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WEATHER SHOCKS AND INTER-HEMISPHERIC SUPPLY RESPONSES: IMPLICATIONS FOR CLIMATE CHANGE EFFECTS ON GLOBAL FOOD MARKETS

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Climate models predict more weather extremes in the coming decades. Weather shocks can directly reduce crop production, but their effect on food markets is partly buffered by storage and supply responses that can be complex and nuanced. We explore how inter-hemispheric trade and supply responses can moderate the effects of weather shocks on global food supply by enabling potential intra-annual arbitrage. Our estimates of this effect in the case of wheat and soybeans suggest that it may be considerable: 25–50% of crop production lost to a shock in the Southern Hemisphere is offset six months later by increased production in the North. These results have implications for the potential effects of climate change on global food markets, for how we model these interactions and, possibly, for the design of trade and production-related policies that aim to leverage this inter-hemispheric buffer more effectively.

Keywords: Climate change; extreme weather; international trade; food; agriculture.

1. Introduction

Climate models predict a warmer climate with more frequent extreme weather events in the coming decades (Seneviratne *et al.*, 2012). Intergovernmental Panel on Climate Change (IPCC) reports describe very likely increases in "simple" extreme events such as longer and hotter heat waves and more intense precipitation as well as likely increases in "complex" events such as drought and cyclone intensity[1] (McCarthy *et al.*, 2001). In the wake of food price spikes in 2008 and 2011, more extreme weather outcomes are widely feared for their potential impacts on crop production and food markets (Nelson *et al.*, 2010; Wheeler and von Braun, 2013; Willenbockel, 2012). The media often simplify this link between climate change and food: "Climate change will pose sharp risks to the world's food supply in coming decades, potentially

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[1]See http://www.ipcc.ch/ipccreports/tar/wg2/index.php?idp=354 (accessed on 2 September 2014).

undermining crop production and driving up prices at a time when the demand for food is expected to soar, scientists have found." (*New York Times*, 2013).[2] Although these effects could indeed be fearsome, the connections from climate change in general and more frequent extreme events in particular to the world's food supply are complex and nuanced in important ways. We explore one such complexity that arises from the fact that the 23.5° tilt in the earth's axis creates offset growing seasons for many staple crops. Specifically, we argue that these offset seasons can moderate the effects of extreme weather events on global food supply by enabling potential intra-annual arbitrage.

Obviously, international trade can buffer the effect of localized weather shocks on food markets, so promoting trade is popular policy advice with greater climate variability looming (e.g., Sumner *et al.*, 1998; Torero, 2011). An often overlooked feature of this trade buffer is how counter-seasonal growing cycles for a given crop shape intra-annual supply responses. For example, extreme December flooding that lowers soybean production in Brazil and raises soybean prices may incent US farmers to allocate more acreage to soybeans when they plant in April thereby buffering the effect of the Brazilian flood on global soybean markets.

In this article, we show that supply responses in one hemisphere to weather shocks in the other hemisphere can significantly buffer the impact of climate variability on global food supply and prices. We estimate the magnitude of the effect econometrically for wheat and soybeans and find that a quarter to half of the production lost to a weather shock in the Southern Hemisphere is offset six months later by expanded production of the crop in the Northern Hemisphere. These results have implications for the potential effects of climate change on global food markets and for how we model the interactions between a changing climate and these markets. This inter-hemispheric trade buffer also implies that the North–South distribution of crop production may make global markets for some staple crops more vulnerable to climate change than others. Future work to understand the magnitude of these inter-hemispheric supply responses and associated factors may provide an impetus for more specific trade policy recommendations to mitigate the effects of climate change on food markets.

2. Empirical Approach

Wheat, rice, soybeans, and corn contribute about 75% of calories consumed worldwide (Roberts and Schlenker, 2013). We focus our empirical analysis on two of these commodities: wheat and soybeans. Most of the world's wheat is milled into flour and used as the major ingredient in breads, cakes, pasta, and similar products for human consumption. In contrast, soybeans are processed into oil, which is widely used in

[2] This article described a leaked draft of a report under development by a United Nations panel, the Intergovernmental Panel on Climate Change.

processed foods, and meal, which is predominantly used for animal feed. We do not study corn and rice, the two other major grains, because reliable Southern Hemisphere production forecasts — which are the basis for both our empirical approach as described below and the very inter-hemispheric response we are studying — do not exist for these commodities.

Figure 1 shows the distribution of global production of wheat and soybeans by Northern and Southern producers. Soybean production is (now) split evenly across Northern and Southern Hemispheres, concentrated almost entirely in the Americas. By comparison, wheat production is spread much more widely across the Eastern and Western Hemispheres, but is much more skewed to the North, with Argentina and Australia the only major producers in the South of the equator. This pronounced difference in the North–South balance of production suggests that the inter-hemispheric response potentially buffers the soybean market much more than the wheat market.

The timing of Northern and Southern growing cycles is important for our analysis. Figure 2 shows that soybeans are planted in the late spring and harvested in the fall. Thus, information about the Southern soybean crop is revealed early in the calendar year, during which time Northern producers can change planting decisions. Wheat production is more complicated because the two main types or classes have different growing seasons. Winter wheat is planted in the fall and harvested the following summer, whereas spring wheat is planted in the spring and harvested in the late summer. Information on Southern wheat production is revealed in the second half of the calendar year, during which time Northern producers have some flexibility to adjust winter wheat planting and full flexibility to adjust spring wheat planting decisions. The percentages in Fig. 2 indicate the share of global production and consumption (in brackets), which together determine how much events in these locations may affect global commodity markets.

Following Adjemian and Smith (2012), we estimate the effect of Southern production shocks on US futures prices. We regress the log change in prices from the date of one forecast release to the next on the change in expected production in each

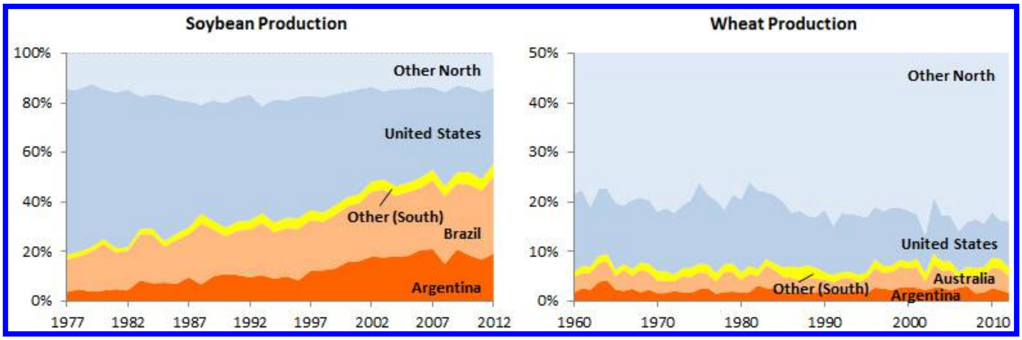

Figure 1. Distribution of global production of soybean and wheat (different scale as ∼80% of production is in the North) across selected Northern and Southern countries.

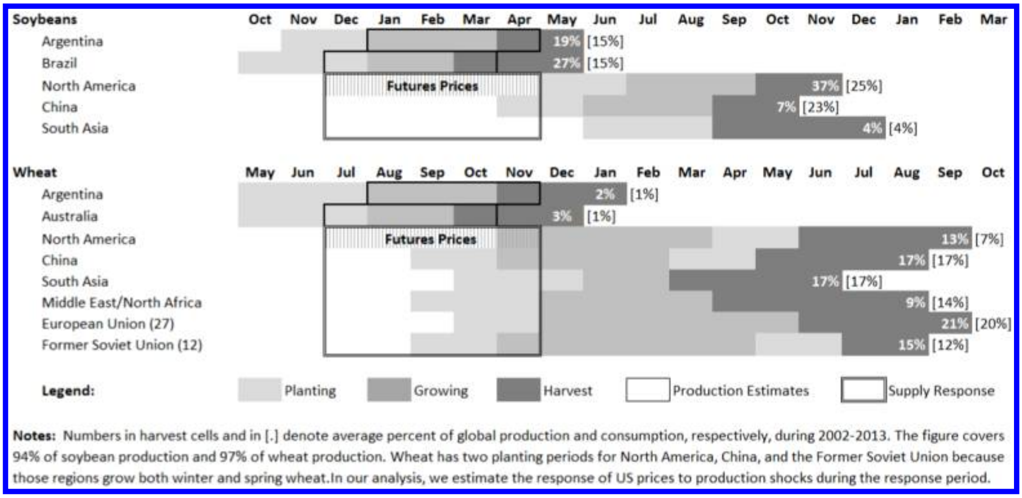

Figure 2. Offset seasonal soybean and wheat production of Northern and Southern countries.

country. We normalize production forecasts by expected world supply. This normalization allows our regression coefficients to be easily interpreted as capturing the effect of a given percent shock to world supply. The regression equation is therefore:

$$\ln(F_{t,T}) - \ln(F_{t-1,T}) = \beta_0 + \beta_1 \frac{Q^A_{t,T} - Q^A_{t-1,T}}{Q^W_{T-1}} + \varepsilon_t \qquad (1)$$

where F indicates the futures price at date t for delivery at date T, and Q indicates acreage estimated at date t for harvest expected at date T. For each country A, t denotes the date of the current US Department of Agriculture World Agricultural Supply and Demand Estimate (WASDE) release and $t-1$, the date of the previous WASDE release. The denominator used for normalization is constant within crop years. It equals the previous year's world production (as a proxy for expected production in the current year) plus the previous year's ending stocks. We add stocks because it is the size of a production shock relative to total supply that matters.

3. Analysis and Results

3.1. *Data*

We measure expected production using the monthly WASDE reports. These reports provide forecasts of production and use of agricultural commodities. We take growing-season production forecasts for soybeans in Argentina and Brazil and wheat in Australia and Argentina. For soybeans, the mean absolute error falls steadily over the season for Brazil, but not for Argentina. For wheat, the mean absolute error of these predictions falls steadily as the growing season progresses for Australia, but not for Argentina. Combined this evidence suggests that the WASDE forecasts are likely to be relatively less informative for Argentine production. We use 28 years of data, covering the 1986–2013 Southern Hemisphere soybean harvests and wheat harvests from 1985/86 through 2012/13.

As an implicit response variable, we use the soybean and wheat prices that are most relevant for Northern producers' planting decisions, namely, Chicago futures prices for post-harvest delivery. We use the November soybean contract and the July wheat contract.

3.2. *Northern hemisphere price response*

We provide results for the regression in (1) separately for each country. We also estimate pooled models, in which we stack the equations for each country. The pooled regressions contain each price observation twice, so we cluster by date when estimating standard errors. We interpret the pooled regressions as weighted averages of the country's regressions.

In addition to providing estimates for the full 28-year sample, we provide two other estimates. First, to allow for the possibilities that WASDE forecasts have improved in quality, markets have become more integrated, the impact of farm subsidies on supply response to market price has lessened, or Northern supply response has changed over time, we also report results for only the period since the 1996 US Farm Bill (1997–2013). Second, we report results from "placebo" regressions, which estimate the response of wheat prices to soybean production shocks and soybean prices to wheat production shocks. Soybeans and wheat rarely compete for land, so we expect these placebo regressions to show no significant effect.

The price response for soybeans has the expected negative sign in all cases (Table 1). The coefficient is statistically insignificant for Argentina and larger and

Table 1. US price responses to Southern hemisphere production shocks.

Soybeans	Argentina		Brazil		Pooled		Placebo
	86-13	97-13	86-13	97-13	86-13	97-13	
Price Response	−1.52	−2.46	−2.81*	−5.41*	−2.26*	−3.79*	−0.85
	(−1.05)	(−1.43)	(−2.17)	(−2.85)	(−2.17)	(−3.65)	(−0.84)
R^2	0.01	0.04	0.07	0.16	0.04	0.08	0.00
Sample Size	112	68	112	68	224	136	224
Wheat	Argentina		Australia		Pooled		Placebo
	86-13	97-13	86-13	97-13	86-13	97-13	
Price Response	0.74	5.14	−6.58*	−7.37*	−5.44*	−6.07*	−0.35
	(0.11)	(0.52)	(−2.28)	(−2.32)	(−2.08)	(−2.32)	(−0.12)
R^2	0.00	0.00	0.04	0.06	0.02	0.02	0.00
Sample Size	112	68	112	68	224	136	224

*denotes significance at 5% level. Heteroskedasticity-robust *t*-statistics in parentheses. In pooled regressions, we also cluster by date. The intercept is small and statistically insignificant in all cases, so we exclude it from the table for brevity.

statistically significant for Brazil. The estimated price response is also larger for the last 17 years than for the full sample, which suggests improved data quality and improved market integration as soybean production expanded in South America. For wheat, the Argentina coefficients are estimated very imprecisely in all cases, suggesting that the WASDE reports provide poor estimates of Argentinean production, relative to other information that drives futures prices. In contrast, the coefficients for Australia are large and significant in both samples. Both placebo regressions show negligible price responses.

To put these estimates in perspective, consider poor growing season weather in Brazil such as occurred for soybeans in 2005 and 2012. These shocks each reduced expected world production by about 2.5%. Using the 1997–2013 coefficient for Brazil, we estimate that US prices would rise in response by $5.41 \times 2.5 = 13.5\%$ (95% confidence interval (CI) [4.2, 22.8]). Similarly, consider a 40% drop in expected Australian wheat production (such as occurred in both 2006 and 2007) that reduced world wheat production by 1.2%. The 1997–2013 coefficient for Australia suggests such a shock increased prices by an estimated $7.37 \times 1.2 = 8.8\%$ (95% CI [1.4, 16.3]). Overall, Southern shocks of a magnitude observed recently cause US prices to increase roughly 10%.

3.3. *Northern hemisphere supply response*

How much are Northern producers likely to respond to the price effects we show in Table 1? To answer this question for soybeans, we need to incorporate an additional production fact: That most Northern Hemisphere soybeans are grown in the US and planted in rotation with corn. This implies that if farmers grow more soybeans, they likely grow less corn. It follows that Southern Hemisphere soybean production shocks should also affect corn prices and that the supply response for these two commodities should depend on the relative price of soybeans to corn. Thus, we report in Table 2, the results from regressions of the response of this relative price to soybean production shocks:

$$\ln\left(\frac{F_{t,T}^{\mathrm{SOY}}}{F_{t,T}^{\mathrm{CORN}}}\right) - \ln\left(\frac{F_{t-1,T}^{\mathrm{SOY}}}{F_{t-1,T}^{\mathrm{CORN}}}\right) = \beta_0 + \beta_1 \frac{Q_{t,T}^{A} - Q_{t-1,T}^{A}}{Q_{T-1}^{W}} + \varepsilon_t \tag{2}$$

The estimates in Table 2 are 30–40% smaller than those reported in Table 1 for soybeans, implying that a 2.5% shock to world soybean production would increase the relative price by $3.71 \times 2.5 = 9.3\%$. Hendricks *et al.* (2014) estimate an acreage elasticity of 0.3 for US soybeans grown in the central corn belt, so we would predict an increase in soybean acreage of about $9.3 \times 0.3 = 2.8\%$ as a result of a 2.5% shock to world soybean production (all else equal). We may expect a larger supply response outside the corn-belt because of more land available for adjustments on an extensive (non-rotational) margin. Extrapolating this estimate to the US as a whole, and using the fact that the US produces about 40% of world soybeans, we estimate a world supply response of about $0.4 \times 2.8 = 1.1\%$, which may be an underestimation since this assumes that soybean

Table 2. US soybean/corn relative price responses to Southern soybean production shocks.

Soybeans	Argentina		Brazil		Pooled		Placebo
	86-13	97-13	86-13	97-13	86-13	97-13	
Price Response	−1.03	−1.28	−2.40*	−3.71*	−1.79*	−2.34*	−0.85
	(−1.20)	(−1.20)	(−3.09)	(−3.02)	(−2.57)	(−2.22)	(−0.84)
R^2	0.01	0.02	0.10	0.15	0.04	0.06	0.00
Sample Size	112	68	112	68	224	136	224

*denotes significance at 5% level. Heteroskedasticity-robust *t*-statistics in parentheses. In pooled regressions, we also cluster by date. The intercept is small and statistically insignificant in all cases, so we exclude it from the table for brevity.

production occurs exclusively in rotation with corn. This rough calculation (with a wide confidence interval) suggests that almost half the lost soybean production is replaced six months later by the US supply response.

Wheat production is spread more widely around the world than soybean production, and wheat planting occurs throughout much of the year thanks to different wheat varieties.[3] This heterogeneity implies that production substitutes for wheat differ widely from one location to another and complicates the calculation of even rough supply response estimates. There are, however, a few such estimates in the literature. For example, Antle and Capalbo (2001) estimate supply elasticities for the US of 0.36 for winter wheat and 0.14 for spring wheat. This suggests that wheat supply response is similar in magnitude to the soybean response. Continuing our example from the previous section and using a supply elasticity of 0.3, we estimate an increase in wheat acreage of $0.3 \times 0.13 \times 8.8 = 0.3\%$, which is one quarter of the lost production. Since the US accounts for only a fraction of total Northern Hemisphere wheat production (see Fig. 1), even a weak supply response elsewhere in the North (especially Canada, Europe and the former Soviet Union) could be sufficient to replace another quarter or more of lost production.

4. Discussion

Understanding the potential effects of climate change on food markets is a global priority because price spikes can negatively affect households and society more broadly. We show in this paper that international trade can help mitigate production shocks through a previously underappreciated channel, namely, inter-hemispheric supply responses for crops with offset North–South growing seasons. Our results suggest that between a quarter and a half of the lost wheat or soybean production

[3]Although not our focus here, the range of wheat varieties bred for to be sown at different times during the year — most notably winter and spring — wheat can serve as an important intra-annual buffer within a given production location. This gives rise to another source of crop-specific heterogeneity in the effect of climate volatility on food and food markets.

associated with a weather shock in the South is replaced six months later by expanded production in the US. This intra-annual response reduces optimal commodity inventories, thereby lowering storage costs and improving efficiency, and reduces the variance of crop prices. The dynamic, long-run implications of these effects on global food markets could be considerable.

Our analysis considers only one direction (South-to-North) of what is potentially a bi-directional response. Data limitations currently prevent us from estimating the North-to-South response, but this remains a worthwhile research pursuit. As we think about this other direction of supply response or consider other crops, it is important to appreciate how polices and market institutions influence the strength of this inter-hemispheric response. We find evidence that this response has strengthened in recent years, perhaps due to more integrated international markets and better transmission of production and price information. Understanding more about the factors that shape this response may lead to trade-climate change policy recommendations that are more specific by crop and region. For example, expanded production and increased market integration of southern Africa with world markets would increase the ability for the Southern Hemisphere to mitigate shocks in the Northern Hemisphere. More general recommendations, such as mechanisms that improve the transmission of price signals to producers, might also garner greater support with an improved understanding of these factors.

Several final considerations regarding the potential for inter-hemispheric supply responses to mitigate shocks in practice are worth noting. First, if countries impose trade restrictions in the wake of a production shock — as some countries did for rice in 2008 and 2011 — then the observed price transmission effect is likely to be even larger than our estimates. Second, the inter-hemispheric supply response would be dampened if weather shocks during growing seasons were strongly correlated across hemispheres, i.e., if weather shocks in one hemisphere tended to be followed by shocks in the other hemisphere six months later. Although global weather systems imply that weather events are spatially and temporally dependent, we know of no models that predict significant intra-year correlation in weather events across hemispheres in this way. Third, some of the supply response we showcase is likely to come from substitution of one food or feed crop for another, rather than cultivation of idle land or increase use of yield increasing inputs. Therefore, the "calorie production response" would likely be less than the supply response for a single crop. Nonetheless, these induced changes in the production mix have important implications for food markets because different crops enter the food system differently, which can shape the distribution of impacts across producers and consumers.

Next, the importance of understanding, leveraging and accounting for inter-hemispheric supply responses is likely to grow both as extreme climate events occur with greater frequency and as our ability to model and anticipate climate variability improves. Numerous models now exist to simulate the potential impacts of climate change on global food markets. von Lampe *et al.* (2014) compare 10 commonly-used models, six of which are full economy computable general equilibrium models and four of which are partial equilibrium models of the agriculture sector. These models differ in scope, detail, and functional forms, but they all use annual time steps and solve for an equilibrium *annual* price conditional on some production technology. As such, they do not allow for intra-season supply response to weather shocks. Rather, as described by Robinson *et al.* (2014), supply in these models is atemporal. The models treat production in each year independently and do not distinguish between the output price received and the decision-relevant price for farmers, which is the expected price at planting time.

These models estimate the effects of climate change by first predicting the change in average yield due to climate change and then changing the production function parameters to adjust average yields accordingly (von Lampe *et al.*, 2014). This structure makes them ill-equipped to simulate the effects of extreme events because they miss intra-annual, inter-hemispheric responses to these events — responses that potentially moderate subsequent effects on global food markets. For example, consider an extreme growing-season weather event in South America that lowers crop yields. Using one of the models in von Lampe *et al.* (2014), a researcher could simulate the effects by changing a parameter to reduce productivity in the South America region. This parameter change would generate an equilibrium in which South American farmers potentially grow different crops, depending on the assumed elasticities of substitution, and change the mix of variable inputs such as labor and fertilizer. The equilibrium price of the affected crops would increase due to lower South American production, but producers in the rest of the world also have upward-sloping supply curves, so they will produce more than they would have without the weather shock, mitigating the price effect. In the model, these responses all happen simultaneously; rather starting at one point in time, generating a shock, and watching the response over time, the model evaluates the effect of a shock by comparing one time-independent equilibrium to another.

In practice, South American farmers have little capacity to respond to their own weather shock because their production decisions are mostly made before shocks hit. This lack of response exacerbates the price effect. On the other side of the globe, farmers in the Northern Hemisphere have significant capacity to respond because they make production decisions after having observed the shock in South America. Models with annual time steps cannot capture these responses and consequently tend to underestimate the Northern Hemisphere response and overestimate the South American response.

The magnitude of any potential errors made by standard models depends critically on the parameterization of those models. Because many models do not use the most decision-relevant prices but rather solve for a one-shot equilibrium, they use the same productivity parameter to capture both weather shocks and changes in average productivity. Dynamic producer responses to these two types of events fundamentally differ and cannot therefore be captured by the same parameter. Such models are consequently limited in ways that might previously have been overlooked or at least underappreciated. The potential magnitude of these effects on global food markets may be both large and increasing as market information disseminates to even remote producers and as markets become more integrated. Models must abstract from the richness of reality in many ways, but model builders ought not to dismiss these dynamic intra-annual and inter-hemispheric responses without carefully weighing the modeling tradeoffs — particularly if the ultimate goal is to understand potential climate change effects on global food markets.

As a final implication of our findings, inter-hemispheric supply responses raise potentially important dimensions of climate change vulnerability for different staple markets. This, in turn, has direct implications for heterogeneous climate change vulnerability at national and regional levels. Based on our analysis, the distribution of global production between the North and South for a given crop directly shapes how strong the potential inter-hemispheric supply response may be.[4] In our case, soybean production is more balanced between Northern and Southern Hemispheres than wheat production, but less balanced East-to-West. These dimensions bring different diversification benefits that are worth taking into account differently. Moreover, the concentration of production of a given crop in a given location is also likely to increase inter-hemispheric supply response by stimulating investments in information and broader institutions that facilitate price transmission and market integration. In sum, the response we study suggests that different staple markets with different spatial distributions will have quite different vulnerabilities to climate change — and that these differences may map directly into global food markets.

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