Market-oriented ethanol and corn-trade policies can reduce climate-induced US corn price volatility

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Abstract
Agriculture is closely affected by climate. Over the past decade, biofuels have emerged as another important factor shaping the agricultural sector. We ask whether the presence of the US ethanol sector can play a role in moderating increases in US corn price variability, projected to occur in response to near-term global warming. Our findings suggest that the answer to this question depends heavily on the underlying forces shaping the ethanol industry. If mandate-driven, there is little doubt that the presence of the corn-ethanol sector will exacerbate price volatility. However, if market-driven, then the emergence of the corn-ethanol sector can be a double-edged sword for corn price volatility, possibly cushioning the impact of increased climate driven supply volatility, but also inheriting volatility from the newly integrated energy markets via crude oil price fluctuations. We find that empirically the former effect dominates, reducing price volatility by 27\%. In contrast, mandates on ethanol production increase future price volatility by 54\% in under future climate after 2020. We also consider the potential for liberalized international corn trade to cushion corn price volatility in the US. Our results suggest that allowing corn to move freely internationally serves to reduce the impact of near-term climate change on US corn price volatility by 8\%.

Keywords: climate change, corn yields, ethanol, biofuels, US corn price volatility

1. Introduction
Global warming is causing not only gradual changes in temperature and precipitation but also increased likelihood of extreme weather events. There is now mounting evidence that global warming will occur even after greenhouse gas concentrations have been stabilized (Meehl \textit{et al} 2005; review by Diffenbaugh and Field 2013), with episodes of severe heat becoming more likely (IPCC 2012). The agricultural sector is directly and acutely affected by weather extremes, manifesting in price spikes such as those seen recently (rice in 2007,
wheat in 2010 and corn in 2012). Even though new varieties of crops that are resistant to higher temperatures and erratic precipitation (Trethowan et al. 2010) can be helpful, such varieties take time to develop and disseminate, and recent evidence suggests that corn yields in the US are actually becoming more sensitive to drought (Lobell et al. 2014). In the event of short run price spikes, stemming from extreme events, adaptation strategies like adjusting cropping region and planting and harvesting dates, have limited potential and it falls to commodity stocks and adjustment in industrial use and consumption to absorb most of the changes in supply. Stockholding operations are usually expensive, take time to build, involve grain losses and require judicious management to be successful. Trade policy interventions, including import-subsidies and export-bans, to ensure national grain supply availability are a beggar-thy-neighbor policy, as they contribute to increased world price volatility. Therefore, this paper explores other options, specifically the role of the ethanol sector as a flexible source of grain demand, for reducing price fluctuations in the wake of extreme weather events.

Diffenbaugh et al. (2012) showed that, in the absence of biophysical adaptation, climate change could cause annual US corn yield’s standard deviation to double between the periods 1980–2000 and 2020–2040, and the increased yield volatility could have a sharp impact on US corn price volatility. They also found that it matters whether corn sales to ethanol are driven by the renewable fuel standard (RFS) mandate or market signals such as high oil prices. Those authors did not, however, explore the possibility of corn prices inheriting volatility from the energy markets due to the interaction between food and fuel markets, and they also abstracted from the role of trade policies in transmitting price volatility across countries. With evidence for prices of ethanol and crude oil being linked (Zhang et al. 2009, Serra 2011) and oil prices showing considerable volatility in recent decades (Dviv and Rogoff 2009), the ‘inherited’ energy volatility could be an important source of corn price volatility. Evaluating the impact of the ethanol sector on corn prices in the US thus involves forces that both accentuate and reduce US corn price variability, depending on biofuels policy choices. International corn trade is another channel that can either inhibit or facilitate price volatility in response to extreme events. Restricting trade in the event of a commodity shortage has been known to contribute to increased price volatility (Abbott et al. 2011). Could freeing international trade enhance the resilience of the global system to adverse climate shocks?

4 Stable prices are important as signal to farmers as they base their cropping and investment decisions on expectations about prices. Impact of high and fluctuating prices affects not only the income of farmers but also affects consumers, particularly those with food expenditures constituting almost 70% of their incomes.

5 Diffenbaugh et al. call the climate associated with 1980–2000 the present climate and that associated with 2020–2040 the future climate. Our definitions of the scenarios are outlined in table 1.

6 We do not consider the ethanol credit and import tax in US as they were not extended beyond 2011.

We include weather and oil price fluctuations, along with ethanol sector and corn trade policies, within a single framework designed to investigate their potential to reduce climate-induced corn price volatility. We use the inter-annual standard deviation in US corn prices as our metric of price volatility. Our analysis considers US corn price volatility as driven by climate change, under three different scenarios for the economy in the year 2020.

2. Conceptual framework

Our conceptual framework is illustrated in figure 1. Corn can be exported (γ is the export share), or used domestically (domestic sales’ share: 1 − γ) for seed, livestock-feed, human consumption in the form of processed food-beverage products, and as fuel (β is the share of the domestic corn sales going to, the ethanol industry). Use of corn in the US ethanol industry, was greatly boosted by the ban on use of methyl tertiary butyl ether (MTBE) as an oxygenate additive. Any increase in oil prices will reduce overall fuel use, thereby leading to reduced demand for ethanol as oxygenate. This relationship between oil prices and ethanol demand stands in contrast with demand for ethanol as substitute for oil in gasoline blends (α denotes the share of ethanol being used as petroleum substitute). The ease of substitution between ethanol and oil depends on elasticity of substitution (denoted σ). A high value of this substitution elasticity means that a modest oil price rise will significantly boost demand for ethanol as petroleum substitute. This value is influenced by technical considerations (e.g., the blend wall) and economic factors (share of flex-fuel vehicles in the vehicle fleet). The strength of substitution possibilities between ethanol and oil, and the share of ethanol being used as petroleum substitute, together determine the degree to which the ethanol industry responds to corn supply and oil price shocks.

In this framework, following Hertel and Beckman (2011), we can derive an expression for percentage change in corn price (p) as a function of corn yield (s) and fuel price (PF).

7 In choosing price variability as metric, we recognize that such volatility is not always bad. Indeed, in the absence of risk aversion, economic theory suggests that consumers should prefer volatile prices, since the consumer surplus from very low prices will more than offset the losses from high prices. However, as the importance of a commodity in consumers’ budgets rises, and as risk aversion increases, this outcome is reversed (Gouel and Sébastien 2012). Barret and Bellémere (2011) argue that it is not food price volatility that matters for the poor, but rather the persistence of high food prices which may have an irreversible impact on nutritional intake. Regardless of these theoretical arguments, food price volatility has attracted a great deal of attention recently, and governments have gone to great efforts to limit the impact of international price volatility on their domestic markets (Anderson et al. 2012 and Martin et al. 2012). We therefore view corn price volatility as an instructive metric.

8 Oxygenates are fuel additives containing oxygen. They help the fuel burn cleaner and thereby reduce exhaust emissions. In US, ethanol has replaced MTBE as oxygenate.
changes—the two variables of interest here:

\[ p_e = \frac{1}{A} \left[ (\eta_p^e + \alpha \sigma) p_f - z_e \right] \]

where

\[ A = \frac{\eta_p^e + \eta_{c}^D - (1 - \beta)(1 - \gamma)\eta_{e}^D}{\beta(1 - \gamma)} + \alpha \sigma \theta_e > 0 \]

The additional parameters are the own price elasticity of liquid fuel demand \( \eta_p^e \leq 0 \), the corn supply elasticity \( \eta_c^e \geq 0 \), corn export demand elasticity \( \eta_e^D \leq 0 \), and domestic non-ethanol corn demand elasticity \( \eta_{co}^D \leq 0 \). The share of corn in the ethanol industry’s cost of production \( \theta_e \geq 0 \) serves to translate change in corn price to change in ethanol price. Noting that \( A > 0 \), we can reach several important conclusions.

### 2.1. Yield shock

As expected, corn prices are inversely related to corn yield change, and the higher the derived demand elasticity \( \alpha \sigma \theta_e \) of corn in the ethanol sector, the smaller the impact of a given change in corn yields on corn prices.

We graphically illustrate this conclusion in figure 2 where a negative yield shock reduces the corn harvest in the US, shifting the supply back from the solid to the dashed line. This increases corn prices (as shown by the vertical
Figure 2. Impact of yield decline on corn price: a negative shock to corn yields reduces the supply of US corn. For this example we assume that supply is reduced by a factor of one-third at initial price. The intersection of the new supply curve (dashed line) determines the corn price increase (arrow on vertical axis). Market driven ethanol sector (when initial oil price is high and there are no mandates on ethanol) introduces an elastic demand for corn, ensuring the percent increase in price to be moderate (panel a) when ethanol sector is nascent (low oil price and no mandates), then the demand for corn is relatively inelastic, and as a result, corn price responds more to the same (percentage) yield shock (panel b). When a certain amount of ethanol is mandates (likely when oil prices are not high enough to make ethanol profitable) to be used in gasoline blend, then the mandate introduces additional inflexibility in corn demand and prices have to adjust more in event of supply shock (panel c). Note that in both figures the red curve shows only the substitute demand for corn, because corn prices do not impact additive demand, it is not shown in the figures. Corn export demand is combined with domestic non-ethanol corn demand.

In each of the three panels, the initial price for corn is the same \( p_0 \) and an adverse climate event reduces corn supply by a factor of one-third (at the initial price). Panel (a) represents the case of market driven ethanol production (high oil prices, high \( \alpha \) and high \( \sigma \)) and therefore high derived demand elasticity of corn in ethanol industry. Corn demanded by ethanol is reduced in the face of higher corn price and a relatively larger elasticity of substitution between ethanol and petroleum. (Appendix-table A provides key parameter values across the different scenarios considered below.) Panel (b) represents a nascent ethanol sector and no government mandates on ethanol production. Very little ethanol is demanded as oil substitute so the derived demand elasticity is effectively zero. Panel (c) depicts the case where oil prices are not high enough to make ethanol lucrative as oil substitute; at prices of corn above \( p_0 \), and therefore for any price above \( p_0 \), the mandate dictates the amount of ethanol being produced and mixed with gasoline. For ease of comparison we assume that the same amount of ethanol is produced in both panels (a) and (c), at initial prices, but with mandates binding in panel (c), a negative supply shock does not translate into a reduction in ethanol sector’s use of corn as input, and therefore price rises much more than under panel (a).

Note that in all three panels the initial level of corn price plays an important role in determining how much the corn price would increase. In panel (a), if corn price was initially so high that the system operated in the realm where ethanol as substitute is not profitable, then corn price would be determined by the non-ethanol demand segment only, and would increase much more. Similarly, if the initial corn price was low enough that even with a low oil price (panels b and c) some ethanol was used as oil substitute, then corn price would increase less than it does in the current depiction of the two panels.

This analytical framework can also be used to infer the conditions under which fuel price and corn price will move together, in the event of fuel price increase.

2.2. Oil price shock

Whether corn and fuel prices move in the same or opposite directions depends on the relative sizes of \( \eta_f \) and \( \sigma \). The greater the possibility of substitution between ethanol and
crude-oil, and the greater the share of ethanol that goes to the price sensitive portion of the corn market, the more likely the corn and fuel prices are to move in the same direction.

Figure 3 explores the impact of a rise in oil price on the price of corn. Each panel depicts the same scenario as in figure 2, however, now rather than supply, it is demand that shifts. A higher oil price reduces liquid fuel demand \( \eta_D < 0 \) under all three scenarios. This reduces ethanol’s demand as oxygenate, thereby reducing corn demand in ethanol. But the oil price increase also induces the oil substituting ethanol demand curve to shift outwards (from solid to dashed curves), thereby increasing the corn demand in ethanol. The direction of change in total corn demand and therefore corn prices, in response to a rise in oil price, is therefore not certain.

If oil price is high to begin with, then there exists a possibility for ethanol’s substitution demand to dominate \( \eta_D < \alpha \sigma \), due to high \( \alpha \). With a further increase in oil price from initial high levels, and assuming the blend wall is not a concern, using more ethanol in gasoline blend becomes even more profitable. This increases the demand for corn going to ethanol plants, and pushes up the price of corn. This situation is depicted in panel (a).

However, if oil prices are very low initially, so that the demand for ethanol as substitute for oil is negligible, then either of the situations depicted in panels (b) or (c) could exist. With a low oil price, the demand for ethanol as substitute for oil is smaller and additive demand dominates unless corn price is extremely low \( p < p^{pc} \). If oil price rises enough to: (i) induce substitution of ethanol for petroleum and (ii) allow this substitution effect to dominate the fall in additive demand that comes with the oil price increase, then corn price will rise. In our panels (b) and (c) this happens at any price of corn below \( p \) which is defined as the corn price at which the change in additive demand for ethanol in response to oil price increase just offsets the change in its substitute demand. For \( p < p^{pc} \) the substitution effect dominates. If, however, the increase in oil price is not enough to make ethanol profitable as an energy source and the mandate is binding, then ethanol’s role as a fuel additive dominates and price corn price falls. There could also exist a scenario in which the demand for ethanol as an oil substitute increases (shown by dashed curves), but the increase is more than offset by the reduction in demand for ethanol as oxygenate. In both of these cases, total corn demand in ethanol falls and therefore corn price falls when the oil price rises. In panels (b) and (c), this occurs for corn prices higher than \( p \). So, whether the corn and oil prices move together or in opposite directions depends effectively on whether the oil price change has a greater effect on ethanol as substitute or as fuel additive. The latter in turn depends on (1) whether oil price is initially low or high, (2) the size of the ethanol sector, and (3) whether oil price increases enough in comparison to corn price to make ethanol profitable.

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Figure 3. Impact of fuel price increase on corn price: increase in oil price reduce demand for ethanol as oxygenate but increases its demand as oil substitute. Resulting corn price could go either way and depends on whether additive or substitute demand for ethanol dominates. Panel (a) shows that when ethanol sector is driven by high initial oil price, and ethanol demand as oil substitute is the dominant component of total ethanol demand (high \( \alpha \)), corn price rises with oil price increase. With low initial oil price (panels b and c), the corn price could increase or fall, depending on the initial level of corn price. Note that in order to illustrate the different possible outcomes under panels (b) and (c), we do not start at the same initial price across the three panels unlike figure 1.

10 Technically fuel is used directly as well as indirectly (fertilizers) as input in corn production, it would therefore affect corn supply. But empirically we did not find the supply side impact to be big enough to overpower the demand side and therefore for simplicity we abstract from discussing the supply side impacts in our conceptual framework. However the numbers presented in result tables 2 (B and C) do incorporate the supply side effect.
3. Methods

The stylized framework portrayed in figure 1 is empirically implemented using the same GTAP-BIO model (Birur et al 2008), as used by Diffenbaugh et al (2012). We quantify the impacts of US corn supply and world oil price variations on US corn price volatility under four alternative characterizations of the future economy (table 1). Only one component (boldfaced) deviates from the baseline in each scenario. In terms of figures 2 and 3, ethanol policy affects the slope (depicting its ability to respond to oil prices) and position of the ethanol corn demand curve (showing the size of the ethanol sector in US in 2020). Climate change magnifies the supply shocks for US corn, and trade policy influences corn exports which are aggregated with domestic non-ethanol corn sales in figures 2 and 3.

For all four scenarios in table 1, we sample from the distribution of projected US corn yields for the period 2020–2040, and the observed world oil price for the period 2000–2010. Diffenbaugh et al (2012) projected the standard deviation of US corn yields to more than double (from 22% to 48%, a factor of 2.18) between the periods 1980–2000 and 2020–2040 due to climate change. More details on the statistical crop-yield model (modified from Schlenker and Roberts 2009) and climate model can be found in the appendix to Diffenbaugh et al (2012). For other corn-producing regions, we use those regions’ historical corn yield distributions. For oil prices, our calculations using data for period 2000–2010, suggest a standard deviation in year-on-year percent change of 15% (EPA 2012) which applies to all regions. We assume the same volatility applies to oil prices whether they are high (US$169 per bbl) or low (US$53 per bbl) in year 2020.11 Given the future corn yield distribution and the historical oil price distribution, we calculate the corn price distributions under the baseline and the alternative scenarios.

4. Results and analysis

Sampling from the distributions of corn yield and world oil price, under alternative scenarios gives the results reported in table 2. Note that the numbers reported in the table are standard deviations of year-on-year changes in corn price and corn demand, in response to corn supply and oil price fluctuations.

Our results indicate that US corn price is least volatile (101) when ethanol production is free to respond to oil price signals; because corn demand adjusts most under this scenario, prices need to adjust less. Looking across columns for the components of demand (export, ethanol, and total domestic demand), we see that the biggest adjustment for corn demand comes from demand for corn in the ethanol sector. In contrast, ethanol demand is very inflexible when dictated by mandates, as also shown in the vertical portion of demand curve in panel (c) of figures 2 and 3. Therefore, when mandates are in place corn price has to adjust more to balance the demand and supply of corn.

Though table 2 reports responsiveness of corn price to fluctuations in both corn supply and oil price, the results are similar in nature to those of corn price change responding to corn supply-only shocks (table B, appendix). This suggests that supply fluctuations dominate derived demand fluctuations in this context. There are two reasons for this outcome. First, when we compare the results of equal magnitude perturbations (10% change) in corn yield and oil price individually, we observe that corn prices are more responsive to yield shocks than to oil prices (table B and C, appendix). This is so,

| Scenario | US ethanol policy | Climate change | Trade policy |
|----------|------------------|----------------|--------------|
| Baseline | No mandate       | Corn yield volatility in US doubled | World corn tariffs at their current levels |
|          | Low oil prices   |                |              |
| Market-driven ethanol production | No mandate | Corn yield volatility in US doubled | World corn tariffs at their current levels |
|          | High oil prices  |                |              |
| RFS-driven ethanol production | RFS mandate | Corn yield volatility in US doubled | World corn tariffs at their current levels |
|          | Low oil prices   |                |              |
| Free corn trade | No mandates | Corn yield volatility in US doubled | No tariffs on corn trade |
|          | Low oil prices   |                |              |

Table 1. Different scenarios for US Economy in year 2020.

| Scenario | Demand for US corn |
|----------|--------------------|
|          | US price | Export demand | Domestic demand | Total demand |
|          |          |              |                  |              |
| Baseline | 138      | 60           | 13               | 25           | 35 |
| Market-driven ethanol production | 101      | 58           | 44               | 33           | 38 |
| RFS-driven ethanol production | 213      | 68           | 0.02             | 20           | 31 |
| Free corn trade | 127      | 69           | 12               | 23           | 37 |

Table 2. Corn yield and oil price induced variation in corn demand and prices (standard deviation of year-on-year percent change).
because the corn yield change affects the corn market, and therefore corn price, directly. In the case of a fuel price change, the impact is on corn prices indirect as it must first work through corn’s demand in the ethanol sector. Therefore, we should expect the stochastic results to be dominated by the yield shocks. Second, the corn yield distribution has a wider spread than the oil price distribution (standard deviations of 48% versus 15%). A wider distribution translates into bigger shocks (in terms of percentage change around a given mean), and therefore the resulting responses are further dominated by the corn yield and display characteristics associated with the yield-only shock results (table B, appendix). Nonetheless, a comparison with the estimates from Diffenbaugh et al. (2012) shows that the assumption of no change in oil prices underestimates the climate change induced increase in future US corn price variation, suggesting that corn prices do inherit volatility from energy markets by being linked to ethanol.

Economic policy has the potential to influence the impact of climate change on US corn price volatility. Figure 4 graphically represents the response of US corn price volatility to projected near-term climate change under the different scenarios. The horizontal line with intercept ‘1’ corresponds to the normalized baseline standard deviation of US corn prices, under future climate and future economy with a nascent ethanol sector and no change in trade policy. A negative bar shows reduced corn price volatility under a given scenario in comparison to the baseline case, while a positive bar shows increased volatility.

It is immediately evident from figure 4 that in context of the future climate, US corn price volatility is lower with market-driven ethanol production, as well as with corn trade liberalization, but higher with mandated ethanol production. The results can be interpreted as a 27% reduction from baseline corn price volatility (100.7 versus 138.1%) when the ethanol market grows due to high oil prices, a 54% increase (212.9 versus 138.1) from baseline corn price volatility when ethanol production is mandate driven, and an 8% reduction (126.6 versus 138.1%) from baseline corn price volatility with corn trade liberalization.

As argued above, the presence of corn demand adjustment in the ethanol sector is responsible for muted price response to supply disturbances when ethanol production is free to respond to market signals (in absence of mandates), and the absence of the same demand adjustment is the reason for greater price change in comparison to the baseline case when ethanol production is dictated by a mandate. And, although oil price affects corn price differently (greater price response with market-driven ethanol production and smaller price response with mandate-driven ethanol production), the comparative size of supply and oil perturbations cause the supply side to dominate the response of corn price volatility, for the reasons explained above. Freeing international corn trade also moderates the price response to adverse supply shocks however corn price responses associated with global trade liberalization are much smaller than those associated with market driven ethanol sector, because the share of corn exports is much smaller than share of corn sold domestically (table A, appendix).

There are some important limitations to this work. Our analysis overlooks details regarding food and land use change implications of biofuels production, which have been explored in literature elsewhere (Khanna and Crago 2012). In addition, by assuming independence of yield shocks in the US and other regions, we potentially overstate the impacts of climate shocks and understate the value of trade liberalization, assuming that climate shocks across regions are negatively correlated. On the other hand, if extreme events are positively correlated across major producing regions, then this omission will lead us to overstate the effectiveness of trade liberalization in reducing corn price volatility, because trading partners would experience negative supply shocks in the same years as the US supply shocks. (See Ahmed et al. 2012 for an exploration of projected changes in the co-occurrence of extreme climate events in regional and global trading partners). Finally, countries often maintain grain stocks, and engage in stock-operations counter cyclical to supply shocks. Such activities can provide a source of buffer against the type of supply shocks analyzed here (Wright 2011). We also abstract from potentially-important interactions between the energy policies of the US and other countries (Rausser and de Gorter 2013). However, our focus on the interaction of biofuel mandates, oil prices and corn prices provides an important complement, by highlighting how corn prices can rise in

One should however abstain from making strict comparison between the two studies, as not all the difference is accountable by oil price volatility. We identify three scenarios that facilitate comparison between the two studies: the baseline, market-driven ethanol production, and RFS driven ethanol production in our work can be compared with the 2020 low oil price without mandates, 2020 high oil price without mandates, and 2020 low oil price with mandates cases in figure 1 of Diffenbaugh et al. (2012). While we calculate the price variations for these cases to be about 138, 101 and 213%, the comparable numbers in Diffenbaugh et al. are 109, 95 and 200% respectively. This clearly shows that corn prices do inherit volatility from energy markets by being linked to ethanol.
response to oil price increases, even without taking into account possibly higher cost of corn production induced by increased oil price.

5. Conclusions

Our work provides a framework to understand the impact of near-term climate change on corn price volatility in the context of energy market uncertainty and alternative energy and trade policies. In addition to adding to the work of Diffenbaugh et al. (2012), this work can also be seen as building upon the framework proposed in Rajagopal et al. (2007), used to show the impacts of ethanol production on corn and fuel prices. While their work did not distinguish between different mechanisms, we show that not just ethanol production but the mechanism driving it—mandate or markets—is very important.

Our results suggest that allowing corn to move freely internationally, and to respond to market signals domestically, will reduce the impact of near-term climate change on US corn price volatility by 8 and 27% respectively. The bulk of this mitigation potential derives from the significant short run adaptation potential offered by the energy sector as a user of corn. Since ethanol use is a relatively small share of total liquid fuel demand, and since petroleum supply is typically more flexible than corn supply, adjustments in ethanol use offer a natural margin for accommodating supply side shocks in the corn market. In contrast, when this avenue of adjustment is eliminated through government mandates, corn price volatility increases sharply—rising by 54% in comparison to the baseline for 2020. Therefore, although economic policies could help offset the impacts of near-term climate change on US corn price volatility, these benefits can only be reaped with careful policy design and implementation.

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Appendix

Numerical simulations

A negative 10% US corn yield change. With a negative shock to US corn yield we expect corn supply to fall and prices to go up, irrespective of whether or not ethanol sector is big or small. How much the price rise depends on how readily demand adjusts to accommodate the supply shock. Based on the forgoing analysis, we expect that demand would adjust more readily with a big ethanol sector in place. Simulation results (table B) confirm that across the three scenarios, demand adjusts the most when ethanol sector is responsive to markets rather than driven by RFS mandates. Also, domestic option (US ethanol) appears to be more effective than international trade in making the market demand more elastic (~8.72 versus ~8.40) and the resulting price increase more modest (14.73 versus 15.18).

Table A. Parameter values across scenarios.

| Scenario            | Corn’s export share (γ) | Corn’s domestic sales share (1−γ) | Corn’s ethanol sales share (β) | Market-sensitive ethanol sales share (α) |
|---------------------|-------------------------|-----------------------------------|-------------------------------|-----------------------------------------|
| Baseline            | 0.30                    | 0.70                              | 0.23                          | 0.11                                    |
| Market driven ethanol production | 0.21                    | 0.79                              | 0.48                          | 0.76                                    |
| RFS driven ethanol production | 0.23                    | 0.77                              | 0.43                          | 0.61                                    |
| Free corn trade     | 0.32                    | 0.68                              | 0.23                          | 0.11                                    |

While the changes in total demand reported in the right-most column of table B show relatively modest differences across the scenarios, a closer look at the individual components of corn demand reveals significant differences. The relative importance of shares of the components in total demand is implicit in the results reported in table B; the actual shares are given in appendix, table A. Consider domestic ethanol demand (in both additive and oil substituting roles), table B shows that, while corn demand by ethanol industry provides a great degree of flexibility when the industry is market driven, this adjustment potential is eliminated when the RFS is in place. We expect that, under a mandate-driven system, even with a negative yield shock, the same amount of ethanol would be produced. A reduction in additive demand is matched by an increase in non-additive component, thereby not letting ethanol’s corn demand adjust. With ethanol expected to account for about 43% of corn’s domestic market sales in 2020 (appendix, table A), we calculate corn prices to increase the under this scenario (19.02%). With market-driven ethanol production, ethanol’s corn demand drops by 3.87% (this is the total change in ethanol demand obtained by adding non-additive and additive components ~3.90 + 0.02) in the face of the adverse supply shock. Note also, that in market-driven case exports and non-ethanol corn demand adjust the least. On the trade front, exports adjust most when trade has no tariffs on corn.

An informal validation of our model can be undertaken by comparing the model’s price predictions for the 2012 US drought/heat wave. As of the first week of August 2012, yields were projected to be 20% below 2011 levels (http://usda01.library.cornell.edu/usda/nass/CropProd//2010s/2012/CropProd-08-10-2012.pdf). Implementing a negative 20% yield shock in our model, with binding ethanol mandate,
gives a 48% year-on-year price increase. This is similar to the observed price impact on corn markets. Tyner et al (2012) estimate the expected corn price before the drought to be $5.26\text{bu}^{-1}$. Comparing this with the observed corn price in late August ($7.54\text{bu}^{-1}$) implies a 43% increase in corn prices, so our model prediction is reasonably accurate. Of course drought was not the only factor affecting prices.

World fuel price increase by 10%. The other type of shock, we are interested in, is an oil price shock. A rise in the world oil price increases the price of gasoline and reduces its demand, reducing the demand for ethanol as an additive but increasing the demand for ethanol as an oil substitute. Table C shows the impact of a 10% increase in the world price of oil. It is a little more complicated to analyze the effects of the fuel price change on corn prices than to analyze the effects of corn yield changes on corn prices. This is so, because, unlike corn yield, fuel price does not directly impact corn price. Rather, the fuel price impact is filtered through the ethanol sector and through increased costs of corn production. As a result whenever the share of corn supply to ethanol is large and market-driven, the pass-through to corn prices is larger. Also, due to the indirect impact of the oil price increase on the corn sector, the numbers in table C are much smaller in comparison to the corresponding impacts in table B. In other words, supply-side shocks are more potent in driving the US corn prices than is the world fuel price—provided that the absolute size of the shocks is comparable.

Unlike the yield shock, the oil price shock shifts out the demand curve for corn, thereby boosting production and the price of corn. The one exception is for the RFS driven ethanol production, wherein the additive effect dominates and demand shifts inward, thereby causing corn price to fall. This response can also be seen from the expression (5) for fuel price impact on corn prices in appendix A: without the possibility of substitution under mandate-driven integration, the sign for this expression turns negative. The same direction of change in demand and prices is not as unexpected, as can be seen from figure 3, panel (a): with the supply constant, total demand and corn prices reveal the same ranking across the scenarios (table C).

In the presence of a fuel price shock, domestic price for corn rises more with ethanol production responding to market signals. This response is counter to the results in table B, where price rises less in response to the yield shock when market signals saw ethanol production respond. This dual nature of intersectoral integration creates a ‘double-edged sword’: on one hand, food-fuel market nexus creates a more elastic demand and dampens the price response to supply shocks; on the other hand, it leaves the sector more exposed to oil price variations. This double-edged sword in the deterministic simulations is also one of the reasons that we in the main text turned to a stochastic simulation to evaluate the potential of coexistence of food fuel markets in cushioning the impacts of extreme climate events on corn prices.

### Table B. Effect of 10% decline in US corn yield (in % change).

| Scenario                        | US price | Export demand | Domestic demand | Additive ethanol | Non-additive ethanol | Non-ethanol | Total demand |
|---------------------------------|----------|---------------|-----------------|------------------|----------------------|-------------|--------------|
| Baseline                        | 16.27    | −4.04         |                 | −0.01            | −0.48                | −3.37       | −7.91        |
| Market driven ethanol production| 14.73    | −2.78         |                 | 0.02             | −3.90                | −2.03       | −8.72        |
| RFS driven ethanol production   | 19.02    | −3.60         |                 | −0.04            | 0.04                 | −3.42       | −7.02        |
| Free corn trade                 | 15.18    | −5.01         |                 | −0.02            | −0.42                | −3.05       | −8.40        |

### Table C. Effect of 10% increase in world oil price (in % change).

| Scenario                        | US price | Export demand | Domestic demand | Additive ethanol | Non-additive ethanol | Non-ethanol | Total demand |
|---------------------------------|----------|---------------|-----------------|------------------|----------------------|-------------|--------------|
| Baseline                        | 0.290    | 0.01          |                 | −0.39            | 0.67                 | −0.15       | 0.152        |
| Market driven ethanol production| 2.75     | −0.63         |                 | −0.31            | 3.33                 | −1.01       | 1.36         |
| RFS driven ethanol production   | −0.20    | −0.06         |                 | −0.35            | 0.35                 | −0.15       | −0.21        |
| Free corn trade                 | 0.291    | 0.06          |                 | −0.38            | 0.63                 | −0.16       | 0.153        |
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