil, sweeteners and starch for use in a wide range of processed foods. Corn is therefore heavily used as an input for many food sectors, and it is reasonable to consider the amount of corn used to produce ethanol to have an impact on food prices [74]. The proportion of corn for ethanol has increased from 6% to its current value of 40% over the last 10 years.

We begin by assuming a linear dependence of the corn quantity supplied for food use, $Q_f(t)$, on the price of food, $P(t)$, as in the model described above with $\lambda = 1$, leading to the equilibrium equations for price and quantity:

$$P(t) = \frac{\alpha_d(t) - \alpha_s(t)}{\beta_d + \beta_s} \qquad \textbf{[10]}$$

$$Q_f(t) = \frac{\alpha_d(t)\beta_s + \alpha_s(t)\beta_d}{\beta_d + \beta_s} \qquad \textbf{[11]}$$

We now assume that the use of corn for ethanol production, $Q_x(t)$, causes a dominant supply shock for corn used directly and indirectly for food, so that

$$\alpha_s(t) \sim Q_f(t) \sim Q_t(t) - Q_x(t) \qquad \textbf{[12]}$$

where $Q_t(t)$ is the total amount of corn produced. In this model, a change in price would then be caused only by supply shocks. This does not imply that the supply and demand aside from corn ethanol production is static. For example, a growing world population creates a growing demand, but if this demand is met by a corresponding growing supply prices need not change. The total quantity demanded at equilibrium would then follow the shifts of the demand intercept, so that the difference $Q_t(t) - \alpha_d(t) \approx Q_t(t_0) - \alpha_d(t_0)$ would not be time dependent. The assumption that ethanol is a dominant shock is equivalent to the assumption that the price without the ethanol production would be relatively constant. Substituting in Eq. 10 and dropping the time dependence for the total corn production and the demand intercept yields

$$Q_x(t) = (\beta_d + \beta_s)P(t) + Q_t - \alpha_d \qquad \textbf{[13]}$$

The supply and demand model of Eq. 13 can be considered a quite general first order model of the food index as a function of many factors, $P = P(f_i)$, one of which is the amount of corn to ethanol conversion. We can perform a Taylor series expansion of such a generalized function with respect to its dependence on ethanol due to both direct and indirect effects. Even though the change in corn ethanol production is a large fraction of US corn production, we can consider an expansion to linear order of its effect on food prices generally. The total change in price, ΔP, is then written as a sum over partial derivative relative to all factors and their change with respect to corn ethanol production:

$$\Delta P = \left(\frac{dP}{dQ_x}\right) Q_x = \sum_i \left(\frac{\partial P}{\partial f_i}\right)\left(\frac{\partial f_i}{\partial Q_x}\right) Q_x \qquad \textbf{[14]}$$

where the reference price is for $Q_x = 0$. Comparing with the previous equation we see that this has the same behavior as a supply and demand model with an effective elasticity given by:

$$\beta_d + \beta_s = \left(\sum_i \left(\frac{\partial P}{\partial f_i}\right)\left(\frac{\partial f_i}{\partial Q_x}\right)\right)^{-1} \qquad \textbf{[15]}$$

The approximation that is needed for validity of this expression is that the dominant shock in the agriculture and food system is due to the corn use for ethanol. The validity of this assumption may be enhanced by the cancellation of other effects that contribute to both increases and decreases in prices.

Thus, if the assumptions of the model are correct, the change in quantity of corn ethanol would be proportional to the change in food price. This implies that the time dependence of the corn used for ethanol and of the food price index should each have the same functional form. The existence of an ethanol production byproduct use for feed (distillers grain), which is a fixed proportion of the corn, does not influence the functional form. We test this hypothesis in Fig. 2, where we plot both the time dependence of corn ethanol and the FAO food price index between 1999 and 2010. Values are normalized to range from 0 (minimum) to 1 (maximum) during this period in order to compare the functional forms of the two curves. If we exclude the 2007-2008 price peak, both curves can be accurately fit by quadratic growth (R^2 values of 0.986 for food prices and 0.989 for ethanol fraction). The Pearson correlation of the two curves is $\rho = 0.98$.

This model differs from the supply-demand model described earlier in that here we consider the total value of the change in ethanol use (i.e. $Q_x(t)$), and not just the surplus as reflected in reserves. The combination of the large change in food prices and the large change in the amount of grain used for ethanol production (over 15% of total global corn production), along with the proportionality we find between the two quantities, is strong evidence for a causal link between them.

Section D: Dynamic Model of Speculators. In this section we present a simple dynamic model of the role of trend-following speculators and their ability to cause deviations from equilibrium supply and demand prices. In the next section we will augment the model to incorporate the specific conditions of the commodity markets, the demand shock of corn to ethanol conversion discussed above, and investor shifting between markets.

Our model directly describes the possibility of speculators causing price deviations from equilibrium supply and demand. A progressive departure from equilibrium leads to supply and demand conditions increasingly countering that deviation. The interplay of these effects leads to the oscillations of bubble and crash dynamics.

We construct our speculator model starting from a supply and demand one. The price dynamics based upon supply and demand for a single commodity can be represented by [75]:

$$Q_d(t) = \alpha_d - \beta_d P(t) \qquad \textbf{[16]}$$

$$Q_s(t) = \alpha_s + \beta_s P(t) \qquad \textbf{[17]}$$

$$P(t+1) = P(t) + \gamma_0(Q_d(t) - Q_s(t)) \qquad \textbf{[18]}$$

where $Q_d(t)$ is the quantity demanded at time t, $Q_s(t)$ is the quantity supplied and $P(t)$ is the price of the commodity. We assumed a linear relationship between quantity and price, and we replaced the equilibrium condition, $Q_e = Q_d = Q_s$, with Eq. 18, the Walrasian adjustment mechanism [76]: P rises if the demand exceeds supply and vice versa, where γ_0 is the strength of the restoring force toward equilibrium. This is equivalent to a single first order difference equation in P [77],

$$P(t+1) + P(t)(k_{sd} - 1) = k_c, \qquad \textbf{[19]}$$

where $k_{sd} = \gamma_0(\beta_d + \beta_s)$ and $k_c = \gamma_0(\alpha_d - \alpha_s)$. This can be solved to give:

$$P(t) = (P_1 - P_e)(1 - k_{sd})^t + P_e \qquad \textbf{[20]}$$

where $(P_1 - P_e)$ is the initial deviation from the equilibrium and $P_e = P_0 = k_c/k_{sd}$ the equilibrium price. This behavior is summarized in Figure 3, where $k_{sd} < 1$ and Q_d and Q_s are displaced by a small percentage from their equilibrium value at $t = 0$, in order to simulate a supply/demand shock. Eq. 20 is similar to the solution of the classic Cobweb Model [78], with the difference that the term raised to the t_{th} power is proportional to the ratio of the supply and demand slopes, $1 - k_{sd} = -\beta_s/\beta_d$, and not to their sum. Therefore, as in the Cobweb Model, we can have convergence ($k_{sd} < 2$) or divergence ($k_{sd} > 2$) depending on the slope of the linear response of supply and demand to prices.

We now introduce the influence of trend-following speculators. If the price change of the commodity is positive in the previous time step, speculators are willing to buy a quantity $\mu[P(t) - P(t-1)]$ of commodity, otherwise they sell $\mu[P(t-1) - P(t)]$. The quantity bought (sold) is added (subtracted) from the term $(Q_d(t) - Q_s(t))$ in price setting Eq. 18. The result is a non-homogeneous second order difference equation in P of the type $aP(t+1) + bP(t) + cP(t-1) = g$, so that Eq. 19 becomes:

$$P(t+1) + P(t)(k_{sd} - k_{sp} - 1) + P(t-1)k_{sp} = k_c \qquad \textbf{[21]}$$

where $k_{sp} = \mu\gamma_0$. The values of the coefficients are given in terms of both the supply and demand parameters and the speculator response parameter μ. If prices are measured in units of k_c, Eq. 21 can be normalized to:

$$p(t+1) + p(t)(k_{sd} - k_{sp} - 1) + p(t-1)k_{sp} = 1 \qquad \textbf{[22]}$$

where $p(t) = P(t)/k_c$.

Three cases have to be considered, depending on the value of the discriminant $\delta = b^2 - 4ac$. We again consider a small displacement from equilibrium at $t = 0$, so that $P_0 = P_e$.

Case 1: $\delta > 0$

If the discriminant is positive, there are two distinct roots for the characteristic equation of a second order difference equation, and Eq. 21 can be solved to give:

$$P(t) = \delta^{-1/2}(P_1 - P_e)(m_1^t - m_2^t) + P_e \qquad \textbf{[23]}$$

where $m_{1,2} = (-b \pm \delta^{1/2})/2$. If both m_1 and m_2 lie between 0 and 1 in absolute value, then both m_1^t and m_2^t approach zero, and the solution converges exponentially. Otherwise the solution exponentially diverges.

Case 2: $\delta = 0$
If the discriminant is zero, then there is exactly one real root. The solution in this case is:

$$P(t) = (P_1 - P_e)(-b/2)^{t-1}t + P_e \qquad \textbf{[24]}$$

Whether the behavior is convergent or divergent now depends just on the magnitude of b. However, the likelihood of the roots being exactly equal when dealing with economic data is extremely small.

Case 3: $\delta < 0$
If the discriminant is negative, the solution to Eq. 21 becomes:

$$P(t) = (-\operatorname{sign}(b))^{t-1}\sqrt{k_{sp}^t}\left(\frac{P_1 - P_e}{\sqrt{k_{sp}}}\right)\frac{\sin(\theta t)}{\sin(\theta)} + P_e \qquad \textbf{[25]}$$

where

$$\theta = \arcsin\sqrt{1 - \frac{b^2}{4k_{sp}}} \qquad \textbf{[26]}$$

The behavior in this case is oscillating, with a period $T = 2\pi/\theta$. Whether $P(t)$ converges to its equilibrium value (as in Fig. 4) or not (as in Fig. 6) depends on the growth factor k_{sp}. Given the necessary combinations of the four parameters of the supply-demand relationship $(\alpha_s, \alpha_d, \beta_s, \beta_d)$, k_{sp} remains the only relevant parameter. We can distinguish the price dynamics behaviors of the model according to the values k_{sp} assumes when the discriminant is negative:

$k_{sp} = 0$	$P(t)$ decays exponentially to P_e (Figure 3)
$k_{sp} < 1$	$P(t)$ converges to P_e with damped oscillations (Figure 4)
$k_{sp} = 1$	$P(t)$ oscillates around P_e (Figure 5)
$k_{sp} > 1$	$P(t)$ diverges with amplified oscillations (Figure 6)

The behavior of the system is summarized in Fig. 7, where the phase diagram of the model is plotted as a function of its two main parameters: k_{sd}, the fundamental supply-demand contribution to price dynamics, and k_{sp}, the speculator contribution. The blue region on the top left corner is the stable region of the system, where price converges to its equilibrium value, while the red region around it defines the domain of price divergence.

The difference between the dark blue region and the light blue one is the sign of the discriminant. When δ is negative (light blue region), we have the damped sinusoidal behavior shown in Fig. 4; when δ is positive, we can either have the exponential decay shown in Fig. 3 (left-side dark blue triangle in the phase diagram) or a damped oscillating behavior (right-side dark blue triangle). The two triangles are separated on the x-axis ($k_{sp} = 0$) by $k_{sd} = 1$: in this case in fact, $\delta = (k_{sd} - 1)^2$ and whether the behavior is oscillating or monotonic depends on the sign of the quantity in parentheses. On the other hand, if $k_{sd} > 2$ the supply and demand elasticities are too high, $\delta > 1$ and the price diverges (red region).

The question of whether speculators stabilize or destabilize prices has been the subject of a large body of literature [79], going back to Milton Friedman, who said "People who argue that speculation is generally destabilizing seldom realize that this is largely equivalent to saying that speculators lose money, since speculation can be destabilizing in general only if speculators on average sell when the [commodity] is low in price and buy when it is high." [80]. Our simple model provides a quantitative assessment of the role of speculators: if we follow the arrow on the phase diagram from the x-axis at $k_{sd} = 3$ and $k_{sp} = 0$, for example, we see how increasing the effect of speculators may actually stabilize the system at first (from point A to point B), but eventually the system leaves the convergent behavior and becomes unstable again. Therefore a small amount of speculation may help prices to converge to their equilibrium value, but if the market power of speculators is too great they will have a destabilizing effect on the price dynamics. This holds true as long as the model parameter $k_{sd} < 4$; otherwise speculators are never able to stabilize the market.

The condition for speculator induced instability of a supply and demand equilibrium, $k_{sp} \geq 1$, can be understood by recognizing that at $k_{sp} = 1$ the additional speculator activity motivated by a price change is precisely enough to cause the same price change in the next period of time. Such momentum of the price is quite reasonably the condition for speculator induced bubbles and crashes. Supply and demand restoring forces are then responsible for the extent of the oscillatory behavior.

The concepts of equilibrium and trend following are manifest in trader strategies that are "fundamental" and "technical" [81]. Fundamental investing relies upon a concept of target price, the expected value. Investors estimate the target price based on supply and demand and use it as a guide to buy or sell. Technical investing considers various patterns in the price time series, the primary of which is the trend of prices itself, which sets direction but not value, except in relation to that pattern. More generally, in a technical strategy, a shift by a constant amount of the price time series would not affect investor decisions to buy or sell. Our model maps these two types of investing behavior onto the first two possible terms in a series expansion of the equation for price change in terms of the prices at previous times. These two terms represent respectively the two different types of investing behavior. The first term has a price difference from a reference (the equilibrium price), and the second term has the difference of sequential prices in the past. The equilibrium price in the first term is the average over the expected target price of all fundamental traders. Even with, or rather because of, a large diversity of individual trader strategies, an aggregation over them can be expected to leave these two terms dominant. Aggregation incorporates the multiple tendencies of individuals, and the diversity across individuals. The aggregate over their decisions has these two primary price impacts.

Finally, we consider the mechanisms by which trend following speculators are related to rational expectations about future prices and their impact on current prices and inventory. In the analysis of inventory changes over time in the "supply of storage" model [82,83], it has been shown that inventories increase when future prices are expected to rise. The inventory change is then achieved by a departure of prices from supply and demand equilibrium at that time. However, this is due to a *future* supply and demand change. In effect this analysis is the basis of all trading that achieves price stability over time due to inventory. Thus, if there is a seasonal supply of grain, the storage of that grain for future use is motivated by a difference in the timing of demand, and prices are adjusted to the demand across time. Given a temporary expected higher demand or lower supply at a time in the future, prices may be adjusted at the current time to sell less grain in order to keep the grain for the future.

Trend following reflects the assumption, as indicated in the speculator model, that extrapolation is a valid representation of expected future prices (including the possibility that the trends represent actual changes in supply and demand). Under these conditions it is rational to increase prices in order to reserve inventory for the future prices, causing a departure from equilibrium. This increase in price caused by the expected future prices then leads to a more rapid increase in price. Absent a way to distinguish the increase in price that is due to the desire to adjust inventory from other increases in price, we now have a recursive process. This is exactly the problem of recursive logic leading to multiple possible truths or self-contradicting paradox. Interpreted as a dynamical system, because of iterative rather than synchronous steps, the result is the dynamics of bubble and crash behavior described above. In particular, the trend following trader assumption of extrapolated trends predicting future price increases is inherently (globally) irrational due to its recursive tendency toward infinite or zero prices, only moderated by supply and demand traders. This does not imply that it is not locally rational, i.e. contextually or at a particular time it is a rational behavior, but any attempt to generalize local to global rationality encounters analytic problems. The absence of rationality is manifest *a posteriori* in empirical data by the occurrence of crashes after bubbles. Our analysis, however, shows that an empirical crash is not necessary to prove irrationality of trend following because of its inherent paradoxical nature. Nevertheless, as we found in our model, a limited amount of trend following can improve market behavior, in essence because trend following has a limited degree of validity in rational prediction of future prices. We might say that a small amount of an irrational behavior can contribute to increased rational collective action.

As discussed below, using food price data, we find the current world market to be at point C in the phase diagram. This is a region where the price diverges with amplified oscillations. In this domain, speculation can strongly destabilize the supply and demand equilibrium price.

Section E: Food Price Model: Speculators and Ethanol Demand. We construct an explicit model of price dynamics to compare to the food price index. Since our analysis has eliminated all supply and demand factors except ethanol conversion as a major shock, and the only other factor of known relevance is speculators, our model is constructed in order to represent these two effects. We build the simplest possible model of these two factors, minimizing the number of empirically adjustable parameters, and find a remarkably good fit between theory and empirical data.

We combine the ethanol model and the speculator model described in the two previous sections. We consider only the FAO food price index to characterize the combined effect on food prices. Because a majority of financial holdings in agricultural futures markets are now due to commodity index funds [84], it is reasonable to model aggregate effects of speculators on commodities rather than on individual ones separately. Similarly, corn ethanol conversion impacts food prices through a number of parallel mechanisms. The mutual influences of grain prices through substitution and replacement, as well as geographical heterogeneity of individual countries or regions, require detailed modeling that need not be done at a first level of representation.

Starting from the supply and demand model with Walrasian adjustment

$$P(t+1) = k_c + [1 - k_{sd}]P(t) \qquad \mathbf{[27]}$$

we include the effects of assuming a dominant ethanol conversion demand shock described above. Since the equilibrium price is given by $P_e = k_c/k_{sd}$, we constrain k_c to be:

$$k_c(t) = (a + bt^2)k_{sd} + b(2t+1) \qquad \mathbf{[28]}$$

where a and b are the coefficients of the corn ethanol model obtained above. The factor $(a + bt^2)$ is the time-dependent equilibrium price from the corn ethanol model. The additional term $b(2t+1)$ corrects for the lag in update of the dynamic model with respect to the equilibrium model, causing the dynamic model to track the equilibrium model price rather than a price that is lower, i.e. lagging in time, during the initial period. This term does not substantially affect the overall fit of the speculator and ethanol model.

We incorporate the effect of trend following speculators as in the previous section by adding a term $k_{sp}[P(t) - P(t-1)]$ which interacts with the price dynamics due to the supply and demand terms. The last step in our construction of the speculator model is to add the effect of alternative investment markets on the price of the commodity. We assume that when the price change of an alternative investment is positive in the previous time step, speculators sell a quantity $\mu_i[P_i(t) - P_i(t-1)]$ of commodity contracts, where $P_i(t)$ is the price at time t of investment i and $\mu_i < 0$, in order to shift part of their capital to the new market. This sale of commodities competes against the purchase of commodities given by $\mu_i[P_i(t-1) - P_i(t)]$, representing the maximum profit seeking behavior of speculators who transfer capital between markets. In summary, Eq. 21 becomes:

$$\begin{aligned} P(t+1) &= k_c(t) + [1 - k_{sd}]P(t) + k_{sp}[P(t) - P(t-1)] \\ &+ \sum_{i=1}^{N} k_i[P_i(t) - P_i(t-1)] \qquad \mathbf{[29]} \end{aligned}$$

where N is the number of alternative investments taken into account, and $k_i = \mu_i\gamma_0$ are the alternative investment coupling constants. The model has effectively $N+3$ fitting parameters: two deriving from supply and demand considerations (k_c and k_{sd}) and $N+1$ deriving from trend-following considerations.

In Fig. 8, we show the best fit of this model to the FAO Food Price Index. We start the fit in 2007, when speculators presumably started moving their investments from the stock market to other markets, as suggested by the bubble dynamics of Fig. 3. The date of the start, May 2007, is chosen for best fit. A more gradual increase in investor interest would be more realistic and represent the data more closely, but the simple model using a single date for investor interest is sufficient. The alternative markets we consider besides commodities are equities (using the S&P500 Index time series) and bonds (using the US 10-year treasury note price time series), which have peaks right before and right after the peak in the commodity time series (top panel of Fig. 8) so that $N = 2$.

The resulting price curve is constructed directly from the model using only the adjustment of four model parameters (k_{sd}, k_{sp}, and the two market coupling parameters, k_1 and k_2) and the alternative market prices as input. The two large peaks are precisely fit by the model, as is the intermediate valley and smaller intermediate peak. The stock market plays a key role in the fit due to a shift of investment capital in 2009 in response to a stock market increase. The bond market plays a smaller role and the coefficient of coupling between the commodity and bond markets is small. The parameters that are obtained from the fitting (k_{sd}, k_{sp}) are shown as point C in Fig. 7. The point lies in the unstable region of the system, with the caveat that we fit the Food Price Index with Eq. 29 that includes the alternative markets but we plot the phase diagram for Eq. 21 without those markets.

Our results for the Food Price Index yield parameters that can be compared with expectations about speculator influence on commodity markets. In particular, the value of $k_{sp} = 1.29$ is consistent with a speculator volume that can move prices 30% more than the price change that is found in the previous time.

The value of the supply and demand parameter $k_{sd} = 0.098$ combines with the speculator behavior to yield a bubble and crash cycle of $2\pi/\theta = 23.6$ months (see Eq. 26), almost exactly two years, consistent with a single year of price increases. This corresponds to the natural assumption of an annual cycle for the maturation of futures contracts for delivery that impact on actual supply and demand. The maturation of such contracts leads to increases in inventories and thus a restoring force toward supply and demand equilibrium. Furthermore, according to this analysis, we predict an increase in inventories of grains starting at the peak of the speculative bubble, one year after the departure from equilibrium prices. As shown in Fig. 4, this is consistent with the available data on observed inventories of grains [70]. In particular, the inventories increased from September 2008 to September 2009.

The result that our dynamic speculator model is able to fit the FAO Food Price Index and that the supply-demand model described above is not able to do so is consistent with the hypothesis that speculators played an important role in determining food prices. In conjunction with the other evidence for speculator involvement (see main text), our quantitative model provides specific evidence not just for a role of speculators, but for the extent of impact of speculators on the food and other commodity markets.

Section F: Supply and demand shock without speculation and speculation without a supply and demand shock. In this section we consider two models testing whether a simpler model than that used in the main text can match the dynamics of food prices. These models remove either supply and demand or speculation, leaving just the other. We can consider these as alternative null models that validate the need for both supply and demand and speculation.

First we consider the possibility of a supply and demand model without speculation. We note that the ethanol shock by itself is insufficient, but perhaps other supply and demand factors may contribute. We thus construct a model based upon surplus of production over demand. Since this data is naturally available for individual commodities rather than food as an aggregate quantity, we consider this for each of four food commodities. We use Eq. 8 to fit the price time series of a given commodity $P(t)$, and Eq. 9 to fit its consumption, $Q_d(t)$. The only input into the model is the surplus $S(t)$, estimated from inventories provided by the US Department of Agriculture [70], and three parameters are used for fitting the price and consumption: the transformation parameter λ, one slope (either β_d or β_s) and the initial value of one of the intercepts (either $\alpha_d(0)$ or $\alpha_s(0)$). The other slope/intercept is determined by setting initial values to empirical data, $P_e(0) = P(0)$ and $Q_e(0) = Q(0)$. Empirical price data was adjusted for the US consumer price index, so that $P_e(t, \lambda)$ represents constant prices. Fig. 1 shows that this simple model is able to capture most features of commodity price fluctuations for wheat, corn, rice and sugar, but it fails to reproduce the 2006-2008 spike. Instead, the model predicts price peaks starting from 2000-2002. However, in order to fit the spike in the price time series, the model creates a jump in demand which does not occur in the actual data, as demonstrated by the poor fit of the consumption time series. Absent a mechanism for shifting of price increases by a time delay of 3-4 years, distinct causes of the supply-demand change in 2000-2002 and price peaks of 2006-2008 are necessary. Policy-based reductions in reserves are a possible explanation of the changes in 2000-2002 [7, 72]. Commodity speculation can account for the peaks in 2007-8 (explained further below).

Second we consider fitting inflation adjusted food prices without a supply and demand shock, i.e. price changes away from a fixed reference equilibrium price are driven by speculative band wagon effects. The results shown in Figure 9 imply that the speculative behavior alone is unable to account for the underlying trend in food prices.

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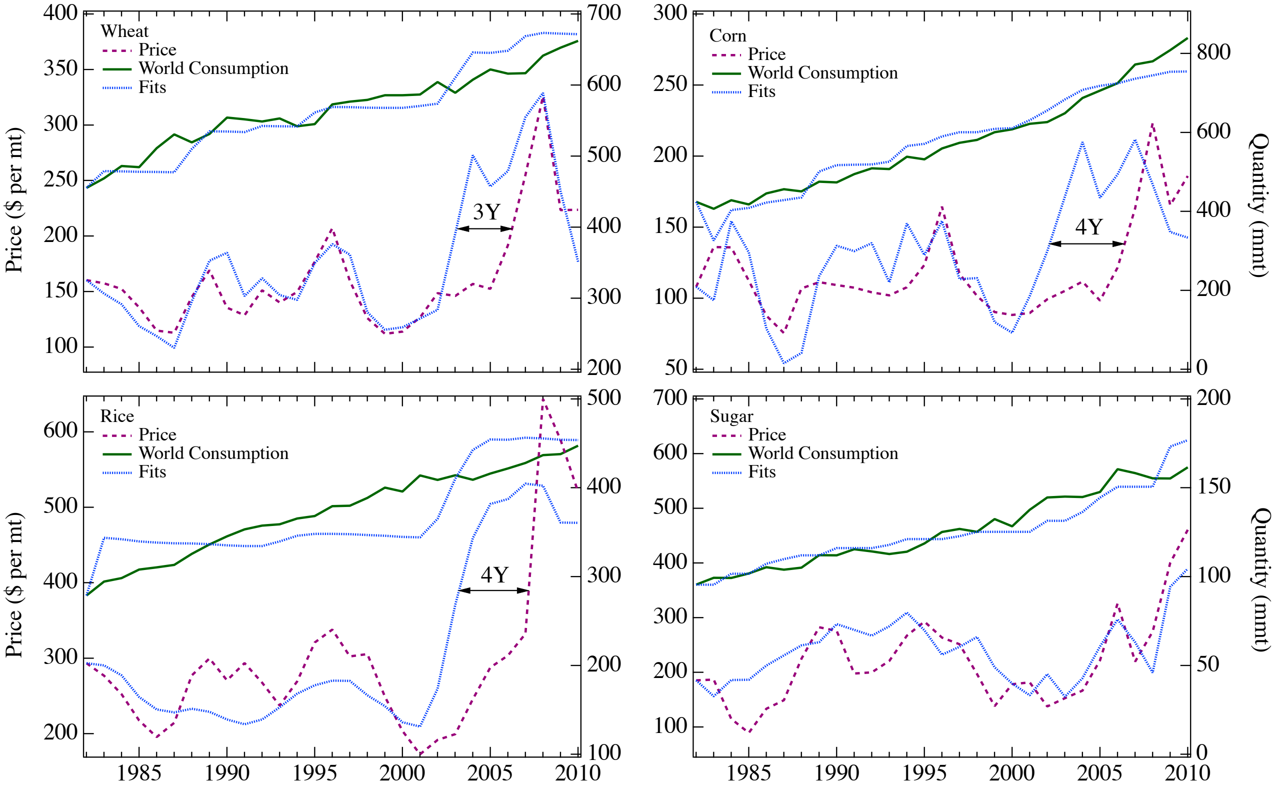

Fig. 1. **Supply and demand model -** For wheat, corn, rice, sugar (left to right and top to bottom). Price time series of the commodity (dashed purple lines) and global consumption time series (solid green lines). Blue dotted curves are best fits according to Eq. 8 and Eq. 9 for prices and consumption, respectively. Annual surplus (supply minus demand) values are from [70], and prices from [71]. Values of the fitting parameters: wheat - $\lambda = 1 \pm 0.01$, $\alpha_d(1982) = 309 \pm 53$ and $\beta_d = 1.01 \pm 0.13$, corn - $\lambda = 0.94 \pm 0.01$, $\alpha_d(1982) = 114 \pm 22$ and $\beta_d = 1.91 \pm 0.23$, rice - $\lambda = 0.95 \pm 0.01$, $\alpha_d(1982) = 87 \pm 77$ and $\beta_d = 0.64 \pm 0.19$, sugar - $\lambda = 0.86 \pm 0.07$, $\alpha_d(1982) = 26 \pm 20$ and $\beta_d = 0.31 \pm 0.12$.

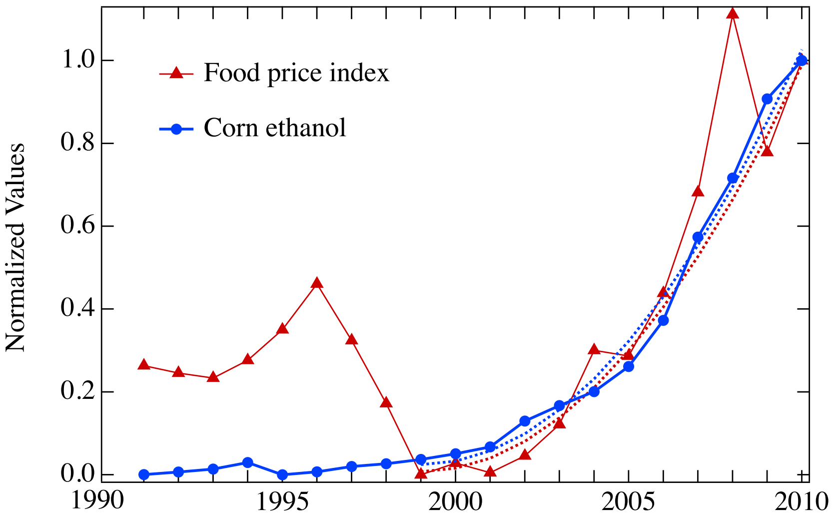

Fig. 2. **Model results** - Annual corn used for ethanol production in the US (blue circles) and the FAO Food Price Index from 1991-2010 (red triangles). Values are normalized to range from 0 (minimum) to 1 (maximum) during this period. Dotted lines are best fits to quadratic growth, with quadratic coefficients of 0.0083 ± 0.0003 for corn ethanol and 0.0081 ± 0.0003 for FAO index. Goodness of fit is measured with the coefficient of determination, $R^2 = 0.989$ for corn and $R^2 = 0.986$ for food. The 2007-2008 peak was not included in the fit or the normalization of the FAO index time series.

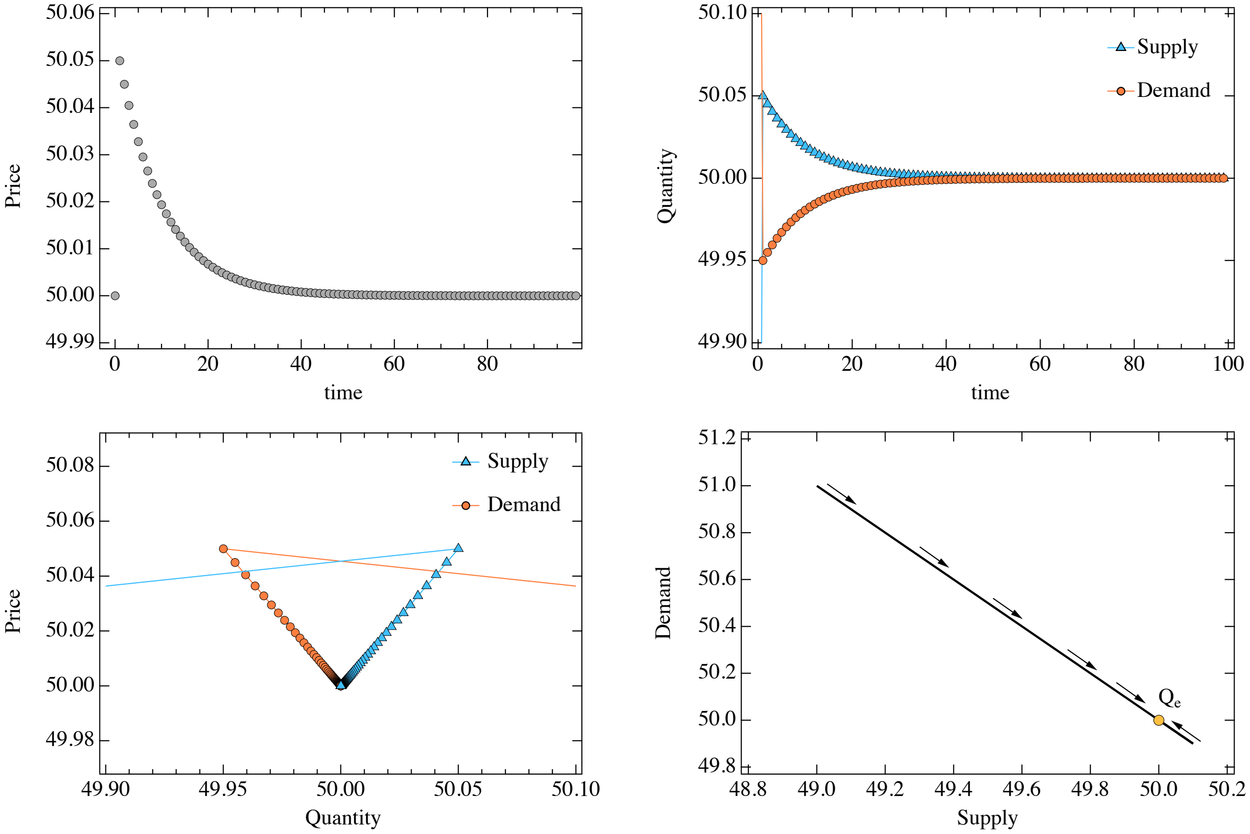

Fig. 3. **Dynamics without speculators** - Dynamic response of the system to a supply/demand shock at time $t = 0$. *Top Left*: Exponential convergence of P to its equilibrium value. *Top Right*: Supply and demand as a function of time. *Bottom Left*: Price/quantity relationship. *Bottom Right*: Dynamic evolution of Q_d vs Q_s. Value of parameters: $k_{sd} = 0.1$, $k_c = 5$.

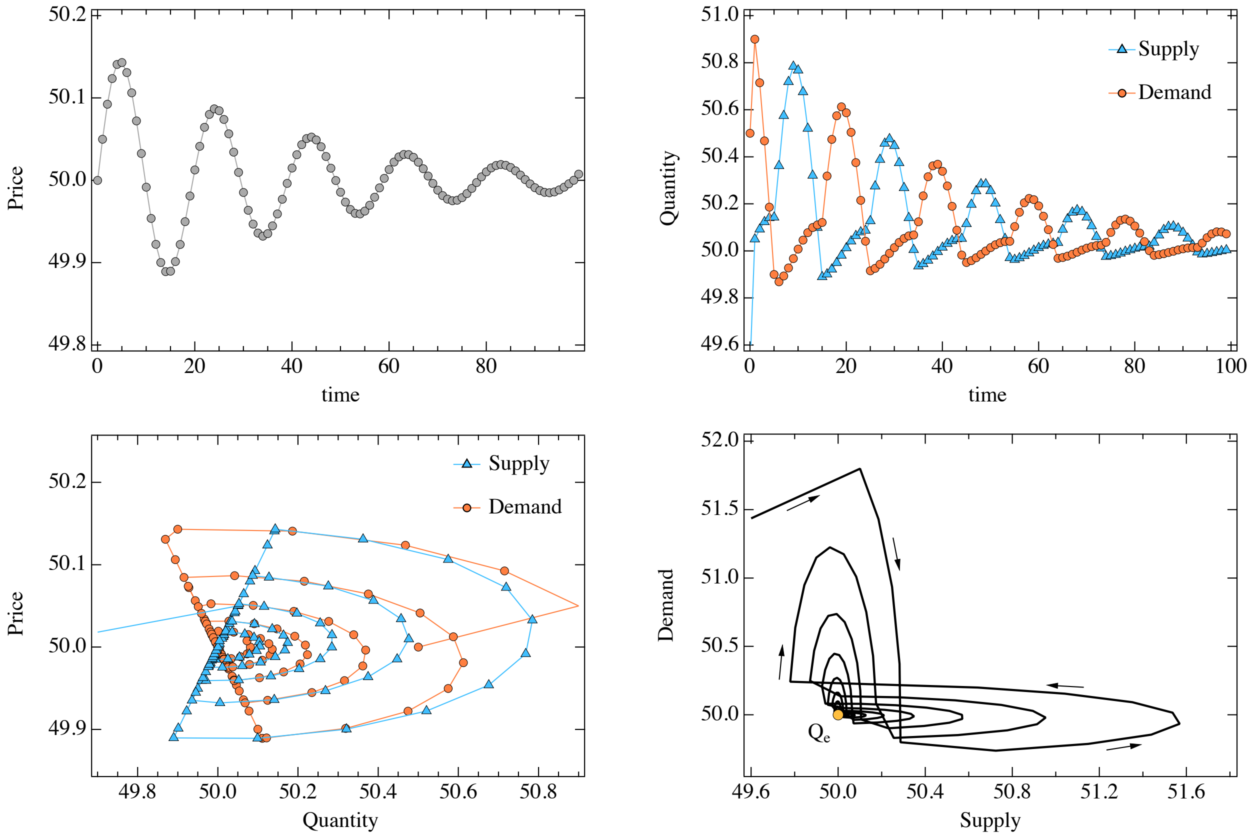

Fig. 4. **Dynamics with speculators:** $k_{sp} < 1$ - Dynamic response of the system to a supply/demand shock at time $t = 0$. *Top Left*: Oscillating convergence of P to its equilibrium value. *Top Right*: Supply and demand as a function of time. *Bottom Left*: Price/quantity relationship. *Bottom Right*: Dynamic evolution of Q_d vs Q_s towards Q_e.

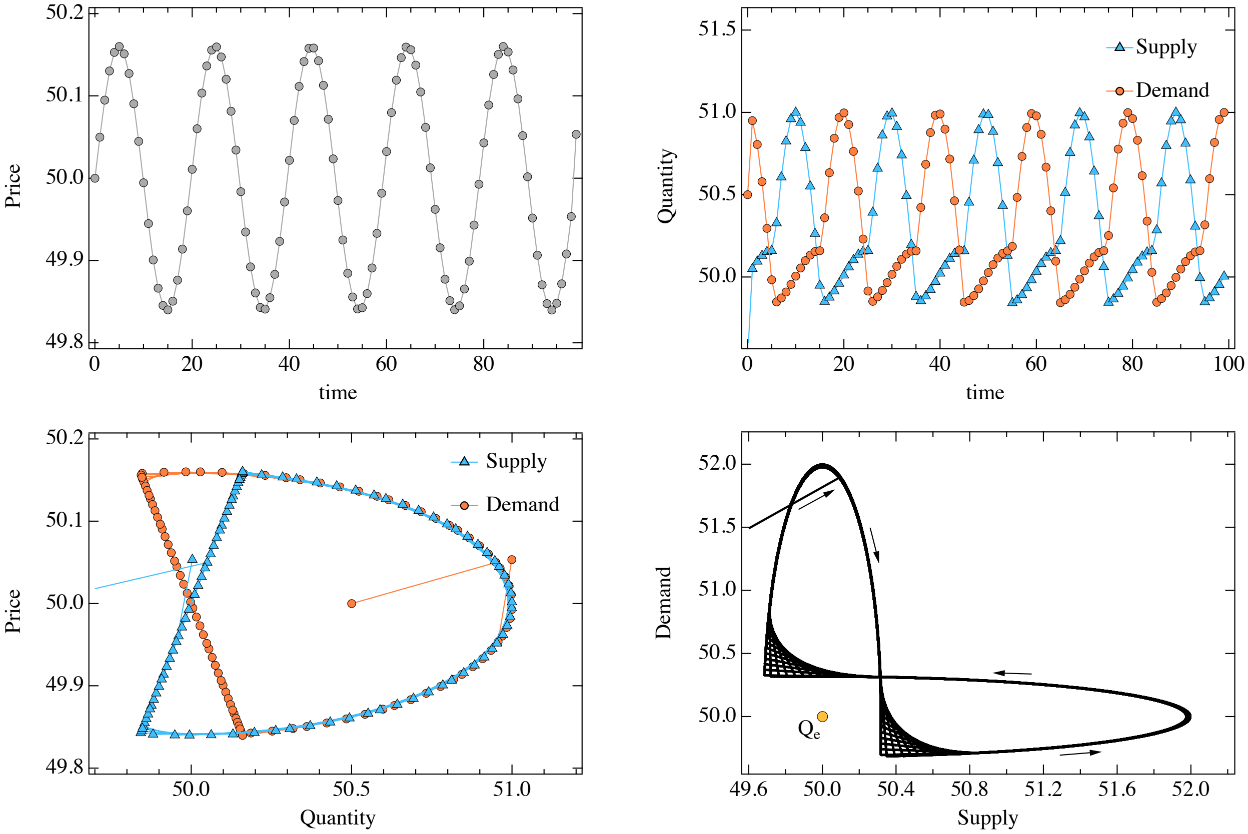

Fig. 5. **Dynamics with speculators:** $k_{sp} = 1$ - Dynamic response of the system to a supply/demand shock at time $t = 0$. *Top Left*: Oscillations of P around its equilibrium value. *Top Right*: Supply and demand as a function of time. *Bottom Left*: Price/quantity relationship. *Bottom Right*: Dynamic evolution of Q_d vs Q_s.

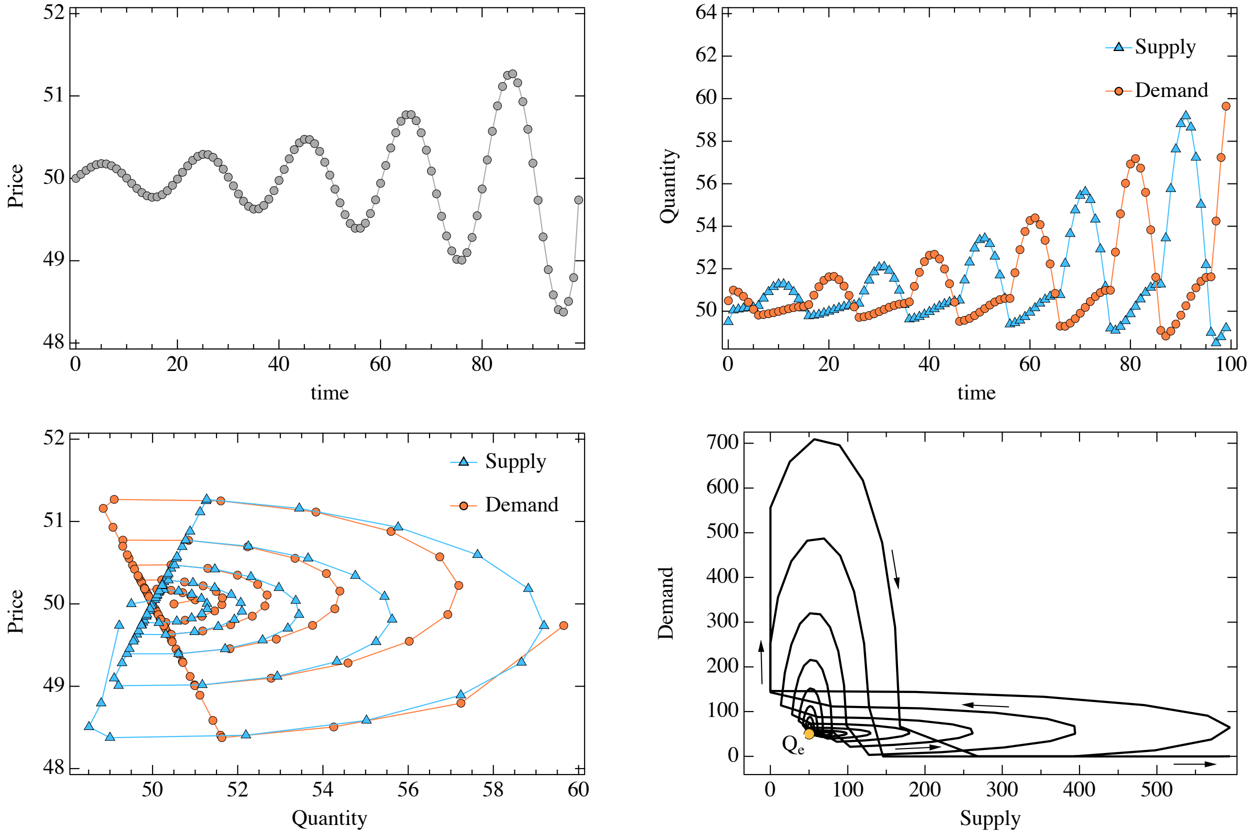

Fig. 6. **Dynamics with speculators:** $k_{sp} > 1$ - Dynamic response of the system to a supply/demand shock at time $t = 0$. *Top Left*: Oscillating divergence of P to its equilibrium value. *Top Right*: Supply and demand as a function of time. *Bottom Left*: Price/quantity relationship. *Bottom Right*: Dynamic evolution of Q_d vs Q_s away from Q_e.

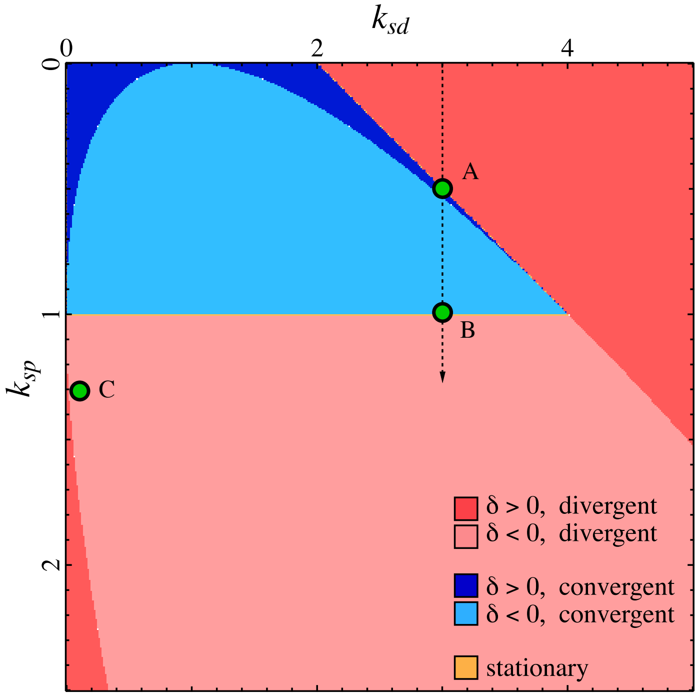

Fig. 7. **Model Phase Diagram** - Behavior of the model for different values of its two main parameters, k_{sd} and k_{sp}. Dark red regions correspond to a divergent behavior according to Eq. 23, light red to a divergent behavior according to Eq. 25 (see also Fig. 6), light blue to a convergent behavior (Eq. 25 and Fig. 4), as well as dark blue (Eq. 23). A thin yellow line between the light blue and light red regions defines a stationary point at $k_{sp} = 1$ (Eq. 25 and Fig. 5). The region from point A to point B represents the stabilizing effect of speculators as k_{sp} increases at $k_{sd} = 3$. C is the point in the phase space (k_{sd}, k_{sp}) corresponding to the values obtained with the fitting of food price data (see Fig. 8).

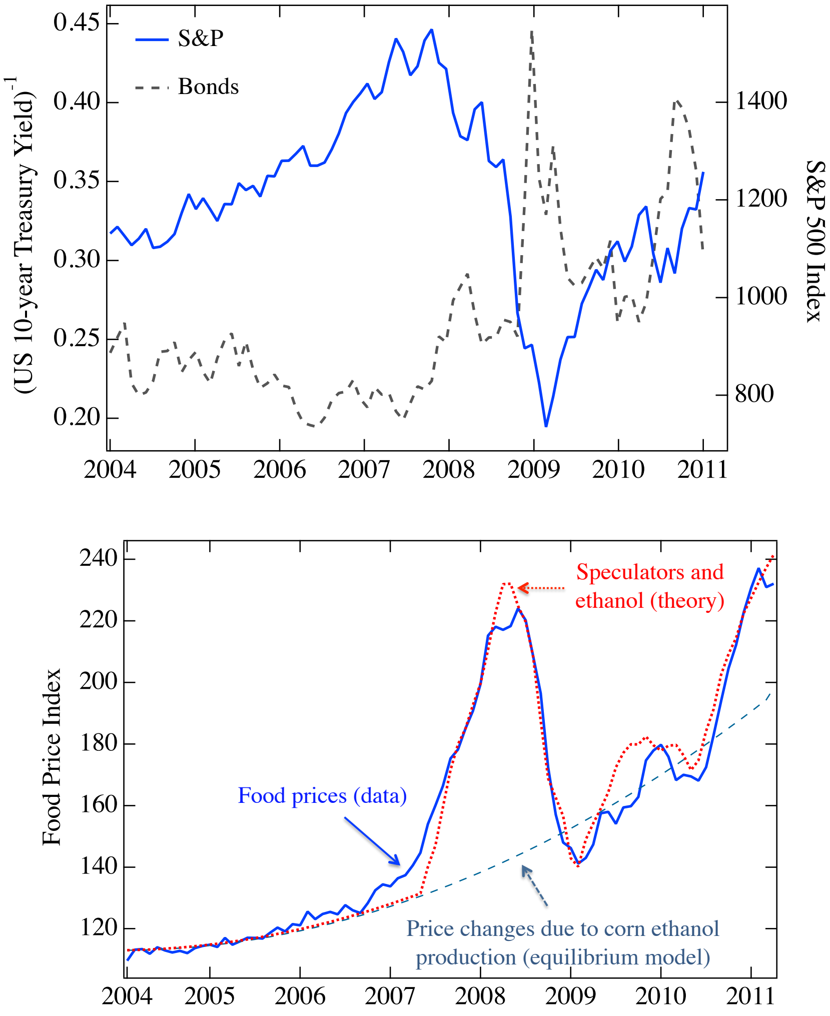

Fig. 8. **Model Results** - *Top*: Solid line is the monthly FAO Food Price Index between Jan 2004 and Apr 2011. Dashed line is the best fit according to Eq. 29. The effect of speculators is turned on in the first half of 2007, when the housing bubble collapsed. Values of parameters are: $k_{sd} = 0.098$, $k_{sp} = 1.29$, $\mu_{equity}\gamma_0 = -0.095$, $\mu_{bonds}\gamma_0 = -67.9$. *Bottom*: Time series used as input to the speculator model, S&P500 index (stock market, in blue) and inverse of the US 10-year Treasury Note Yield (bonds, in black).

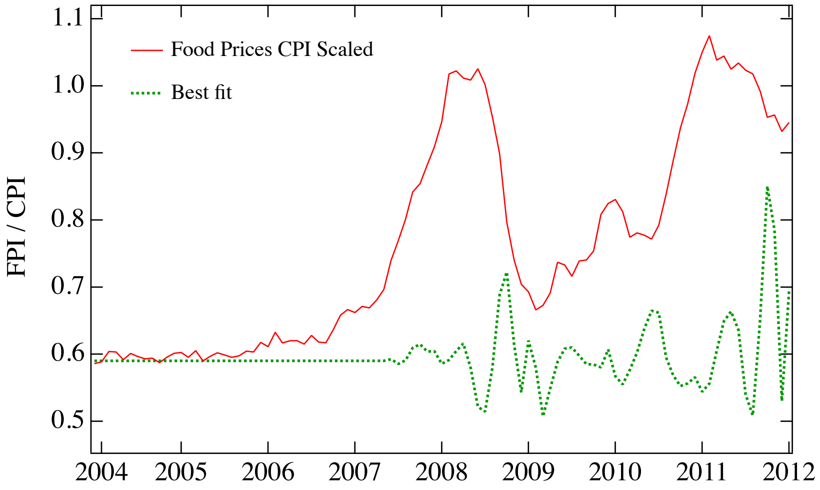

Fig. 9. **Model results without supply and demand shock**: Solid red line is the monthly FAO Food Price Index scaled by the Consumer Price Index between Jan 2004 and Jan 2012. Dashed green line is the best fit according to Eq. 29 without an ethanol shock term. The effect of speculators is turned on in the first half of 2007, when the housing bubble collapsed.

Table S1. Literature review, part 1. See text for notation.

Paper	Change of diet (meat)	Weather	Biofuels	Speculation	Oil	Currency exchange	Other causes	Time range
[1]	no	yes (wheat)	yes	*yes (no rice)	yes	*at times (via speculators)	trade policies, thin market, panic (rice), depletion of inventories, price transmission between commodities	2007-8 rise & fall
[2]	no	no	yes	yes	yes	yes	trade policies	2007-8 rise & fall
[3]	*no		yes	yes	*yes ($\sim 30\%$)	#yes	fiscal expansion, lax monetary policy	2007-8 rise & fall
[4]		*no	yes	yes	yes	maybe	trade policies, thin market (rice), R&D decline	2007-8 rise
[5]	#yes	#yes	#yes				production decline: *no	2007-8 rise
[6]	no		*yes	maybe	no	*no		2007-8 rise & fall
[7]	*no	yes (wheat)	yes	maybe	yes	yes	trade policies, depletion of inventories	2007-8 rise & fall
[8]			yes					2007-8 rise
[9]			*yes					
[10]	#yes	#yes	#yes	#yes	#yes	#yes	climate change, productivity and R&D decline, trade policies	2007-8 rise
[11]	*no	#yes	*yes	yes	#yes	maybe	trade policies, population increase	2007-8 rise & fall
[12]	no	yes	yes	yes	yes	yes	trade policies (rice), depletion of inventories	2007-8 rise
[13]	yes	yes	yes	yes	yes	yes	trade policies, population increase	2007-8 rise
[14]	maybe	maybe	maybe	*yes	#yes	maybe		2007-8 rise
[15]				yes				2007-8 rise
[16]				*yes				2007-8 rise
[17]			*yes					
[18]		#yes	*yes		yes	yes and no	income growth	
[19]	yes (long term)	yes (long term)	yes (long term)	maybe	yes	yes (long term)	trade policies	2007-8 rise
[20]			no		yes			
[21]	no	yes (wheat)	yes	maybe	yes	no	depletion of inventories, trade policies	2007-8 rise & fall
[22]	no		no	no	yes	yes	countries hoarding, trade policies	2007-8 rise & fall
[23]			yes					2007-8 rise
[24]			yes					
[25]	#yes	#yes	#yes		yes		productivity and R&D decline	2007-8 rise
[26]			*yes		*yes (via biofuels)			2007-8 rise & fall
[27]			yes					2007-8 rise
[28]			yes					2007-8 rise
[29]					maybe			2007-8 rise
[30]		yes (short term)	yes (short term)		yes (short term)	yes (long term)		2007-8 rise & fall
[31]	yes		yes		yes	yes		2007-8 rise
[32]					*yes (via biofuels)	*yes		

Table S2. Literature review, part 2. See text for notation.

Paper	Change of diet (meat)	Weather	Biofuels	Speculation	Oil	Currency exchange	Other causes	Time range
[33]			yes		yes			2007-8 rise & fall
[34]			yes					
[35]			yes	no	yes			2007-8 rise
[36]			maybe					2007-8 rise
[37]							financial crisis	2007-8 fall
[38]			yes		yes	yes	recession	2007-8 rise & fall
[39]		yes			yes	yes	land degradation	2007-8 rise
[40]							monetary policy	2007-8 rise & fall
[41]			yes					2007-8 rise
[42]					*yes	*yes		1998-2008
[43]			#yes			#yes	trade policies	2007-8 rise
[44]	#yes	#yes	*yes (corn, soybeans) *no (rice and wheat)	#yes	#yes	#yes	trade policies, productivity decline	2007-8 rise
[45]	yes	yes	yes	yes	yes	yes		2007-8 rise & fall
[46]		no (rice)	maybe (rice)	yes (no rice)	no	yes		2007-8 rise & fall
[47]	yes	#yes	yes		yes	yes		2007-8 rise
[48]	yes	yes	yes	no	yes	yes	trade policies	2007-8 rise & fall
[49]			yes					2007-8 rise
[50]			*yes					2007-8 rise
[51]	yes (long term)	*no	yes.		no		fertilizer cost: no; panic: yes	2007-8 rise & fall
[52]							trade policies	2007-8 rise & fall, 2011 rise
[53]			maybe					
[54]			yes					2007-8 rise
[55]	no	no	yes	maybe	yes		trade policies	2007-8 rise & fall
[56]							available land, climate change, population growth	
[57]				maybe				
[58]			yes					2007-8 rise & fall
[59]			yes					
[60]	#yes	#yes	yes	maybe	#yes	#yes		2007-8 rise & fall
[61]			yes				delayed effect of easy credit	2007-8 rise
[62]					*no			1984-2009
[63]						*yes (2-5%)		1975-2005