A Model of Asynchronous Bi-Hemispheric Production in Global Agricultural Commodity Markets

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Abstract

The past 40 years have witnessed a rapid expansion of grain and oilseed production in the southern hemisphere, particularly in South America. The growth of southern hemisphere production is significant, not only because it has increased supplies to meet growing world food needs, but also because it has effectively shortened the global crop growing cycle from twelve months to six. In this paper, we develop and analyze a semi-annual stochastic spatial-temporal equilibrium model of a generic agricultural market with two major exporting regions, North and South, which plant and harvest at different times of the year. As a case study, we calibrate our model parameters to reflect the stylized facts of the global soybean market between 1980 and 2019, with the United States serving as North and Brazil and Argentina serving as South. We find that more balanced production, with both hemispheres producing nearly equal amounts at different times of the year, has, from a global perspective, shortened the traditional crop "season" from 12 months to 6, allowing semi-annual adjustments to planned production that stabilize supply and prices in all regions, while reducing global inventories.

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Introduction

The past 40 years have witnessed a rapid expansion of grain and oilseed production in the southern hemisphere, particularly in South America. Driven by income growth and changing diets in developing countries like China, global demand for meat and livestock products has soared which, in turn, has increased demand for protein meal and feed grains as feedstocks for expanding livestock, dairy and poultry production. Similarly, demand for biofuels such as ethanol and biodiesel account for a growing share of consumption as use of renewable fuels has increased exponentially over the past 15 years (FAO, 2017).

Expanded land use and increased productivity have propelled South America from accounting for about 20 percent of global soybean exports and 11 percent of global maize exports in 1980, to over 60 percent and 43 percent in 2019, respectively (see figure 1). During that period, South America has surpassed the United States as the world's largest soybean and maize exporter (USDA/FAS, 2020b).

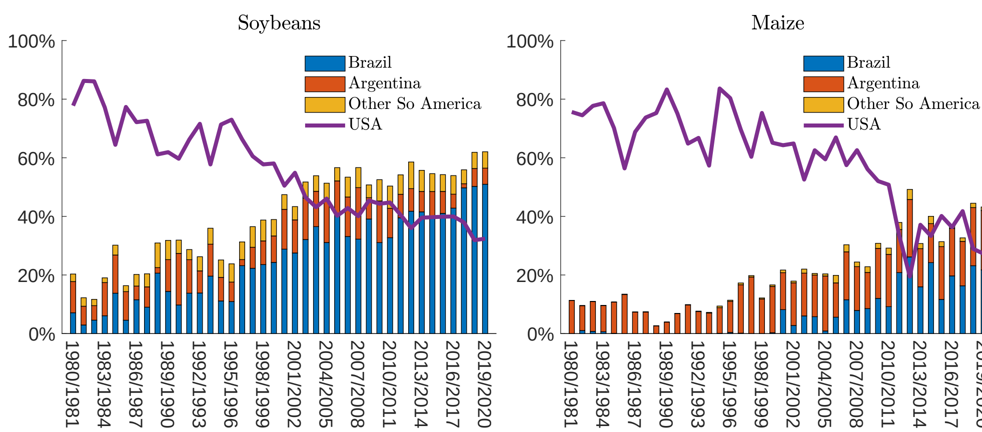

Figure 1: Shares of Global Soybean and Maize Exports, 1980-2019. *Source: USDA/FAS, 2020b*

Projected grain and oilseed trends by various forecasters point to expected continued growth in southern hemisphere production over the next 10 years (USDA/OCE, 2019; FAPRI, 2019; OECD/FAO, 2019). Moreover, to meet world food needs by 2050, the Food and Agriculture Organization of the United Nations concludes that much of the needed production gains will have to come from South America and Sub-Saharan Africa, where there remain ample supplies of arable land and where yields lag potential (Bruinsma, 2011; Alexandratos and Bruinsma, 2012; FAO, 2017).

The growth of southern hemisphere production is significant, not only because it has increased supplies to meet world food needs, but also because it has effectively shortened the global crop growing cycle from twelve months to six. Since production of most grains and oilseeds in the northern and southern hemispheres are counter-seasonal, producers in one hemisphere can react rapidly to production shortfalls in the other. For example, in response to the widespread North American drought in the summer of 2012, Brazilian producers planted a record 15.8 million hectares of maize, which provided needed supplies to a tight world market, and helped to dampen price hikes (USDA/FAS, 2020b).

What is less well understood, however, is the effect of the growth of southern hemisphere production on seasonal trade, inventories and pricing. For example, how do shifts in production and consumption affect intra-year seasonal patterns of trade between the northern and southern hemispheres and the Rest of the World (ROW)? Have incentives to hold inventories in both hemispheres changed and do the changes vary seasonally? How are seasonal price patterns affected in importing and exporting regions when the share of production and consumption shifts between hemispheres? Lastly, how closely are prices integrated between exporting and importing markets when new supplies are available to the market every six months?

In this paper, we develop and analyze a stochastic spatial-temporal equilibrium model of the global soybean market with two major exporting regions, North and South, which plant and harvest at different times of the year. Our objective is to explain how cross-hemispheric trends in agricultural production over the past four decades have affected seasonal stockholding, exporting, and price and supply stability, and how these trends can be expected to affect the global soybean market in the future.

Our model provides a novel contribution to the modeling of commodity trade and storage under uncertainty. Early studies that modeled the effects of trade in a static open economy under uncertainty largely ignored the role of competitive storage (Bale and Lutz, 1979; Tyers and Anderson, 1992). Pioneering work by Gustafson (1958) and later (Gardner, 1979) successfully solved stochastic storage models to develop optimal storage rules in a dynamic closed economy. Wright and Williams (1982) and Lowry et al. (1987) formulated storage models in the context of rational price expectations that gave insights into the economic role of intra-seasonal storage in linking prices through time. However, those models ignored the allocative role of trade in distributing supplies across space.

Work by Williams and Wright (1991) and Miranda and Glauber (1995) marked early attempts at modeling trade and competitive storage under uncertainty assuming rational price expectations. Those models were highly stylized two-country models that examined how trade and storage interact under various assumptions. With the development of computational power and numerical techniques, empirical studies such as Larson et al.'s 2014 analysis of food security in the Middle East allowed for simulation of optimal storage policies in net food importing countries. Gouel and Jean's 2015 examination of optimal trade and storage policies in the context of open economies yielded important insights on the impact of domestic policies on international prices. Glauber and Miranda (2016) extended the trade/storage model to a two-hemisphere model where production was static but unresponsive to price and thus did not capture the reaction of growers to current supplies and expected carryouts in the other hemisphere. This paper builds on that model by introducing price responsive supply in both hemispheres.

The remainder of the paper is organized as follows. In the following section, we summarize the stylized facts of global soybean production, consumption, and exports from 1980 to 2019. We then introduce a stochastic spatial-temporal model of storage and trade for a generic storable commodity that is harvested in different hemispheres at different times of the year. In the subsequent section we report the results of stylized simulations of our model in which we compare a world with a single producer-exporter that plants and harvests on an annual cycle to a world with two producer-exporters of equal size who plant and harvest at alternating times of the year. We then report the results of simulations of our model parameterized to reflect global soybean market conditions between 1980 and 2019 and projections for 2020-2029. We find that more balanced production, with both hemispheres producing nearly equal amounts at different times of the year, has, from a global perspective, shortened the traditional crop "season" from 12 months to 6, allowing global demand to be met with reduced inventories. It has also allowed for semi-annual adjustments to planned production by one exporter to variations in available supplies in the competing exporter, thereby stabilizing supply and price in all regions.

Soybean Production, Consumption and Exports

Table 1 reports average annual soybean production, consumption, and exports to the Rest of the World during the decades spanning 1980-2019, and United States Department of Agriculture projections for the period 2020-2029, for the United States, South America, and the Rest of the World (USDA/OCE, 2019; USDA/FAS, 2020b). The table also reports the average annual exponential rates of growth in these for the historical period 1980-2019, as well as the rates of growth projected for 2020-2029. Table 2 presents each region's share of production, consumption, and exports to the Rest of the World over the same periods.

Table 1: Mean Annual Production, Consumption and Exports to Rest of World, 1980-2019 by Decade, with USDA Projections for 2020-2029, and Mean Annual Rates of Growth, Historical 1980-2019 and Projected 2020-2029, by Region.

						Mean Annual Rate of Growth	
	1980s	1990s	2000s	2010s	2020s	1980-2019	2020-2029
	million metric tons					*percent*	
Production							
United States	52	63	80	102	120	2.3	1.7
South America	24	40	93	149	205	6.4	3.2
Rest of World	19	29	38	57	76	3.7	2.9
World	94	132	211	308	400	4.0	2.6
Consumption							
United States	32	42	50	55	64	1.8	1.6
South America	19	32	63	88	106	5.2	1.8
Rest of World	43	58	97	164	228	4.5	3.4
World	94	132	210	307	399	4.0	2.6
Exports							
United States	20	21	30	47	58	2.9	2.1
South America	4	8	30	61	94	9.4	4.5

Source: USDA/FAS, 2020b. World totals may not equal sum of regions due to rounding.

Four major trends characterize the global soybean market over the period 1980-2019. First, global production and consumption have expanded rapidly, with both growing an average annual rate of 4.0 percent. USDA, however, projects growth of both to slow to about 2.6 percent per year over the decade of 2020-2029. A variety of factors are expected to cause the slowing of global production and consumption, including: 1) a general slowing of per-capita income growth in China, which in turn is expected to slow the growth in demand for meat among Chinese consumers and the attendant demand for livestock feedstuffs, most notably soybeans; 2) higher tariffs imposed by the Chinese government on US soybean imports as a result of continuing trade conflicts between the two countries; and 3) the impact of African Swine Fever, which has decimated China's hog production over the past few years.

Table 2: Mean Annual Production, Consumption and Exports to Rest of World as a Percentage of Global Production, 1980-2019 by Decade, with USDA Projections for 2020-2029, by Region.

	1980s	1990s	2000s	2010s	2020s
Production					
United States	55	48	38	33	30
South America	25	30	44	48	51
Rest of World	20	22	18	19	19
Consumption					
United States	34	32	24	18	16
South America	21	24	30	29	27
Rest of World	46	44	46	53	57
Exports					
United States	21	16	14	15	14
South America	5	6	14	20	24

Source: USDA/FAS, 2020b.

Second, between 1980 and 2019, growth in soybean production has occurred largely in South America. During that period, South American soybean production grew at an average annual rate of 6.4 percent, greater than the global rate of 4.0 percent, and well exceeding the US rate of 2.3 percent. South America produced 25 percent of the world's soybeans in the 1980s, rising to 48 percent in the 2010s. In contrast, the US produced 55 percent of the world's soybeans in the 1980s, falling to 33 percent in the 2010s. Over the coming decade, USDA expects the rate of growth in soybean production to slow to 1.7 percent and 3.1 percent in the US and South America, respectively, with the US share of global production falling modestly to 30 percent and the South America share of global production rising modestly to 51 percent. The percentage of soybeans produced in the Rest of the World has changed relatively little between 1980 and 2019, hovering around 20 percent, and is expected to change little over the coming decade.

Third, between 1980 and 2019, growth in soybean consumption also has occurred largely in South America and, to a slightly lesser extent, in the Rest of the World. During that period, soybean consumption grew at an average annual rate of 5.2 percent in South America and 4.5 percent in the Rest of the World, both greater than the global rate of 4.0 percent, and well exceeding the US rate of 1.8 percent. South America and the Rest of the World consumed 67 percent of global production in the 1980s, rising to 82 percent of global production in the 2010s. In contrast, the US consumed 34 percent of global production in the 1980s, falling to 18 percent in the 2010s. Over the coming decade, USDA expects the annual rate of growth in soybean consumption to slow to 1.6 percent in the US, 1.8 percent in South America, and 3.4 percent in the Rest of the World, with the US share of global consumption falling modestly to 16 percent, the South America share rising modestly to 27 percent, and the Rest of the World share rising slightly to 57 percent.

Fourth, between 1980 and 2019, growth in soybean exports to the Rest of the World also has occurred largely in South America. During that period, South American soybean exports grew dramatically at an average annual rate of 9.4 percent, rising from 5 percent of global production in the 1980s to 20 percent in the 2010s. In contrast, between 1980 and 2019, US soybean exports grew at a more modest average annual rate of 2.9 percent, falling from 21 percent of global production in the 1980s to 15 percent in the 2010s. Over the coming decade, USDA expects the rate of growth in exports to the Rest of the World to slow to 2.1 percent in the US and 4.5 percent in South America, with the US share of exports to the Rest of the World dropping to 14 percent of global production and the South America share of exports to the Rest of the World rising slightly to 24 percent of global production.

A Semi-Annual Bi-Hemispheric Model of Agricultural Commodity Storage and Trade

Consider the global market for a storable field crop, say, soybeans, which consists of two major producer-exporters, North, $i = 1$, and South, $i = 2$, and the Rest of the World (ROW), $i = 3$. Soybeans are produced, consumed, exported, and stored in the North and South. Although production and stockholding occur in the Rest of the World, the Rest of the World is treated as a net importer of exports from North and South. Time t is marked in semi-annual seasons. North plants at the beginning of "spring-summer", t odd, and harvests at the beginning of "autumn-winter", t even; South plants at the beginning of autumn-winter, t even, and harvests at the beginning of spring-summer, t odd.

Each season t begins with predetermined quantities available q_{it} in the two exporting regions $i = 1, 2$; the realization of demand shocks $\tilde{\epsilon}_{it}$ in the two exporting regions $i = 1, 2$ and in the Rest of the World $i = 3$; and a planned production shock $\tilde{\nu}_{it}$ in the planting region i. Given the quantities available and the demand and planned production shocks, market equilibrium conditions determine the contemporaneous values of: p_{it}, the market prices in the two exporting regions $i = 1, 2$ and in the Rest of the World $i = 3$; c_{it}, consumption in the two exporting regions $i = 1, 2$; x_{it}, exports to the Rest of the World from the two exporting regions $i = 1, 2$, the sum of which equals consumption in the ROW; z_{it}, end of season inventories in the two exporting regions $i = 1, 2$; and y_{it}, planned production for the following season in planting region i. The equilibrium conditions are:

Material Balance. The predetermined quantity of soybeans available in exporting region $i = 1, 2$ in season t must be either consumed, exported or stored:

$$q_{it} = c_{it} + x_{it} + z_{it}. \tag{1}$$

Consumption Demand. The quantity consumed in exporting region $i = 1, 2$ in season t must meet the demand for consumption at the prevailing regional price:

$$c_{it} = D_{it}(p_{it})\tilde{\epsilon}_{it}. \tag{2}$$

Here, D_{it} is a positive, continuously differentiable, strictly decreasing, convex function of the regional price, and $\tilde{\epsilon}_{it}$ is a positive exogenous demand shock with mean 1.

Trade Balance. Total exports from both exporting regions $i = 1, 2$ to the Rest of the World in season t must meet the demand for imports in the Rest of the World at the prevailing price:

$$x_{1t} + x_{2t} = D_{3t}(p_{3t})\tilde{\epsilon}_{3t}. \tag{3}$$

Here, D_{3t} is a positive, continuously differentiable, strictly decreasing, convex function of the ROW price, and $\tilde{\epsilon}_{3t}$ is a positive exogenous demand shock with mean 1.

Intertemporal Price Equilibrium. Competition among expected-profit maximizing storers in exporting regions $i = 1, 2$ in season t eliminates arbitrage profit opportunities from storing:

$$\delta E_t p_{it+1} = (1 + \kappa_i)p_{it}. \tag{4}$$

Here, δ is the semi-annual discount factor and κ_i is the semi-annual unit cost of storage in region i as a proportion of the prevailing price.

Spatial Price Equilibrium. Competition among profit maximizing exporters in exporting region $i = 1, 2$ in season t eliminates arbitrage profit opportunities from exporting to the Rest of the World:

$$p_{3t} = (1 + \tau_i)p_{it}. \tag{5}$$

Here, $\tau_i > 0$ is the unit cost of exporting from region i to the Rest of the World as a proportion of the prevailing price.

Planned Production. Producers in exporting region $i = 1, 2$ in season t plan production based on the price they expect to receive the following season:

$$y_{it} = \begin{cases} Y_{it}(E_t p_{it+1})\tilde{\nu}_{it}, & i \text{ and } t \text{ both odd or both even} \\ 0, & \text{otherwise.} \end{cases} \tag{6}$$

Here, Y_{it} is a continuously differentiable, strictly increasing, strictly concave function of the price expected the following season $E_t p_{it+1}$, and $\tilde{\nu}_{it}$ is a positive exogenous planned production shock with mean 1.[1]

[1]Planned production is simply area planted times the ex-ante expected yield per unit of area planted. As such, $\tilde{\nu}_{it}$ is an exogenous shock to area planted that is distinct from $\tilde{\eta}_{it+1}$, which is an exogenous shock to final production due to weather realized during the growing season after planting.

Availability. The quantity of soybeans available in exporting region $i = 1, 2$ at the beginning of season $t+1$ equals the quantity stored at the end of season t plus new production, if any:

$$q_{it+1} = \begin{cases} z_{it} + y_{it}\tilde{\eta}_{it+1}, & i \text{ and } t \text{ both odd or both even} \\ z_{it}, & \text{otherwise.} \end{cases} \tag{7}$$

Here, $\tilde{\eta}_{it+1}$ is an exogenous shock to final production due to weather that is realized after production planning and stockholding decisions are made in season t.

Expectations. We close the model by assuming that producers and storers form rational price expectations. Under rational expectations, prices expected the following season are functions of end of season inventories and planned production:

$$E_t p_{it+1} = \begin{cases} E_t \hat{p}_{it+1}(z_{1t} + y_{1t}\tilde{\eta}_{1t+1}, z_{2t}; \tilde{\epsilon}_{t+1}), & t \text{ odd,} \\ E_t \hat{p}_{it+1}(z_{1t}, z_{2t} + y_{2t}\tilde{\eta}_{t+1}; \tilde{\epsilon}_{t+1}), & t \text{ even.} \end{cases} \tag{8}$$

Here, $\hat{p}_{it}(q_{1t}, q_{2t}; \tilde{\epsilon}_t)$ is the equilibrium market price in season t in exporting region i, given the quantities available in the two exporting regions (q_{1t}, q_{2t}) and the exogenous shocks $\tilde{\epsilon}_t \equiv (\tilde{\epsilon}_{1t}, \tilde{\epsilon}_{2t}, \tilde{\epsilon}_{3t}, \tilde{\nu}_{it})$ realized at the beginning of the season.

The equilibrium price functions $\hat{p}_{it}$ are not known a priori and have no known closed-form expression. They are, however, fully characterized by a system of functional equations that can be solved numerically to any degree of accuracy, given an explicit parameterization for the model. In this paper, we apply standard collocation methods to derive finite-dimensional approximations to the equilibrium price functions of the form

$$\hat{p}_{it}(q_1, q_2; \epsilon) \approx \sum_{j=1}^{n} b_{itj}\phi_j(q_1, q_2, \epsilon)$$

for $i = 1, 2$, where the ϕ_j are n prescribed Tchebychev polynomials and the basis function coefficients b_{itj} are fixed by requiring the price function approximants to satisfy the equilibrium conditions at a prescribed set of equally many Tchebychev nodes (Miranda and Fackler, 2002; Judd, 1998).

To make the model amenable to numerical solution and simulation, we assume the following functional forms and shock distributions: The deterministic portions of the demand functions assume constant elasticity forms:

$$D_{it}(p_{it}) \equiv \alpha_{it} p_{it}^{-\beta_{it}}, \tag{9}$$

were $\alpha_{it} > 0$ and $\beta_{it} > 0$. The deterministic portions of the planned production functions assume constant elasticity forms:

$$Y_{it}(E_t p_{it+1}) = \theta_{it}(E_t p_{it+1})^{\gamma_{it}}, \tag{10}$$

were $\theta_{it} > 0$ and $1 > \gamma_{it} > 0$. The demand shocks $\tilde{\epsilon}_{it}$, planned production shocks $\tilde{\nu}_t$, and production shocks $\tilde{\eta}_t$ are mutually and serially independent and lognormally distributed with mean 1 and log standard deviations $\sigma_{\epsilon_{it}} > 0$, $\sigma_{\nu_t} > 0$ and $\sigma_{\eta_t} > 0$, respectively.

Controlled Model Simulations

We begin our analysis by presenting results from "controlled" simulation experiment designed to expose how asynchronous bi-hemispheric production affects seasonal exports and stockholding, inter-annual price variability, and interregional price integration. Specifically, we simulate our structural model under two counterfactual scenarios. In the first scenario, the world consists of a single producer-exporter, "North", and the ROW. The producer-exporter produces all global output on an annual cycle, planting in spring-summer and harvesting in autumn-winter. On average, it consumes 70 percent of annual production, exporting the remaining 30 percent to ROW. In the second scenario, the world consists of two producer-exporters of equal size, "North" and "South", and the Rest of the World (ROW). On average, each producer-exporter produces one-half of the world's global output, with North planting in spring-summer and harvesting in autumn-winter and South planting in autumn-winter and harvesting in spring-summer. On average, the two producer-exporters together consume 70 percent of annual global production and export the remaining 30 percent to Rest of World (ROW), both in equal shares.

To simplify the analysis, we assume that demand and supply elasticities, shock volatilities, and transportation and storage costs are invariant across regions and time and that all shocks are spatially and temporally independent. Table 3 presents the parameter values employed in our simulations. Estimates for the demand and supply elasticities and shock volatilities are drawn from the stochastic model developed by the Food and Agricultural Policy Research Institute (FAPRI, 2011). Estimates of transportation costs are drawn from USDA's Agricultural Marketing Service (USDA/AMS, 2020).

Storage costs were obtained by calculating the average percent difference between the January and November soybean futures contract taken at time of planting to obtain a proxy for the “full” carrying charge (Paul, 1970). Those costs were multiplied by three to obtain an estimate of the semi-annual storage charge. The constant terms of the demand and supply functions were chosen so that annual production and prices under uncertainty are, without loss of generality, normalized to 1.

Table 3: Global Parametric Assumptions.

Parameter	Symbol	Value
Domestic demand elasticity	β	0.200
Planned production elasticity	γ	0.600
Demand volatility	σ_ϵ	0.100
Planned production volatility	σ_ν	0.100
Yield volatility	σ_η	0.200
Unit cost of transportation	τ	0.050
Semi-annual unit cost of storage	κ	0.025
Semi-annual discount factor	δ	0.975

Given that the model parameters are assumed to be time-invariant, the model defines a stationary multivariate stochastic process with a well-defined ergodic distribution. The moments of the distribution reported in tables 4 and 5 were estimated by performing Monte Carlo simulations of the model over a one-million-year span.

Table 4 presents estimates of the means of seasonal production, consumption, exports and end of season inventories under both scenarios. Consider first a world with only one producer-exporter planting on an annual cycle. As seen in table 4, intertemporal and spatial arbitrage enforced by profit maximizing storers and traders ensure that production is nearly uniformly distributed over time and space to meet demand throughout the year and throughout the world. Domestic consumption and exports to ROW are essentially invariant across seasons, respectively equalling approximately 35 percent and 15 percent of annual global production each season. Due to the cost of storage, domestic consumption and exports are slightly greater during the producer-exporter's harvest season, than during its planting season, but only marginally so. As such, its inventories at the end of its harvest season, on average, will be marginally greater than half, 55 percent, of its annual production. Only a small quantity of pipeline stocks, 5 percent of annual production, are held at the end of its planting season.

Table 4: Mean Seasonal Production, Consumption, Exports and End of Season Inventories as a Percentage of Annual Global Production, by Scenario, Region and Season.

	Single Producer-Exporter		Two Asynchronous Producer-Exporters	
	Spring-Summer	Autumn-Winter	Spring-Summer	Autumn-Winter
Production				
North	—	100.0	—	50.0
South	—	—	50.0	—
Total	—	100.0	50.0	50.0
Consumption				
North	34.8	35.2	17.4	17.6
South	—	—	17.6	17.4
Total	34.8	35.2	35.0	35.0
Exports				
North	14.9	15.1	5.4	9.6
South	—	—	9.6	5.4
Total	14.9	15.1	15.0	15.0
Inventories				
North	4.9	54.6	1.9	24.7
South	—	—	24.7	1.9
Total	4.9	54.6	26.6	26.6

Consider now a world with two producer-exporters harvesting at different times of the year, but collectively producing and consuming the same amounts as the single producer-exporter. As seen in table 4, the existence of two equally-sized producer-exporters producing in alternating seasons has only a limited impact on the distribution of production over time and space *on a global scale*, again due to the arbitrage activity of profit-maximizing storers and traders. On average, global production continues to be nearly uniformly distributed across time and space to meet demand, with each producer-exporter consuming approximately 17.5 percent of annual global production each season and ROW consuming 15 percent of global annual production each season.

However, with two asynchronous producer-exporters, the *sources* of exports to ROW and the location in which inventories are held vary significantly between seasons. On average, each producer-exporter ships a greater portion of its annual exports (64 percent) during its harvest season than during its planting season (36 percent). As such, in either season, the majority (64 percent) of exports to ROW emanate from the harvesting producer-exporter and the remainder (36 percent) emanate from the planting producer-exporter. At the end of either season, the majority of global inventories (93 percent) are held by the harvesting producer-exporter, with the remainder (7 percent) held by the planting region as pipeline stocks.

Shifting exports from the planting season to the harvest season allows each producer-exporter to reduce the stocks it holds at the end of its harvest season. This results in systemic global gains in efficiency through a general reduction of global inventories and the attendant costs of storage. With a single producer-exporter, global inventories average one-half of global production throughout the year. With two asynchronous producers, inventories average approximately one-quarter of global production throughout the year, given that export needs can be met with new production in the harvesting region.

Table 5 reports the effects of bi-hemispheric asynchronous production on seasonal and regional prices. With a single producer-exporter, prices, on average, are lower during its harvest season than during its planting season, reflecting the cost of carrying stocks between seasons. Although demand in both the exporting region and ROW are subject to independent idiosyncratic demand shocks, spatial arbitrage enforced by trade ensures that the exporter's price and the ROW price remain closely integrated, with the difference reflecting a stable cost of transportation; inter-year correlation between the two prices approaches one. As such, the ROW price will also be higher during the exporter's harvest season than during its planting season. Due to the linking of seasonal and regional prices through storage and trade, price variability is very similar across seasons and regions. In both the exporting region and in ROW, prices are slightly more variable during the exporter's harvest season than during its harvest season, reflecting the impact of production variability experienced at the beginning of the harvest season in that region. Prices are also slightly more variable in the ROW than in the exporting region in both seasons, in grand part because the ROW experiences an additional demand shock that is independent of the demand and production shocks experienced in the exporting region.

Table 5: Market Price Means, Percent Coefficients of Variation and Inter-Regional Correlations, by Scenario, Region and Season.

	Single Producer-Exporter		Two Asynchronous Producer-Exporters	
	Spring-Summer	Autumn-Winter	Spring-Summer	Autumn-Winter
Mean				
ROW	1.047	0.984	0.998	0.998
North	1.027	0.973	1.031	0.969
South	—	—	0.969	1.031
Variation				
ROW	32.8	34.2	23.6	23.6
North	31.9	33.7	25.9	22.6
South	—	—	22.6	25.9
Correlation				
ROW-North	0.992	0.995	0.936	0.993
ROW-South	—	—	0.993	0.936
North-South	—	—	0.907	0.907

With two producer-exporters, prices in both exporting regions, on average, are lower during their harvest season than during their planting season, again reflecting the cost of carrying stocks between seasons. With two balanced producer-exporters, ROW price, on average, is invariant across seasons, tending to reflect costs of transportation from the harvesting producer-exporter, which alternates between season. The ROW price is most closely integrated with the harvesting producer-exporter's price, given that the harvesting producer-exporter is the dominant exporter during that season. The correlation between ROW price and the harvesting exporter's price is nearly one at 0.993, whereas the correlation between ROW price and the planting exporter's price is lower at 0.936. Given that our two producer-exporters are identical, save that they plant and harvest in different seasons, the correlation between their prices is the same in both seasons, 0.907. Price integration between the two producer-exporters is less than complete because the two do not trade with each other. Producer-exporter prices are linked through their mutual trade with ROW, but imperfectly so as consumption and exports must be adjusted in both countries in response to supply and demand shocks.

With two producer-exporters, prices are significantly less variable from year to year than with a single producer-exporter. With one exporter, the inter-year coefficient of variation of price in approximately between 32 percent and 34 percent, depending on season and region. With two exporters, the inter-year coefficient of variation of price in the exporting regions range between 22.6 percent in the planting season and 25.9 percent in the harvest season; the inter-year coefficient of variation of ROW price is identically 23.6 percent in both seasons. The reduction of price variability with two exporters is largely due to the ability of one exporter to respond to supply conditions in the competing exporter, with adjustments taking place semi-annually, thereby mitigating price variability.

It is also true that, unlike with a single producer-exporter producing on an annual cycle, with two producer-exporters harvesting in alternating seasons, producer-exporter prices are more variable during their *planting* season than during their *harvest* season. This is primarily due to the fact that an exporter can make significant adjustments to its relatively large inventories during its harvest season in response to local demand shocks, but has far less flexibility to do so during its planting season when its inventories are low.

Historical Model Simulations

In this section, we present results from simulation experiments in which our model has been parameterized to more closely capture the key stylized facts of global soybean market dynamics over the past four decades, which has seen a steady increase in both South American production and Chinese imports, as reported in table 1. For the purposes of our simulations, the United States, which plants in the spring-summer season and harvests in the autumn-winter season, represents the northern hemisphere, and South America (Brazil and Argentina combined), which plants in the autumn-winter season and harvests in the spring-summer season, represents the southern hemisphere. All other producing and consuming regions are combined as Rest of the World (ROW) and treated as importers of northern and southern hemisphere production.

We further assume that consumption demand in all three regions is invariant across seasons and that supply in the two exporting regions are invariant across years, with elasticities equal to those presented in table 3.

We examine five scenarios. In the first four scenarios, the model is calibrated to reflect soybean market conditions prevailing in the decades of the 1980s (1980-1989), the 1990s (1990-1990), the 2000s (2000-2009), and the 2010s (2010-2019), respectively. In the fifth scenario, the model is calibrated to reflect soybean market conditions projected by the United States Department of Agriculture for the decade of the 2020s (2020-2029) (USDA/OCE, 2019). However, the simulation results presented below should not be strictly interpreted as historical. Rather, they should be treated as predictions regarding *seasonal* flows of exports and *seasonal* inventory holdings during those periods, to be validated by comparison to the limited data on exports and inventories available at a sub-annual resolution.

Seasonal Exports

Table 6 reports the simulated shifts in seasonal trade flows between the United States and South America and the ROW between 1980 and 2019. Simulated exports to ROW, expressed as a percentage of global annual production, grow from 12.8 percent in the 1980s to 17.2 percent in the 2010s, with an expectation that will grow to 19.6 percent in the 2020s. Both the United States and South America generally ship most of their annual exports during their harvest season. In the 1980s, the United States, then the dominant world producer, is the leading exporter throughout the year. However, in the 2000s, South America overtakes the United States as the world's leading exporter during its spring-summer harvest season, and is on pace to become the world's leading exporter year-round.

Table 7 reports simulated exports to ROW as a percentage share of seasonal and global totals. Our simulations indicate that both the United States and South America generally ship most of their annual exports during their harvest seasons. The portion of annual exports shipped during the harvest season, however, rises in the United States as its share of global production diminishes, but falls in South America as its share of global production grows. More specifically, the US ships 56 percent of its annual exports during its autumn-winter harvest season in the 1980s, rising to 66 percent in the 2010s. Conversely, South America ships 69 percent of its annual exports during its spring-summer harvest season in the 1980s, dropping to 63 percent in the

Table 6: Mean Annual Exports to Rest of World as a Percentage of Global Production, by Decade, Season and Region.

	1980s	1990s	2000s	2010s	2020s
Spring-Summer					
United States	8.5	6.3	5.3	5.1	4.5
South America	4.3	4.7	8.7	12.1	15.0
Total	12.8	11.0	14.0	17.2	19.6
Autumn-Winter					
United States	11.0	8.6	8.8	10.1	10.2
South America	1.9	2.5	5.2	7.1	9.3
Total	12.9	11.1	14.0	17.2	19.5

2010s.

Our simulations further indicate that, between 1980 and 2019, the United States is the world's leading exporter during its autumn-winter harvest season. However, as its share of global production declines over time, its share of global exports during that season falls from 85 percent in the 1980s to 59 percent in the 2010s, with an expectation that it will fall further to 52 percent in the 2020s. Prior to 2000, the United States is also the world's leading exporter during its spring-summer planting season. However, around 2000, South America overtakes the United States as the world's leading exporter during its spring-summer harvest season. South America accounts for only 33 percent of global exports during its spring-summer harvest season in the 1980s, rising to 70 percent in the 2010s, with an expectation that they will rise further to 77 percent in the 2020s.

End of Season Inventories

Table 8 reports simulated regional end of season inventories as a percentage of annual global production. Due to increased South American production between 1980 and 2019, US inventories at the end of its autumn-winter harvest season show a marked decline while South American inventories at the end of its spring-summer harvest season show a marked increase. Given that both exporters hold only marginal stocks at the end of their respective planting seasons, seasonal global inventories reflect changes in inventories held by the harvesting exporter. Specifically, simulated global end of autumn-winter

Table 7: Percentage Share of Exports to Rest of World, by Decade, Season and Region.

	1980s	1990s	2000s	2010s	2020s
United States					
Spring-Summer	44	42	37	34	31
Autumn-Winter	56	58	63	66	69
South America					
Spring-Summer	69	66	63	63	62
Autumn-Winter	31	34	37	37	38
Spring-Summer					
United States	67	57	38	30	23
South America	33	43	62	70	77
Autumn-Winter					
United States	85	78	63	59	52
South America	15	22	37	41	48

season inventories fall from 30.3 percent global production in the 1980s to 18.1 percent in the 2010s, with an expectation that they will grow to 17.1 percent in the 2020s. Simulated global end of spring-summer season inventories grow from 16.9 percent in the 1980s to 25.4 percent in the 2010s, with an expectation that they will grow to 27.4 percent in the 2020s.

Table 8: Mean End of Season Inventories as a Percentage of Annual Global Production, by Decade, Season and Region.

	1980s	1990s	2000s	2010s	2020s
Spring-Summer					
United States	3.2	2.8	2.1	1.9	2.0
South America	13.7	16.4	22.3	23.5	25.3
Total	16.9	19.1	24.3	25.4	27.4
Autumn-Winter					
United States	28.5	24.8	19.0	15.9	14.8
South America	1.8	2.0	2.3	2.2	2.4
Total	30.3	26.8	21.2	18.1	17.1

Table 9 reports simulated regional end of season inventories as a percentage share of seasonal totals. Generally, each exporter is holding the overwhelming portion of global inventories at the end of its harvest season. Due to increased South American production between 1980 and 2019, however, the share of global inventories held by the United States at the end of its autumn-winter harvest season decline from 94 percent in the 1980s to 86 percent in the 2010s, with an expected continued decline to 86 percent in the 2020s. The share of global inventories held by South America at the end of its spring-summer season, on the other hand, increases from 81 percent in the 1980s to 92 percent in the 2010s, with an expected continued increase to 93 percent in the 2020s.

Table 9: Percentage Share of End of Season Inventories, by Decade, Season and Region.

	1980s	1990s	2000s	2010s	2020s
Spring-Summer					
United States	19	14	8	8	7
South America	81	86	92	92	93
Autumn-Winter					
United States	94	93	89	88	86
South America	6	7	11	12	14

Exporters will adjust their planting decisions in response to global inventories, the overwhelming majority of which are held by the competing exporter at planting time. They plant more if the inventories held by the competing exporter are relatively low and less if the inventories are relatively high. Table 10 reports estimates of the elasticity of each exporter's planned production to inventories held by the competing exporter. In the 1980s, when the US is the world's dominant producer, we estimate that US planned production was relatively unresponsive to South American inventories, exhibiting an elasticity of only -0.10; in contrast, we estimate that American planned production was relatively responsive to United States inventories, exhibiting a higher elasticity of -0.25. However, as South America increasingly challenged the United States for global dominance, the pattern reverses. We estimate that, by the 2010s, US planned production becomes more responsive to South American inventories, exhibiting an elasticity of only -0.25; in contrast, we estimate that, by the 2010s, South American planned production becomes less responsive to United States inventories, exhibiting an elasticity of -0.14. In the 2020s, these trends are expected to continue, with US planned production becoming even more responsive to South American inventories, and South America planned production becoming even less responsive to US inventories.

Table 10: Elasticity of Exporter's Planned Production with Respect to Competing Exporter's Inventories, by Season and Decade.

Decade	Spring-Summer USA Planned Production SA Inventories	Autumn-Spring SA Planned Production USA Inventories
1980s	-0.10	-0.25
1990s	-0.13	-0.21
2000s	-0.19	-0.16
2010s	-0.23	-0.14
2020s	-0.26	-0.13

Relative Seasonal Prices

Table 11 reports simulated inter-annual price coefficients of variation. Our model simulations indicate that price in either exporting region is more variable during its *planting* season than during its *harvest* season. Our simulations also suggest that prices, for the most part, have become more stable in the United States and the ROW between 1980 and 2029, in both the spring-summer and autumn-winter seasons. However, both spring-summer and fall-winter price variability in South America have exhibited irregular pattern of change during that period. Given USDA projections that rates of growth in demand and supply in the 2020s are expected to diverge significantly from historical trends, predictions regarding price variability in the future also do not follow the trends established in the preceding decades.

Table 12 reports simulated inter-regional price correlations by season. Generally, an exporter's price is more highly integrated with the ROW price during its harvest season than during its planting season, with correlations nearing one, given that exports are greatest during the harvest seasons, ensuring that the exporter's price is most tightly linked with the ROW price

Table 11: Price Coefficient of Variation, by Decade, Region and Season.

	1980s	1990s	2000s	2010s	2020s
Rest of World					
Spring-Summer	25.8	24.0	22.8	22.1	21.2
Autumn-Winter	23.7	22.6	21.6	21.7	22.6
United States					
Spring-Summer	27.9	26.7	24.8	24.2	24.0
Autumn-Winter	23.9	22.8	20.8	20.8	21.3
South America					
Spring-Summer	21.0	21.2	22.4	22.0	21.2
Autumn-Winter	24.3	24.2	25.1	24.7	24.6

due to the arbitrage activity of traders. Our simulations further indicate that the ROW and South America prices in both seasons become more integrated over time as South America's share of global production increases, but the ROW and US prices becomes less integrated in both seasons over time as the US share of global production decreases. Generally, the US and South America prices are more fully integrated during the dominant exporter's planting season.

Table 12: Inter-Regional Price Correlation, by Decade and Season.

	1980s	1990s	2000s	2010s	2020s
ROW-United States					
Spring-Summer	0.991	0.975	0.951	0.948	0.936
Autumn-Winter	0.999	0.995	0.991	0.995	0.994
ROW-South America					
Spring-Summer	0.938	0.945	0.991	0.999	1.000
Autumn-Winter	0.887	0.892	0.941	0.965	0.983
United States-South America					
Spring-Summer	0.904	0.878	0.917	0.937	0.931
Autumn-Winter	0.872	0.856	0.907	0.947	0.968

Seasonality and the Global Soybean Market

In this section we consider recent shifts in the global soybean market and draw insights from our storage model. Figure 2 shows monthly US and Brazil soybean exports from September 2005 to October 2020 (Trade Data Monitor, Inc, 2020). Note the well defined seasonality that develops as Brazil's market share increases over time. US exports are largest during the fall harvest season and then decline sharply as the Brazil harvest begins in the early spring. Over 2013-17, US exports during the first six months of the marketing year (September-February) accounted for 77 percent of total soybean exports. Over the same months during that time period, Brazil shipped only 14 percent of its exports.

The seasonality in exports was disrupted in 2018 when China placed tariffs on US soybean imports in retaliation for tariffs placed on Chinese goods by the Trump Administration. The supplemental tariffs caused large shifts in China imports towards Brazil and other suppliers. As a result, US exports were diverted to other markets such as the EU and Egypt. The shift also affected the timing of exports. As can be seen in Figure 2, proportionately more US exports were shipped in the second half of the year over 2018 and 2019 (40 percent of exports compared to 23 percent over 2013-17).

As predicted by our model, seasonality is even more pronounced in countries where both northern and southern hemisphere suppliers are present. Table 13 shows export patterns to the top ten importing markets for soybeans for 2015-17. The table shows the market share of southern and northern suppliers over that period and the percent of total US soybean exports shipped in the first six months of its marketing year. As expected, in those markets where the US is largely dominant (e.g., Mexico, Indonesia) exports are distributed fairly evenly across the first and second half of the marketing year.[2] In those markets where Brazil or other southern hemisphere suppliers have a dominant market share (e.g., China, EU, Thailand), the US tends to market most of its production in the first half of the year.

[2]The US accounted for 98 percent of Indonesia soybean imports over 2015-2019. Nonetheless, total soybean imports remain relatively small, averaging less than 2.5 million MT over 2015-19, far less than the 90 million tons typically imported by China (UNCTAD, 2020).

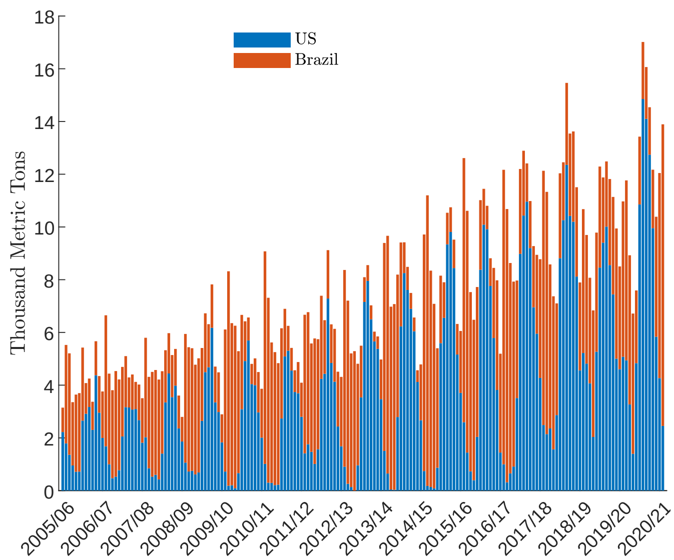

Figure 2: Monthly US and Brazil Soybean Exports. *Source: Trade Data Monitor, Inc (2020).*

Table 13: Top Ten Soybean Markets and their Suppliers, 2015-17.

Importer	Average Annual Imports (thousand MT)	Exporter Market Share (percent)			Percentage of US Exports Shipped First Half of Marketing Year
		Southern Hemisphere Suppliers	Northern Hemisphere Suppliers	United States	
China	90,273	61	39	37	88
European Union	14,382	56	44	35	60
Mexico	4,375	0	100	100	47
Japan	3,206	14	86	40	55
Thailand	2,786	69	31	27	75
Taiwan	2,569	41	58	55	65
Turkey	2,507	38	62	25	88
Indonesia	2,468	0	100	98	47
Argentina	2,351	100	0	0	91
Egypt	2,315	53	47	33	31

Source: USDA/FAS, 2020b.

Table 14 shows the impact of a growing southern hemisphere on the pattern of global exporter stocks (USDA/FAS, 2020b). In the late 1990s, global exporter stocks tended to mirror the pattern of stocks held in the

United States. Quarter one ending stocks held by major exporters (December 1) were largest of the year reflecting new crop production in the US while September 1 stocks were the smallest–the end of the marketing year in the US. Carryout at the end of the year is larger than implied in the simulated model results largely because pipeline stocks carried forward to the new crop year tend to be large and the model captures only speculative stocks.

As predicted by the model, as export patterns have shifted, proportionately less US stocks are carried forward into the second half of the year. As a result, it is more often the case that stock levels on June 1 (after the South American harvest) are larger than stocks held on December 1 following the US harvest. Quarterly ending stocks are lowest at the end of quarter 2 (March 1) before the South American harvest.

Table 14: End of Quarter Soybean Stocks held by Brazil, Argentina and the United States, Four-Year Averages, 1998-2018 (million MT).

Year	Dec 1	Mar 1	Jun 1	Sep 1
1998-2002	69.9	45.5	70.0	36.0
2002-2006	83.3	55.2	93.9	54.6
2006-2010	88.3	57.4	101.0	55.8
2009-2014	87.2	55.5	109.9	57.3
2014-2018	122.4	87.1	151.4	84.5

Lastly we consider soybean price movements in the north and south hemisphere. Figure 3 shows the ratio of the Brazil (Paranagua) soybean price to the US (Central Illinois) soybean price at a monthly resolution from January 2000 to September 2020. Through 2017 the data show a distinct seasonal pattern with the differential widening during the US harvest (September-December) and narrowing roughly six months later during the harvest period in the Southern hemisphere (March-June). The exception to this pattern occurs during 2018-19 when China placed counter-retaliatory tariffs on US soybeans. Differentials between Brazil and US prices remained high over the period as China demand for Brazil soybeans created a large premium even during the harvest months in the northern hemisphere.

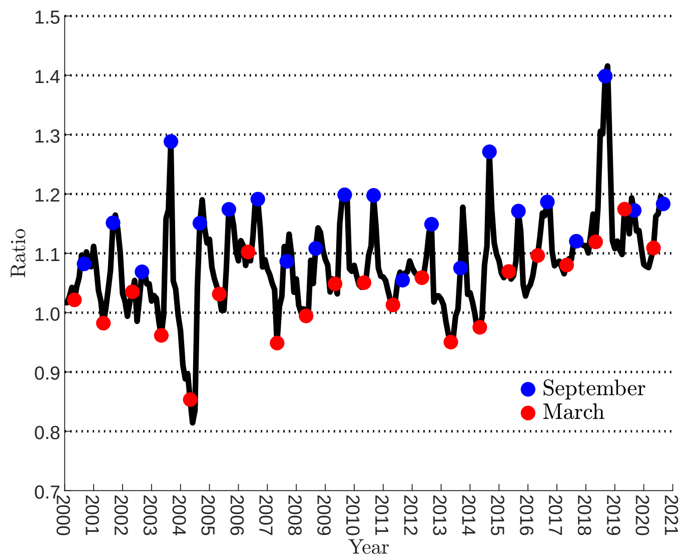

Figure 3: Ratio of Brazilian Soybean Price (Paranagua) to US Soybean Price (Central Illinois). *Source: USDA/FAS 2020a.*

Conclusions

The growth of southern hemisphere production has increased global supplies of grains and oilseeds, helping to meet the large growth in global demand witnessed over the past 40 years. The structural model presented in this paper gives important insights into intra-seasonal patterns of storage, trade and market prices that have accompanied the growth in southern hemisphere production, patterns that are generally not captured in annual models. Simulating our model under counterfactual polar scenarios, we compare a world with one producer-exporter to a world with two equally sized producer-exporters planting in alternate seasons of the year. We find that, in a balanced world, the demand for exports by the ROW can be met primarily by new production in the harvesting region, thereby reducing end-of-harvest-season inventories that might otherwise be held to meet demand during the planting season. As a consequence, global inventories are lower throughout the marketing year in a two-country world with two asynchronous production cycles than in a one-country world with a single annual production cycle. Asynchronous production also allows for semi-annual adjustments to planned production by one-exporter to variations in available supplies in the competing exporter, thereby stabilizing supply and price in all regions.

Simulating our model parameterized to reflect the global soybean market production and consumption trends between 1980 and 2019 also reveals that an increased production share in the southern hemisphere has resulted in more pronounced seasonality in exports between exporters in the northern and southern hemispheres. Our analysis suggests that the shift in production, from a global perspective, has shortened the crop "season" from 12 months to 6. With a new crop available every six months, stock levels in spring are as relevant as those in autumn in indicating supply availability. While trade and storage link market prices across time and space, the analysis suggests that seasonal trade patterns can also result in a more seasonal pattern of integration. Failure to recognize those patterns can obscure and bias analyses of global food security, potentially exaggerating the impact of shortages or surpluses when they occur in one hemisphere but not in the other.

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