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**Article**

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## The Effect of Climate Change and Biofuel Mandates on Agricultural Output and Food Prices

Wolfram Schlenker\*

The four staple commodities—maize, soybeans, rice, and wheat—account for roughly 75 percent of the world’s caloric consumption, either directly as food or indirectly in the form of feedstock for animals. The U.S. share of global caloric production in those four commodities is 23 percent, about three times Saudi Arabia’s market share in oil production. Of particular importance is U.S. maize (sometimes also called corn), the country’s largest crop, accounting for 10 percent of global caloric production. Given its market share, any policy or shock that affects U.S. maize production has worldwide ramifications for commodity prices, which move together because they are close substitutes.

While agriculture constitutes a small fraction of U.S. GDP, it is responsible for a large part of consumer surplus because agricultural demand is highly inelastic. The tripling of commodity prices between 2005 and 2008 reduced global

consumer surplus from the four basic commodities by approximately 1.25 trillion dollars annually. While various causes have been mentioned as possible driving forces behind the recent price increase, my past research has focused on two of them: the effects of weather on agricultural yields and the effect of biofuel mandates on food prices.

### The Effects of Weather/Climate on Yields

Agricultural production, except for some specialty crops that are grown in greenhouses, depends directly on weather. Because weather is predicted to change over the next century, one natural question is how that will affect agricultural production and prices.

#### a) Extreme heat and crop yields

Michael Roberts and I linked a county-level panel of corn and soybean yield, the two largest crops in the United States, as well as cotton, a warm weather-crop, to a fine-scale dataset of weather outcomes that explain the distribution of temperatures within each day.<sup>1</sup> Yields increase linearly in temperatures up to 29°C (84°C) for corn, 30°C (86°F) for soybeans, and

33°C for cotton—above that, further temperature increases become harmful. The relationship above the threshold is again linear, but the slope of the decline above the optimum is an order of magnitude steeper than the incline below it: that is, being 1 degree above the optimum for ten days has the same effect as being 10 degrees above the optimum for one day. Both decrease annual maize yields by 6 percent. Note, however, that we are incorporating the entire temperature distribution within a day, and the largest fraction of a day is usually below the threshold. It takes several days with a maximum above the threshold to obtain a 24-hour exposure period above the threshold.

Most U.S. counties are expected to suffer yield declines under climate change. The predicted increase in the frequency of temperatures above the threshold accounts for the largest share of the estimated effect on yield, and trumpets the effect of temperature changes below the threshold, as well as precipitation changes.

Adaptation to extreme heat seems difficult or prohibitively costly. We obtain the same statistical sensitivity to extreme heat whether we look at the panel, a pure time-series linking annual overall U.S. yields to weather, or a cross-section linking aver-

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age yields in a county to average weather outcomes (climate in a location). In other words, the difference in average productivity explained by differences in climate shows the same sensitivity as the sensitivity of yields in a given place to year-to-year weather fluctuations. It would seem that farmers who repeatedly face higher temperatures should have more of an incentive to adapt to these high temperatures than farmers who face a one-time weather shock, yet the effects are the same empirically. In a different study, Anthony Fisher, Michael Hanemann, and I find a comparable sensitivity to extreme heat in the cross-section of U.S. farmland values, which includes as an adaptation strategy switching between crops.<sup>2</sup>

The crucial importance of extreme heat is also consistent with underlying agronomic models of crop growth: high temperatures decrease the water supply (through evaporation or plant transpiration) and at the same time increase the water demand to sustain a given level of carbon uptake, affecting both the supply and the demand for water. On the other hand, precipitation only affects the water supply. My co-authors and I use the agronomic crop model APSIM to examine the exact mechanism.<sup>3</sup> APSIM suggests that extreme temperatures do not affect the plant itself through heat stress, but rather through increased vapor pressure deficit (water stress). The sensitivity to extreme heat in APSIM is comparable to statistical studies of observed crop yields.

#### ***b) Evolution of heat sensitivity over time***

We find no evidence for adaptation in hotter places, but one might wonder whether there has been progress in heat tolerance over time. *Average* yields have tripled between 1950 and 2005, yet Roberts and I find that *sensitivity* to extreme heat is among the highest around 2005 and again roughly comparable in hot and cold climates (which had very different incentives to adapt to extreme heat events).<sup>4</sup> In a longer time-series for Indiana that starts in 1901, we find some improvement in heat tolerance after hybrid corn was introduced in the 1930s, but heat tolerance started to dete-

riorate again once growers switched from double-crossed hybrid corn to single-crossed hybrid corn in the 1960s. Going forward, the predicted increases in temperature would result in significant yield losses using today's corn varieties.

#### ***c) The 2012 U.S. heat wave***

Some breeding companies have claimed that the latest corn varieties have improved heat and drought tolerance. The year 2012, which had the second-largest exposure to temperatures above 29°C since 1950 and was the second driest year, offers a test of how well the new crop varieties can handle heat and drought. One unique feature of 2012 was that the heat wave was concentrated in the month of July. Steven Berry, Roberts, and I estimate a new county-level panel that allows the effect of extreme temperatures to evolve over the growing season.<sup>5</sup> Corn is most sensitive to hot temperatures around a third of the way into the growing season, which coincides with flowering. Since the 2012 heat wave hit the most productive corn growing area in the United States during the time when it was most vulnerable, a model that allows the effect of extreme heat to vary over the growing season yields larger damages than a standard model that assumes the effect to be homogenous across the entire season. More importantly, though, predicted yield declines under both the standard and the revised model are less severe than the preliminary yield forecasts for 2012, suggesting that the statistical model does not exaggerate the damaging effects of extreme heat as recent as 2012. Going forward, climate models suggest that the 2012 temperature outcomes will be a below-average year by mid-century as the temperature distribution shifts upward.

#### ***d) Observed climate trends***

The last three decades have seen increasing temperatures in many parts of the world. David Lobell, Justin Costa-Roberts, and I estimate country and crop-specific temperature and precipitation trends for 1960–80 for the four major staple commodities.<sup>6</sup> We find that the distribution of trends is indistinguishable from

a placebo when we repeatedly estimate trends for random draws from a stationary time-series of the same length. The picture changes dramatically for 1980–2008: observed temperature trends are generally positive and are shifted to the right of the placebo: most parts of the world have experienced warming trends that cannot be attributed to statistical noise. One notable exception is the United States.

In a second step, we estimate a panel linking yields to observed weather outcomes. We compare predicted yields under the observed weather outcomes to a counterfactual where we subtract the observed trends. Global caloric production is predicted to have been 3 percent less than what it would have been without the observed climate trends, which implies a roughly 20 percent increase in commodity prices. The next section outlines how we translate quantity changes into price changes.

## **U.S. Policies and the Effect of Food Prices**

### ***a) Biofuel policies***

The 2009 U.S. Renewable Fuel standard diverted a third of U.S. maize production into ethanol. Given the U.S. share of global maize production, this translates into 5 percent of combined caloric production of the four staple commodities. By comparison, global production shocks (deviations from a trend) ranged from -5.7 percent to +4.4 percent in 1961–2010 as country and crop-specific weather shocks averaged out. The U.S. ethanol mandate diverts as many calories from the world market *every year* as the worst observed supply shock in the last fifty years. Given the size of this market intervention, it can be expected to significantly affect global commodity prices.

The size of the price increase depends on the demand and supply elasticities for staple commodities. Roberts and I develop a novel framework for identifying the elasticities of storable commodities.<sup>7</sup> Concurrent supply shocks have been used as exogenous shifters since P. G. Wright invented instrumental variables.

Following a similar logic, to identify a supply response we can use *past* shocks, which affect inventory levels that link production and price levels between periods, as an instrument for futures prices in the next period.

We find a supply elasticity of 0.11 that is roughly twice the absolute magnitude of the demand elasticity of -0.055. The equilibrium price of calories is predicted to increase by 30 percent because of the outward shift in the demand for calories to meet the ethanol mandate. Two-thirds of the calories required to meet the ethanol mandate will come from new supply, while one-third will come from reductions in the demand for calories, which correspond to the caloric equivalent of feeding 132 million people for one year on a 2000 calorie/day diet. In case one third of the calories used in ethanol production can be recycled as feedstock, the numbers rescale accordingly, that is, the price increase would be 20 percent.

#### **b) Pollution reduction and yield gains**

Current work in progress with Christopher Boone and Juha Siikamäki examines one factor that contributed to the observed increase in average maize yields: reduction in peak ozone levels.<sup>8</sup> Roughly half of the observed trend in U.S. maize yields in 1993–2011 can be attributed to reduction in ozone, one of the ambient air pollutants regulated under the Clean Air Act. We construct a daily

pollution surface over the Eastern United States and use it as an explanatory variable in a panel of U.S. maize yields, while also accounting for weather and other pollution variables. We find a critical threshold of 72ppb in hourly ozone readings. Pollution fluctuations below the threshold have no significant effect on annual maize yields, but yields decrease linearly in hourly ozone levels above 72ppb. The current U.S. ambient standard is set at 75ppb, which is fairly close to our estimated threshold, but the U.S. standard is based on the highest consecutive 8hr average in a day, which can hide hourly spikes. Hourly ozone levels above 72ppb have been declining steadily between 1993 and 2011 and are currently close to zero, suggesting that further pollution reduction will no longer boost maize yields.

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<sup>2</sup> *W. Schlenker, W. M. Hanemann, and A.C. Fisher, "The Impact of Global Warming on U.S. Agriculture: An Econometric Analysis of Optimal Growing*

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<sup>3</sup> *D.B. Lobell, G. L. Hammer, G. McLean, C. Messina, M. J. Roberts, and W. Schlenker, "Understanding the Critical Role of Extreme Heat for Maize Production in the United States," Nature Climate Change, forthcoming.*

<sup>4</sup> *M. J. Roberts and W. Schlenker, "Is Agricultural Production Becoming More or Less Sensitive to Extreme Heat? Evidence from U.S. Corn and Soybean Yields" NBER Working Paper No. 16308, August 2010.*

<sup>5</sup> *S. T. Berry, M. J. Roberts, and W. Schlenker, "Corn Production Shocks in 2012 and Beyond: Implications for Food Price Volatility," NBER Working Paper No. 18659, December 2012.*

<sup>6</sup> *D. B. Lobell, W. Schlenker, and J. Costa-Roberts, "Climate Trends and Global Crop Production Since 1980," Science, 333(6042) (2011): pp. 616–20.*

<sup>7</sup> *M.J. Roberts and W. Schlenker, "Identifying Supply and Demand Elasticities of Agricultural Commodities: Implications for the US Ethanol Mandate," NBER Working Paper No. 15921, April 2010, and American Economic Review, forthcoming.*

<sup>8</sup> *C. Boone, W. Schlenker, and J. V. Siikamäki, "The Effect of Ground-level Ozone on US Maize Yields," Working Paper, January 2013.*