Yield Variability and Agricultural Trade

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We examine how changes in yield variability affect the welfare of cereal grain and oilseed buyers and producers around the world. We simulate trade patterns and welfare for 21 countries with a Ricardian trade model that incorporates bilateral trade costs and crop yield distributions. The model shows that world trade volumes would need to increase substantially if crop yield variability were to rise. Net welfare effects, however, are moderate so long as countries do not resort to policies that inhibit trade, such as export restrictions or measures to promote self-sufficiency in crops. Low-income countries suffer the most from increases in yield variability, due to higher bilateral trade costs and lower-than-average productivity.

Key Words: crops, geography, grains, trade liberalization, yield variability

This study examines how yield variability affects buyers and sellers of cereal grains and oilseeds. We develop a multi-country Ricardian trade model and parameterize it through econometric estimation. The model links trade patterns and welfare back to crop yield distributions, the costs of bilateral trade, and land markets. We identify winners and losers from counterfactual scenarios for 21 countries. The results vary systematically across these countries with respect to per capita income. Low-income countries get hurt the most by global increases in yield variability, since they tend to have higher bilateral trade costs in conjunction with lower productivity in the crop sector.

Our interest in yield variability comes from the fact that yields of rain-fed grains and oilseeds remain highly variable despite decades of agronomic advances (FAO 2008, Chen, McCarl, and Schimmelpfennig 2004, Isik and Devadoss 2006). Yield variability is largely a function of weather and may be exacerbated by widespread adoption of common high-yielding varieties and uniform agronomic practices (Anderson and Hazell 1987). Recent research shows that global climate change may increase yield variability since it will likely increase the probability of extreme heat stress events, precipitation extremes, El Niño like events, and other climate phenomena (Meehl and Washington 1993, Meehl et al. 2000, Reilly et al. 2002, Intergovernmental Panel on Climate Change 2007). While there is much uncertainty surrounding these predictions, the implication is that yield variability could rise.

International trade is a natural vehicle for adapting to inter-annual yield variability (Bale and Lutz 1979, Newbery and Stiglitz 1981, Randhir and Hertel 2000, Hallstrom 2004). When one region has a crop failure, spatial arbitrage reallocates supplies from regions of abundance, thereby minimizing the fluctuation of prices. International trade is a far less efficient vehicle than theoretically possible, however, since trade is far from costless. Relative to the general economy, market-insulating tariff and non-tariff barriers are pervasive in this sector. Foreign supply shocks are often cited as a rationale for trade restrictions since they can destabilize local prices. For example, poor rice crops in several rice-producing countries contributed to a doubling of world rice prices within a matter of months in 2007–2008. Several leading exporters imposed severe export restrictions due to concerns over scarcity of supplies (Bradsher 2008).

Our approach has some commonalities with studies that forecast how climate change will impact consumers and producers of agricultural products around the globe. For example, a number of studies link a global economic model to the predictions of atmospheric or agronomic models (Randhir and Hertel 2000, Reilly and Hohmann

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1993, Parry et al. 2004, Rosegrant, Strzepek, and Msangi 2005). Relative to such studies, our characterization of climate processes is stylized. While those studies might rely on region-specific climate forecasts, in our approach the parameter with the greatest impact on yield variability is common to all countries.

This parsimony allows us greater detail in other parts of the model, most importantly the way in which we characterize world trade and production patterns. In our approach, a country specializes in a subset of homogeneous crops as determined by its individual productivity distribution and its barriers to trade with specific foreign markets. By contrast, most global economic models employ the Armington (1969) approach, which invokes specialization through differentiation by country. It imposes rigidities in world trade flows, making it less appropriate to a setting in which yield variability may cause frequent shifts in trade patterns (Thompson 1981).

Our approach is better suited to the idea that trading partners change frequently according to who has a bumper crop in a given year, and who has a crop failure. In this way it is like a spatial equilibrium model, which allocates trade flows on the basis of lowest possible transportation cost. While spatial equilibrium models allow for alternating trade patterns, they are typically too simple to replicate and to predict trade flows in a satisfying manner (Thompson 1981). The theoretical framework used here, which relies on a probabilistic representation of crop output, leads to a gravity-type equation, which is highly successful in empirical work. Our gravity model differs from most others since it incorporates structural parameters that govern specialization within the global crops sector. This enables us to carry out the counterfactual simulations of interest.

We show that the median country in our sample suffers fairly little from a shift to greater yield variability, as long as trade is allowed to expand. Low-income countries, however, tend to get hurt much more since they typically have greater import barriers and are less competitive at producing crops. This is particularly the case when countries introduce trade-restricting policies in response to greater yield variability. If overall trade volumes are held fixed while yield variability rises, most countries have a considerable fall in net welfare, with low-income countries suffering the most.

Model

Our conceptual framework draws from the class of Ricardian trade models developed in Eaton and Kortum (2002), Bernard et al. (2003), and Alvarez and Lucas (2005). These allow for multiple countries and commodities as well as geographic barriers. A representative buyer purchases from the nation offering the lowest price as determined by productivity, costs, and trade impediments. Production is constant returns to scale and subject to idiosyncratic productivity shocks. The use of a probability representation of productivity allows comparative advantage to be ascribed in the context of many countries and commodities.

In our application of such approaches, we identify land instead of labor as the key factor of production. Therefore, what is the wage in the standard framework becomes land rent. This is important because it gives a specific, meaningful interpretation of the random productivity shocks. In our version they arise from the weather-induced randomness of agricultural production. With land as the principal factor of production, productivity is defined as crop output per area of land (yield). Since yield data are readily available, we can directly estimate the parameters of this distribution. Another difference with the typical approach is that we focus on one sector—cereal grains and oilseeds—which we refer to as crops, instead of focusing on intermediate inputs trade and how manufactures fit into the broader economy. Our framework is therefore partial equilibrium.

There are N countries indexed alternatively by i and n. In general we index a country by i when referring to its role as a crop *producer* and by n when referring to its role as a crop *purchaser*. Each country i is endowed with a fixed amount of land specific to crops production, denoted L_i. The yield of homogeneous crop j in country i is $z_i(j)$ and the price of cropland in country i is w_i. With constant returns to scale, the cost of producing j in i is $w_i/z_i(j)$, with $z_i(j)$ being constant at this point.

To model bilateral trade, the export country is denoted by i and the import country is denoted by n, with $i = n$ when a country buys from home. Trade costs follow the iceberg assumption, implying that delivery of one unit to country n requires d_{ni} units produced in i. The crops sector is modeled as a continuum of crops indexed on the unit interval $j \in [0,1]$. The representative buyer in country n has symmetric preferences over the different crops, and a fixed amount to spend: X_n. Utility is given by a constant elasticity of substitution function:

$$(1) \qquad U_n = \left[\int_0^1 q_n(j)^{(\sigma-1)/\sigma} dj \right]^{\sigma/(\sigma-1)},$$

where $q_n(j)$ is the quantity purchased and $\sigma > 0$ is the elasticity of substitution among crops. Country n's representative purchaser maximizes U_n subject to spending constraint X_n. In a perfectly competitive market, the price that n pays for crop j from country i is

$$(2) \qquad p_{ni}(j) = \frac{d_{ni} w_i}{z_i(j)}.$$

Since users in country n seek to buy crop j from the cheapest source, they pay

$$(3) \; p_n(j) = \min\left\{ p_{n1}(j), p_{n2}(j), p_{n3}(j), ..., p_{nN}(j) \right\},$$

where N is the total number of countries.

We now let yields be random variable $Z_i(j)$ in place of the constant $z_i(j)$. Since the price at which n can get crops from i depends on $Z_i(j)$, price is also a random variable, denoted $P_{ni}(j)$. Since country n chooses the least-cost supplier, the distribution of prices has an extreme value distribution. This can happen only if $Z_i(j)$ has a Fréchet extreme value distribution (Eaton and Kortum 2002):

$$(4) \qquad F_i(z) = \Pr\left[Z_i \le z \right] = \exp\left(-T_i z^{-\theta} \right),$$

where $T_i > 0$, $\theta > 1$, and $z > 0$. In our application, T_i governs the location of the yield distributions, with higher T_i meaning higher average crop yields in country i. θ has the greatest influence on the amount of variation in the yield distributions, with a lower θ implying a broader yield distribution for each crop in each country.

Alongside the continuum assumption, identical cost and demand structures are assumed for individual crops. Therefore, the index for crops (j) can be dropped, and we do so below whenever notationally convenient. As noted above, the price at which country i can supply country n is a random variable $P_{ni}(j)$. Its cumulative distribution function is derived by incorporating the price equation (2) into the yield distribution (4) for $p > 0$. As shown in Eaton and Kortum (2002), the probability that country i supplies country n at the lowest price is

$$(5) \qquad \Pr\left[P_{ni}(j) \le \min\left\{ P_{ns}(j); s \ne i \right\} \right] = \frac{T_i (w_i d_{ni})^{-\theta}}{\sum_{i=1}^{N} T_i (w_i d_{ni})^{-\theta}}.$$

Equation (5) says that n's probability of buying from i is increased by higher average yields in $i(T_i)$, lowered by trade costs between n and $i(d_{ni})$, and lowered by the input cost associated with land in $i(w_i)$. Equation (5) can also be related to the share of n's spending on crops from i. Let X_n be country n's total spending on crops, and X_{ni} be n's spending on crops from country i, with $i = n$ when a country buys from home. Summing over all sources of supply gives $\sum_{i=1}^{N} (X_{ni} / X_n) = 1$. Due to the continuum of goods assumption, the share of n's spending on crops from i is equal to equation (5), which means

$$(6) \qquad \frac{X_{ni}}{X_n} = \frac{T_i (w_i d_{ni})^{-\theta}}{\sum_{i=1}^{N} T_i (w_i d_{ni})^{-\theta}}.$$

Equation (6) relates data on trade shares back to fundamental determinants of trade, including the yield parameters (T_i and θ), bilateral trade costs (d_{ni}), and the price of cropland (w_i). The price index for country n can be derived using the moment generating function for the extreme value distribution (Eaton and Kortum 2002). The result is

$$(7) \; P_n = \left[\Gamma\left(\tfrac{\theta+1-\sigma}{\theta} \right) \right]^{1/1-\sigma} \left[\sum_{i=1}^{N} T_i (w_i d_{ni})^{-\theta} \right]^{-1/\theta},$$

where Γ is the Gamma function used to express certain types of definite integrals (this derivation is available upon request). P_n relates the actual price paid in country n back to the yield distributions, trade costs, and land rents.

We now consider the market for cropland. Supplies of cropland in each country (L_i) are taken as given, while returns to cropland (w_i) are endogenous. The total domestic product derived from cropland is w_iL_i. This is identically equal to the sum of country i's worldwide sales: $w_iL_i = \sum_{n=1}^{N} X_{ni}$. Using equation (6), returns to cropland can be expressed as a function of the exogenous underlying parameters:

$$(8) \qquad w_i = \frac{1}{L_i}\sum_{n=1}^{N}\left\{X_n\left(\frac{T_i(w_i d_{ni})^{-\theta}}{\sum_{i=1}^{N} T_i(w_i d_{ni})^{-\theta}}\right)\right\}.$$

w_i can be solved for using numerical methods.

The basic model is given by equations (6), (7), and (8). The model is closed by considering trade balance and how the crop sector fits into the broader agricultural economy. We introduce a non-crop agricultural sector as a numeraire good. Total agricultural income for country i, denoted Y_i, equals cropland income (w_iL_i) plus value added in the non-crop sector. The share that crop income has of total agricultural income varies by country. Trade in crops need not be balanced, which means that country n's expenditure on crops (X_n) is not necessarily equal to the income derived from this sector (w_iL_i). The share that country n's expenditure on crops (X_n) has of total agricultural spending is denoted α_n.

Counterfactuals are evaluated according to several criteria. One is the change in land prices, $w_n' - w_n$, where w_n' denotes the new land price that solves equation (8) under the counterfactual simulation. Higher land prices are positively correlated with welfare since this reflects increases in income on the supply side. Another criterion is the change in crop prices ($P_n' - P_n$), where P_n' denotes the price that solves equation (7) under the counterfactual simulation. This price reflects the costs of purchasing on the demand side, and has a negative relationship with that country's welfare. A welfare measure that combines these two concepts is the change in real GDP of this sector, denoted $W_n = Y_n / P_n^{\alpha}$. For simplicity's sake a common α is used across countries. The percentage change in real GDP can be approximated by

$$(9) \qquad \ln\frac{W_n'}{W_n} = \ln\frac{Y_n'}{Y_n} - \alpha\ln\frac{P_n'}{P_n} \approx \left(\frac{w_n' - w_n}{w_n}\right)\frac{w_nL_n}{Y_n} - \alpha\ln\frac{P_n'}{P_n}.$$

The first and second terms on the right-hand side of equation (9) represent income and price effects, respectively. Equation (9) gives the net welfare change for counterfactual simulations.

Estimation of Yield Distributions

The probability density function associated with equation (4) is

$$(10) \qquad f_{ij}(z) = \theta T_i z_{ij}^{-\theta-1}\exp(-T_i z_{ij}^{-\theta}).$$

Equation (10) can be made into an empirical likelihood function with an assumption of independence across countries (i) and crops (j):

$$(11) \quad \text{likelihood} = \prod_{i=1}^{N}\prod_{j=1}^{J}\theta T_i z_{ij}^{-\theta-1}\exp(-T_i z_{ij}^{-\theta}).$$

Equation (11) describes the probability of observing a particular sample of yields z_{ij} given different values of T_i and θ.

We use the yield outcomes for different crops as a source of variation for estimation. We work with a cross section for 2001 since that is the only year for which complete data (including fully reconciled trade flows) are available for our analysis as a whole. Yield data for seven crops and 21 countries are from FAO (2008) and are reported in Table 1. This combination of crops and countries maximizes the number of observations for our cross-section estimation. Among these countries, imports from the other 20 countries as a share of total imports are 73.5 percent on average. To make the yields of different crops comparable, we normalize z_{ij} by j's worldwide average yield ($\sum_i \text{output}_{ij} / \sum_i L_{ij}$). In effect, this is average yield using national acreages as weights. This gives us seven comparable observations on yields for each of 21 countries.

The last column of Table 1 reports the results of maximizing the likelihood function (11). $\hat{T}_i$ ranges from 0.002 for Morocco to 2.224 for France, with $\hat{T}_{USA} = 1.487$. High values of $\hat{T}_i$ do not automatically imply greater competitiveness in international markets, as seen in equation (6). One reason is that land prices (w_i) may be higher in those countries. Another is that a country may be isolated geographically.

Table 1. Crop Yield Distributions

	2001 yield data (kg/hectare)							Equation (11)
Country	Barley	Maize	Oats	Rice	Sorghum	Soybean	Wheat	T_i (std. error)
Argentina	2,114	5,455	1,834	5,698	4,743	2,583	2,240	0.922 (0.349)
Australia	2,234	4,662	1,829	9,282	2,553	1,485	2,108	0.610 (0.232)
Brazil	2,083	3,403	1,330	3,241	1,881	2,795	1,948	0.383 (0.147)
Bulgaria	3,186	2,471	1,874	4,800	2,070	1,000	3,008	0.293 (0.115)
China	3,762	4,700	2,267	6,152	3,456	1,625	3,806	0.934 (0.354)
Ethiopia	1,084	1,743	1,090	1,843	1,139	3,467	1,326	0.107 (0.044)
France	5,747	8,564	4,122	5,360	5,878	2,562	6,617	2.224 (0.842)
Greece	2,394	10,345	1,955	7,118	1,800	2,000	2,509	0.719 (0.273)
Hungary	3,535	6,246	2,469	3,295	2,123	2,016	4,310	0.662 (0.253)
Italy	3,380	9,513	2,218	5,849	6,205	3,812	2,801	1.782 (0.675)
Mexico	2,453	2,578	3,014	4,258	3,380	1,650	4,766	0.503 (0.194)
Morocco	543	211	535	5,277	585	1,000	1,228	0.002 (0.001)
Peru	1,153	2,595	1,031	6,694	2,000	1,492	1,247	0.219 (0.086)
Romania	2,988	3,066	1,743	1,250	903	1,623	3,056	0.088 (0.038)
Russia	2,011	1,813	1,710	3,493	753	941	2,058	0.100 (0.042)
S. Africa	1,795	2,437	1,809	2,286	2,343	1,685	2,571	0.256 (0.101)
Spain	2,089	9,721	1,492	7,580	3,870	2,679	2,300	1.001 (0.378)
Ukraine	2,598	3,243	1,996	3,655	995	1,012	3,102	0.194 (0.078)
Uruguay	912	4,664	1,250	6,704	4,063	2,300	1,149	0.258 (0.102)
USA	3,127	8,673	2,208	7,278	3,761	2,664	2,702	1.487 (0.563)
Zimbabwe	5,490	1,199	2,200	2,400	649	2,271	5,624	0.067 (0.030)
Average	2,368	5,466	1,832	5,942	3,108	2,513	2,879	

Source: FAO (2008).

The estimated yield variation parameter is $\hat{\theta} = 2.489$, with a standard error of 0.161. This is lower than the 3.60–12.86 values that Eaton and Kortum (2002) estimate for the manufactures sector. This reflects the fact that productivity in the world crop sector is much more heterogeneous than productivity in the manufacturing sector. There are large differences in temperature, precipitation, growing season, and soil type across the world, making it difficult to quickly transfer a new technology (e.g., seeds) across regions, especially when investment for such activities remains low for a number of the countries in Table 1 (Ruttan 2001).

Figure 1 displays the estimated probability density functions for two countries, China and the United States. Even though $\hat{\theta}$ is common by country, the location and breadth of the distribution differs by country, since $\hat{T}_i$ varies by country. Note that while we estimate individual crop yield distributions for Ethiopia and the Ukraine, the Global Trade Analysis Project (GTAP) database combines these into a regional composite: *XSS* (rest of sub-Saharan Africa) and *XSU* (rest of former Soviet Union), respectively (Dimaranan and McDougall 2007). For simplicity we refer to Ethiopia and Ukraine in the analysis, but in reality the results below refer to these regional composites.

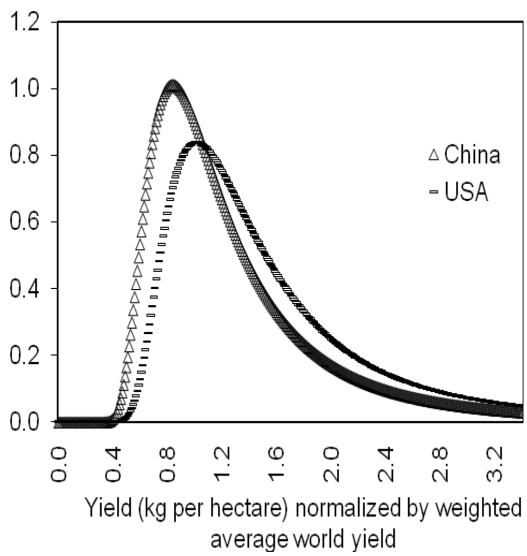

Figure 1. Estimated Probability Density Functions, China and the United States

Estimation of Trade Costs

Using the trade equation (6), we follow Eaton and Kortum (2002) and normalize (X_{ni}/X_n) by the home sales of a buyer (X_{nn}/X_n) to get

$$(12) \qquad \frac{X_{ni}}{X_{nn}} = \frac{T_i (w_i d_{ni})^{-\theta}}{T_n w_n^{-\theta}} = \frac{T_i}{T_n}\left(\frac{w_i}{w_n}\right)^{-\theta} d_{ni}^{-\theta}.$$

Now take the log

$$(13) \qquad \ln\left(\frac{X_{ni}}{X_{nn}}\right) = \ln\frac{T_i}{T_n} - \theta\ln\frac{w_i}{w_n} - \theta\ln d_{ni}.$$

To make this more useful we adopt a measure of competitiveness, $S_i \equiv \ln T_i - \theta \ln w_i$, which corresponds to yield adjusted for land costs. We substitute S_i into equation (13) to get

$$(14) \qquad \ln\left(\frac{X_{ni}}{X_{nn}}\right) = -\theta\ln d_{ni} + S_i - S_n.$$

In estimating equation (14), the S_i can be captured by way of country source dummies. With $\hat{T}_i$ and $\hat{\theta}$ from equation (11), we can recover an estimate of w_i.

Since we cannot directly observe $\ln d_{ni}$, we estimate this effect using variables typically employed in gravity equations. Distance is accounted for by using six dummy variables representing different intervals of "great-circle distance" between capitals. The associated coefficients are d_k ($k = 1,\ldots,6$), where d_1 is the coefficient associated with a distance of 375 miles or less, d_2 is the coefficient associated with a distance of 375 to 750 miles, and so on. We also account for whether two countries share a border (b), share membership in a trade agreement (e_h), and have a common language (l). Finally, we include an overall destination effect (m_n) that proxies for openness to trade. Substituting these in for $\ln d_{ni}$ in equation (14) gives

$$(15) \qquad \ln\left(\frac{X_{ni}}{X_{nn}}\right) = S_i - S_n - \theta m_n - \theta d_k - \theta b - \theta l - \theta e_h + \theta\xi_{ni}.$$

The dummy variable associated with each effect is suppressed for notational simplicity. The error term is $\xi_{ni} = \xi_{ni}^2 + \xi_{ni}^1$, where ξ_{ni}^2 affects two-way international trade and has variance σ_2^2, with $\xi_{ni}^2 = \xi_{in}^2$, and ξ_{ni}^1 affects one-way international trade and has variance σ_1^2. Under this error structure, diagonal elements of the variance-covariance matrix are $E(\xi_{ni}\xi_{ni}) = \sigma_1^2 + \sigma_2^2$, while certain off-diagonal elements are $E(\xi_{ni}\xi_{in}) = \sigma_2^2$. This allows for "reciprocity" in geographic barriers; the disturbance concerning shipments from n to i is positively correlated to the disturbance concerning shipments from i to n. To avoid the dummy variable trap we impose $\sum S_i = 0$, $\sum m_n = 0$, and no overall intercept.

2001 data on bilateral crop purchases (X_{ni}) are from the GTAP database (Dimaranan and McDougall 2007). These data have the important advantage of being fully reconciled in a transparent manner across each exporter i and importer n.

Equation (15) is estimated with Generalized Least Squares for 420 observations [(21×21)–21]. Results are in Table 2. The overall fit of the estimated equation is good, with an adjusted R^2 of 0.71. Looking at the top part of Table 2, we see that most coefficients are statistically non-zero. The negative coefficients on the distance variables indicate that distance reduces trade. In addition, trade is reduced by relatively longer distances. For example, the coefficient for distances within 375 miles is -5.61, while the coefficient for distances over 6,000 miles is -10.38. The coefficients on the border, language, NAFTA, and EU variables are all positive, which implies that these reduce trade costs, as expected.

The $-\theta m_n$ coefficients are reported in the left half of Table 2 and reflect a variety of destination-specific factors that inhibit imports. The countries most open to imports are the United States and France, with coefficients of 5.45 and 3.42, respectively. The countries least open to imports are Zimbabwe and Bulgaria, with coefficients of -4.64 and -3.94, respectively.

The rightmost three columns of Table 2 report estimates of a country's competitiveness (S), which is increased by yields and decreased by land prices. The United States is the most competitive country in 2001 (5.09), followed by Argentina (3.84), another large exporter. Peru and Zimbabwe are the least competitive, at -3.37 and -3.21, respectively.

The remainder of the parameters are inferred from identities in the conceptual model. Using $S_i \equiv \ln T_i - \theta \ln w_i$, we calculate the price of cropland in country i cropland as

$$(16) \qquad \hat{w}_i = \exp\left([\ln \hat{T}_i - \hat{S}_i]/\hat{\theta}\right).$$

Using the result from equation (16) and data on X_{ni}, baseline cropland estimates can be backed out of the land market identity that relates total production (exports plus production for domestic consumption) and land costs:

$$(17) \qquad \hat{L}_i = \frac{\sum_{n=1}^{N} X_{ni}}{\hat{w}_i}.$$

Results from equations (16) and (17) are available on request. Finally, we need to estimate α_n, which is the share that spending on crops (X_n) has of all agricultural spending. We first calculate this for individual countries using the GTAP data, then find a unified α by taking a GDP-weighted average (this assumption does little harm as the standard deviation across countries is very low). We get $\hat{\alpha} = 0.21$. Baseline levels of the endogenous variables P_n, X_{ni}, and w_i are solved using the procedure in Eaton and Kortum (2002).

Main Results

Counterfactual 1: Increased Variability

We couch our simulations in terms of the exogenous parameter θ, which has an inverse relationship with variability. We report the result of a 30 percent decrease in θ. We carry out simulations for other hypothetical changes, but since the elasticities of response tend to be very similar (and space is limited), we report this one example.

As θ falls, bumper crops and crop failures are more likely. Some of these affect local markets to an extent that trade barriers are overcome and spatial arbitrage becomes worthwhile. Columns 1–3 of Table 3 report the effects on net welfare, crop prices, and returns to cropland. A 30 percent fall in θ causes overall world trade to expand by 103 percent. Fifteen of the 21 countries have a decrease in overall welfare. This is generally due to an increase in crop prices. Of those with an increase, the average rise is 29 percent.

The maximum welfare decline is 19 percent, which is for Morocco. While imports are now more necessary, Morocco's crop sector is not especially open to imports ($-\theta m$ = 0.61), and is not particularly competitive (S = -0.70). Morocco's crop prices rise by 52.2 percent, while returns to cropland fall by 39.6 percent.

The other countries suffering welfare losses also tend to have high costs of importation and

Table 2. Bilateral Trade Equation

Source of Barrier		Estimate	*p*-value		Estimate	*p*-value
Dist [0,375]	$-\theta d_1$	-5.61	0.00			
Dist [375,750]	$-\theta d_2$	-6.18	0.00			
Dist [750,1500]	$-\theta d_3$	-7.26	0.00			
Dist [1500,3000]	$-\theta d_4$	-8.26	0.00			
Dist [3000,6000]	$-\theta d_5$	-9.81	0.00			
Dist [6000,max]	$-\theta d_6$	-10.38	0.00			
Border	$-\theta b$	0.59	0.19			
Language	$-\theta l$	1.17	0.00			
NAFTA	$-\theta e_1$	1.45	0.31			
EU	$-\theta e_2$	1.21	0.05			
Mercosur	$-\theta e_3$	-0.70	0.46			
Country	**Destination Country**			**Source Country**		
Argentina	$-\theta m_1$	2.75	0.00	S_1	3.84	0.00
Australia	$-\theta m_2$	1.99	0.00	S_2	1.54	0.00
Brazil	$-\theta m_3$	2.38	0.00	S_3	2.99	0.00
Bulgaria	$-\theta m_4$	-3.94	0.00	S_4	-1.22	0.00
China	$-\theta m_5$	1.81	0.00	S_5	2.54	0.00
Ethiopia	$-\theta m_6$	1.73	0.00	S_6	0.73	0.06
France	$-\theta m_7$	3.42	0.00	S_7	1.96	0.00
Greece	$-\theta m_8$	-0.27	0.65	S_8	-2.52	0.00
Hungary	$-\theta m_9$	-1.13	0.05	S_9	-1.67	0.00
Italy	$-\theta m_{10}$	0.65	0.28	S_{10}	-1.09	0.01
Mexico	$-\theta m_{11}$	-0.53	0.38	S_{11}	-0.49	0.22
Morocco	$-\theta m_{12}$	0.61	0.30	S_{12}	-0.70	0.07
Peru	$-\theta m_{13}$	-3.75	0.00	S_{13}	-3.37	0.00
Romania	$-\theta m_{14}$	-2.17	0.00	S_{14}	-1.34	0.00
Russia	$-\theta m_{15}$	-0.61	0.29	S_{15}	-0.01	0.99
South Africa	$-\theta m_{16}$	1.11	0.05	S_{16}	0.02	0.96
Spain	$-\theta m_{17}$	1.19	0.04	S_{17}	-1.35	0.00
Ukraine	$-\theta m_{18}$	-2.21	0.00	S_{18}	0.49	0.20
United States	$-\theta m_{19}$	5.45	0.00	S_{19}	5.09	0.00
Uruguay	$-\theta m_{20}$	-3.84	0.00	S_{20}	-2.25	0.00
Zimbabwe	$-\theta m_{21}$	-4.64	0.00	S_{21}	-3.21	0.00

Notes: Estimated by Generalized Least Squares using 2001 data and 420 observations. Adjusted R^2 = 0.71.

Table 3. Counterfactuals 1 and 2: Broadening of Crop Yield Distributions

	θ decreases by 30%; world trade volume is flexible			θ decreases by 30%; world trade volume is fixed		
Country	Net Welfare	Crop Prices	Returns to Land	Net Welfare	Crop Prices	Returns to Land
Argentina	2.0	33.3	27.3	-1.4	11.0	3.1
Australia	-1.6	10.8	3.5	-3.0	16.8	3.2
Brazil	-4.0	23.4	5.0	-4.8	22.5	0.4
Bulgaria	-5.8	29.5	2.6	-6.0	27.9	0.2
China	-1.1	0.7	-4.6	-1.6	6.4	-0.9
Ethiopia	-8.4	30.6	-8.4	-9.4	39.7	-3.5
France	5.1	-21.0	2.3	1.8	-5.6	2.4
Greece	3.1	-19.6	-8.8	-2.5	19.0	10.8
Hungary	0.0	28.3	22.4	-2.2	22.5	10.1
Italy	4.3	-24.1	-5.8	0.5	6.5	11.2
Mexico	-0.8	-1.1	-6.7	-4.4	28.4	11.2
Morocco	-19.0	52.2	-39.6	-22.2	78.9	-24.9
Peru	-4.7	10.4	-13.5	-6.7	30.5	-0.1
Romania	-9.6	47.3	2.8	-10.4	45.1	-2.5
Russia	-8.6	33.5	-6.3	-9.7	42.0	-2.6
South Africa	-3.4	6.0	-11.5	-5.8	26.4	-0.4
Spain	3.5	-19.0	-4.4	-1.5	15.0	11.8
Ukraine	-7.4	33.3	-0.5	-7.5	33.9	-0.8
United States	1.0	7.6	10.2	0.1	-2.4	-1.7
Uruguay	-4.5	18.6	-2.7	-6.6	36.1	7.0
Zimbabwe	-9.9	34.2	-12.0	-11.0	47.0	-3.9

Note: All values are percentage changes. A decrease in θ implies that yield outcomes are more heterogeneous across countries. In columns 1–3, world trade increases by 103 percent; it does not change in columns 4–6.

low competitiveness (Table 3). Due to locational advantages and participation in trade agreements, however, their losses are typically mitigated compared to Morocco's. For example, Bulgaria and Romania experience crop price rises of 29.5 percent and 47.3 percent, respectively. Their net welfare losses are moderate compared to Morocco's, however, at -5.8 percent and -9.6 percent, respectively. This is because their domestic crops sector expands and causes returns to land to increase by 2.6 percent and 2.8 percent, respectively, which helps landowners. In the national net welfare calculations, this helps offset the losses experienced by consumers.

Six countries experience a small increase in overall welfare from rising yield variability. The United States, for example, has a rise in net welfare of 1.0 percent due to a rise in the returns to cropland. The United States has the most competitive crops sector ($S = 5.09$), and as it responds to new opportunities in foreign markets, it experiences a 10.2 percent rise in the returns to land. Increased foreign demand also drives up crops prices in the United States (7.6 percent), but this is not so large as to offset the benefits of rising land prices.

Spain is one of the other five countries to have a small welfare gain, but this comes by a different route than with the United States. Spain is among the countries most open to imports ($-\theta m$ = 1.19), which takes pressure off its own domestic crops sector. While land prices fall 4.4 percent, crop prices fall much further (19 percent), giving the country a small overall welfare gain (3.5 percent).

The results vary systematically across rich and poor countries. Figure 2 is a scatterplot of the net welfare change on per capita GDP. This shows that most countries experience a net welfare decline from increased yield variability. It also shows that poor countries, in particular, are hurt the most. This is because poor countries are more likely to suffer increased prices. This is shown in Figure 3, which plots the change in crop prices on per capita GDP. Another reason is that rich countries are more likely to have positive changes in land prices, since they are more likely to have higher productivity, and somewhat more likely to expand their crop sector through exports.

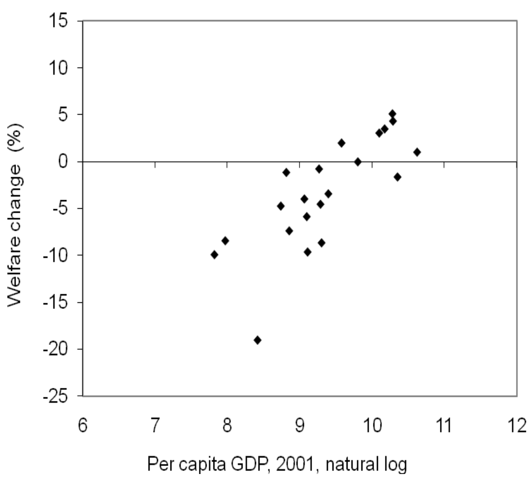

Figure 2. Counterfactual 1: Welfare Changes Plotted Against Income

Counterfactual 2: Increased Variability, but Trade Is Constrained

We now allow for countries to introduce trade-restricting policies in response to greater variability. We consider the above scenario in conjunction with a simultaneous increase in protectionism, as proxied by trade costs. A 30 percent decrease in θ occurs while world trade volumes are fixed at baseline levels.

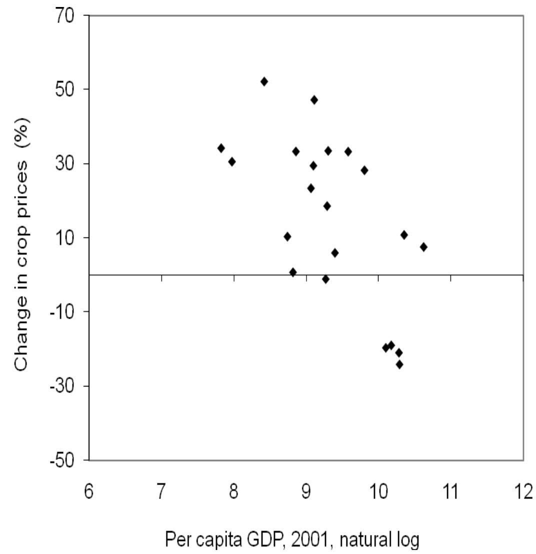

Figure 3. Counterfactual 1: Crop Price Changes Plotted Against Income

Results are reported in Table 3, columns 4–6. Eighteen countries experience a decline in net welfare. This is generally due to a rise in crop prices, which happens in 19 of the 21 countries. The median change is 26.4 percent (South Africa) and the maximum is 78.9 percent (Morocco).

In terms of net welfare, the adverse effect of rising crop prices is typically offset to some extent by rising land prices. Thus, while Mexico experiences a substantial rise in crop prices (28.4 percent), this is moderated by the fact that land prices also rise (11.2 percent). Mexico has a net welfare decline of 4.4 percent. In essence, landowners benefit while crop buyers suffer.

Three countries actually experience a net welfare benefit. The United States has a slight increase in welfare (0.1 percent) because crop prices fall to a greater extent (2.4 percent) than land prices fall (1.7 percent). This is due to slackening foreign demand associated with rising protectionism elsewhere. Italy also has an increase in welfare (0.5 percent), but for a completely different reason. Rising protectionism means it relies more heavily on its crops sector, causing land prices to rise by 11.2 percent. This offsets a 6.5 percent rise in crop prices.

Net welfare and crop price changes are highly correlated with countries' per capita GDP. Figure 4 plots the changes in crop prices against per

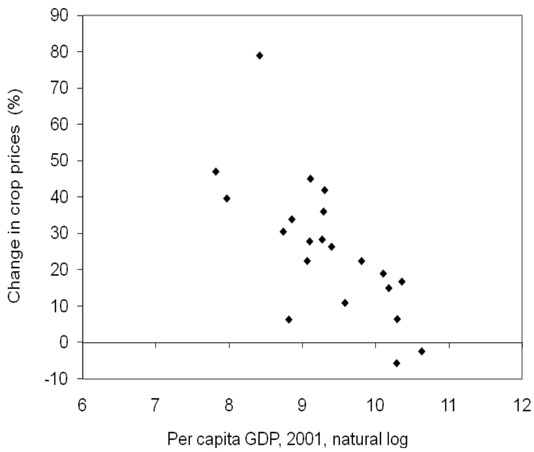

Figure 4. Counterfactual 2: Crop Price Changes Plotted Against Income

capita GDP. It shows that while nearly all countries face higher crop prices, it is poor countries that suffer the most.

To sum up, Counterfactual 1 suggests that there is currently enough flexibility in the world trading system to accommodate a broadening of countries' yield distributions. Indeed, with higher yield variability, the gains from trade are that much higher; what is critical is that countries remain open to trade. Counterfactual 2 shows that the typical country gets hurt if trade barriers rise in concert with yield variability. In both cases, poor countries get hurt the most.

Counterfactual 3: Decreased Yield Variability

Table 4 presents the results of a 30 percent increase in θ. As crop failures and bumper crops become less likely, exports and imports decline. Overall world trade falls by 32 percent, while at-home production increases by an average 1.85 percent. Fifteen countries have an increase in welfare, primarily those that are less competitive in world markets, and/or those that have higher-than-average barriers to imports. Sixteen of 21 countries experience a fall in crop prices.

The most extreme case is Morocco, with a welfare increase of 13.2 percent. Imports are now less necessary, so the relative inefficiency and insulation of Morocco's crop sector is less of a problem. Morocco's crop prices fall by 49.5 percent, while returns to cropland rise by 10.2 percent.

Major exporters such as the United States, Argentina, Brazil, and Hungary experience falls in land prices up to 13.9 percent. This gives the United States and Argentina net welfare declines of 0.2 percent and 0.1 percent, respectively. Net welfare in Brazil and Hungary increases by 2.5 percent and 1.2 percent, however, since consumers gain from the larger-than-average drops in crop prices resulting from falling foreign demand for their products.

Again, there are systematic differences in how rich and poor countries fare. Figure 5 plots net welfare changes against per capita GDP. While most countries experience a welfare gain from declining variability, this time it is *poorer* countries that gain the most in percentage terms.

We previously mentioned some limitations of our model and data, and these should be considered when interpreting our results. For example, the results could differ if we included a different set of countries in our sample, or if we employed a general equilibrium measure of welfare. Despite these caveats, we feel that most such changes would not change the qualitative nature of our results.

Conclusions

This study examines how yield variability affects buyers and sellers of cereal grains and oilseeds. We find that world trade volumes may need to increase substantially as crop yield variability rises. As long as the world trading system remains flexible, welfare in the typical country declines only very modestly.

However, the net welfare predictions are highly uneven across high- and low-income countries. Low-income countries get hurt more when yield variability increases because they typically have greater import barriers and are less competitive at producing crops. The implication is that low-income countries have a particularly large stake in maintaining flexibility in the world trading system, and in improving domestic agricultural productivity.

Historically, countries have responded to random agricultural production by restricting trade and adopting policies that encourage self-sufficiency at home. We therefore consider what

Table 4. Counterfactual 3: Narrowing of Crop Yield Distributions

	θ increases by 30%; world trade volume is flexible		
Country	Net Welfare	Crop Prices	Returns to Land
Argentina	-0.1	-18.1	-13.9
Australia	1.4	-4.3	2.3
Brazil	2.5	-12.8	-1.1
Bulgaria	3.3	-16.1	-1.1
China	0.8	-2.7	1.2
Ethiopia	5.2	-22.8	1.0
France	-2.1	10.1	0.5
Greece	-0.9	11.2	10.2
Hungary	1.2	-15.6	-8.9
Italy	-2.0	14.3	6.7
Mexico	0.6	2.3	7.0
Morocco	13.2	-49.5	10.2
Peru	3.1	-8.3	6.6
Romania	5.6	-27.6	-1.6
Russia	5.3	-23.4	0.9
South Africa	2.7	-4.7	8.2
Spain	-1.3	9.9	5.6
Ukraine	4.1	-19.2	-0.4
United States	-0.2	-4.3	-4.6
Uruguay	2.7	-8.3	4.7
Zimbabwe	6.1	-26.1	2.0

Note: All values are percentage changes. The 30 percent increase in θ implies that yield draws are less extreme. World trade decreases by 32 percent.

would happen if trade barriers were to rise along with yield variability. We consider a scenario in which world trade volumes remain the same as in the baseline. Most of the 21 countries in our sample experience adverse welfare effects due to large increases in crop prices. Again, it is poorer countries that experience the biggest welfare declines.

So while the earlier scenario suggests that increased randomness need not have highly adverse consequences, trade-restricting policies—such as those introduced by some exporters in 2007–2008—cause important welfare losses for most countries. To the extent that the analysis has policy implications, it suggests that countries specialize in those crops for which they have comparative advantage, and trade according to relative abundance in a given year. In this way regions can reap the benefits of economic efficiency while having an avenue to deal with yield variability.

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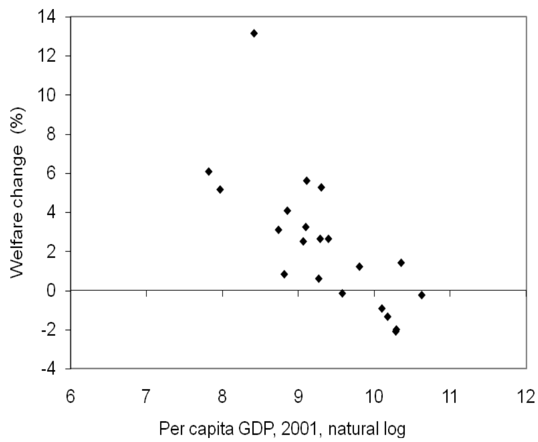

Figure 5. Counterfactual 3: Welfare Changes Plotted Against Income

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