“Adaptation to Environmental Change: Agriculture and the Unexpected Incidence of the Acid Rain Program”

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Online Appendix

Table A-1—Robustness of Reduced Form Estimates to Alternate Model Choices

	(1) Imputed Indicator	(2) Quad Trends	(3) CRR Trends	(4) State Year FE	(5) Drop Plant Counties	(6) O3 Control	(7) Omit Droughts	(8) Just Droughts
Panel A: Corn								
SC X Post	-0.050	-0.051	-0.030	-0.017	-0.068	-0.027	-0.016	-0.050
	(0.014)	(0.014)	(0.009)	(0.005)	(0.015)	(0.007)	(0.006)	(0.014)
Damaging O3 Days						-0.012		
						(0.003)		
Clusters	211	211	211	211	208	201	211	211
Observations	41,964	41,964	41,964	41,964	35,620	29,743	32,280	41,964
Panel B: Soybean								
SC X Post	-0.048	-0.049	-0.026	-0.011	-0.072	-0.025	-0.025	-0.048
	(0.016)	(0.016)	(0.010)	(0.005)	(0.019)	(0.007)	(0.011)	(0.016)
Damaging O3 Days						-0.009		
						(0.004)		
Clusters	175	175	175	175	173	168	175	175
Observations	34,944	34,944	34,944	34,944	29,952	24,417	26,880	34,944

Note: We cluster standard errors at the crop reporting district level. We weight crop regressions by annual county-level acreage. Outcome for corn and soybean is log of crop yield per planted acre. We derive airborne sulfate measures from the APEEP atmospheric transport model using ARP-regulated power plant-level SO2 emissions as inputs. Crop yield per acre is total yield per acre divided by planted acres. refers to an indicator for all years 1995 onward interacted with the count of ARP-regulated boilers with installed sulfur controls, weighted by the APEEP model to calculate a county-level measure (see Section IV). Column headers describe variation in models, and Section VII describes each model modification in detail.

Table A-2—Alternate Instrument Choices for Sulfate

	(1)	(2)	(3)	(4)	(5)	(6)
	Basic Update		1985 Sulfur Weighted		1985 Heat Weighted	
	Phase 1	Phase 1 & 2	Phase 1	Phase 1 & 2	Phase 1	Phase 1 & 2
Panel A: Corn						
Sulfates ($\mu g/m^3$)	0.063	0.062	0.040	0.040	0.040	0.040
	(0.008)	(0.008)	(0.008)	(0.008)	(0.008)	(0.008)
F Stat	16.784	11.588	50.572	29.126	39.560	27.432
Observations	41,964	41,964	41,964	41,964	41,964	41,964
Panel B: Soybean						
Sulfates ($\mu g/m^3$)	0.065	0.066	0.062	0.060	0.064	0.064
	(0.008)	(0.009)	(0.010)	(0.010)	(0.011)	(0.011)
F Stat	14.741	10.162	18.192	10.807	19.086	15.633
Observations	34,944	34,944	34,944	34,944	34,944	34,944

Note: We cluster standard errors at the crop reporting district level. We weight crop regressions by annual county-level acreage. Outcome for corn and soybean is log of crop yield per planted acre. We derive airborne sulfate measures from the APEEP atmospheric transport model using ARP-regulated power plant-level SO2 emissions as inputs. Crop yield per acre is total yield per acre divided by planted acres. The first stage of IV regressions corresponds to variations in the model in Panel A of Figure 2. Column (1) repeats our main instrument. Column (2) adds Phase II updates. Columns (3) and (4) follow a similar pattern, but interact our original instrument with boiler-level SO2 output in 1985. Columns (5) and (6) replace 1985 SO2 output with 1985 heat output. See Section VII for details.

Table A-3—Reduced Form Estimates With Alternate Standard Errors

	(1) Baseline	(2) Unweighted	(3) State Cluster	(4) Conley	(5) Bootstrap
Panel A: Corn					
SC X Post	-0.050	-0.056	-0.056	-0.056	-0.056
	(0.014)	(0.011)	(0.014)	(0.016)	(0.026)
Panel B: Soybean					
SC X Post	-0.048	-0.050	-0.050	-0.050	-0.050
	(0.016)	(0.016)	(0.017)	(0.014)	(0.017)

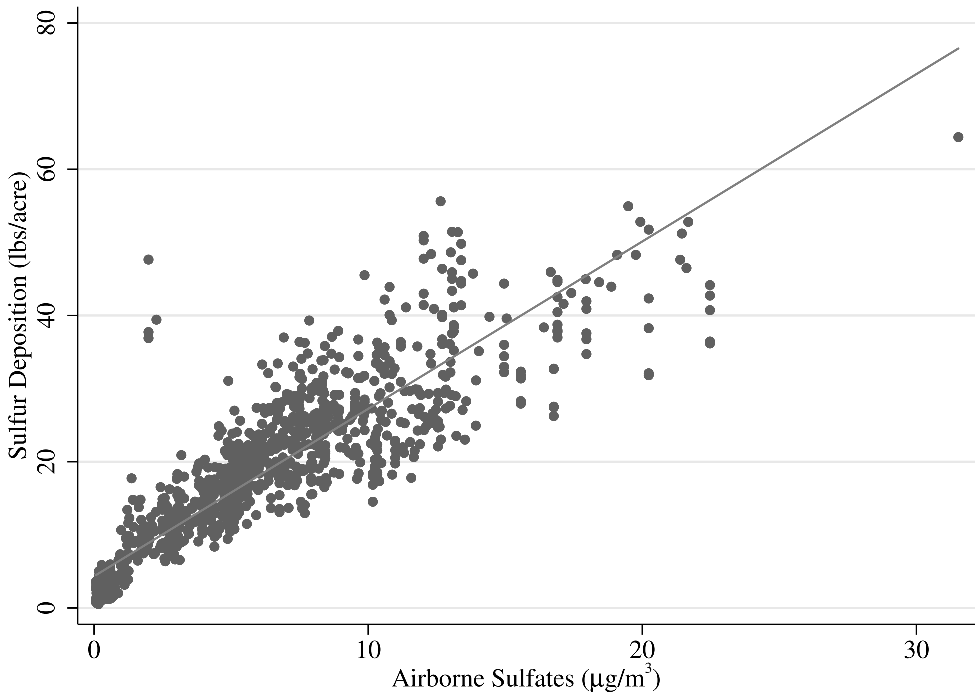
Note: We weight crop regressions by annual county-level acreage. Outcome for corn and soybean is log of crop yield per planted acre. We derive airborne sulfate measures from the APEEP atmospheric transport model using ARP-regulated power plant-level SO2 emissions as inputs. Baseline model in Column (1) corresponds to Column (3) of Table 2. Column (2) omits weights. Column (3) clusters standard errors at the level of state. Column (4) uses geospatially correlated Conley standard errors, using a radius of 200 miles. Column (5) uses bootstrapped standard errors with 10,000 replications, stratified on years with replacement.

Table A-4—Expanded Pollutants

	(1)	(2)	(3)	(4)	(5)
		LUR Data		Monitor Data	
Panel A: Corn					
Sulfates ($\mu g/m^3$)			0.055	0.023	0.026
			(0.007)	(0.005)	(0.005)
Airborne SO2 (LUR)	0.004	0.004	0.001		
	(0.002)	(0.002)	(0.002)		
Airborne NO2 (LUR)		-0.006	-0.006		
		(0.003)	(0.003)		
Airborne O3 (LUR)		-0.003	-0.003		
		(0.001)	(0.001)		
Airborne SO2 (Monitor)					-0.008
					(0.003)
Airborne NO2 (Monitor)					0.004
					(0.002)
Airborne O3 (Monitor)					-1.107
					(1.420)
Clusters	211	211	211	96	96
Observations	41,964	41,964	41,964	11,180	11,180
Panel B: Soybean					
Sulfates ($\mu g/m^3$)			0.042	0.013	0.013
			(0.007)	(0.004)	(0.004)
Airborne SO2 (LUR)	0.002	0.003	-0.000		
	(0.002)	(0.002)	(0.002)		
Airborne NO2 (LUR)		0.002	0.001		
		(0.002)	(0.002)		
Airborne O3 (LUR)		-0.004	-0.004		
		(0.002)	(0.001)		
Airborne SO2 (Monitor)					-0.001
					(0.003)
Airborne NO2 (Monitor)					0.000
					(0.001)
Airborne O3 (Monitor)					-5.276
					(1.433)
Clusters	175	175	175	73	73
Observations	34,944	34,944	34,944	8,320	8,320

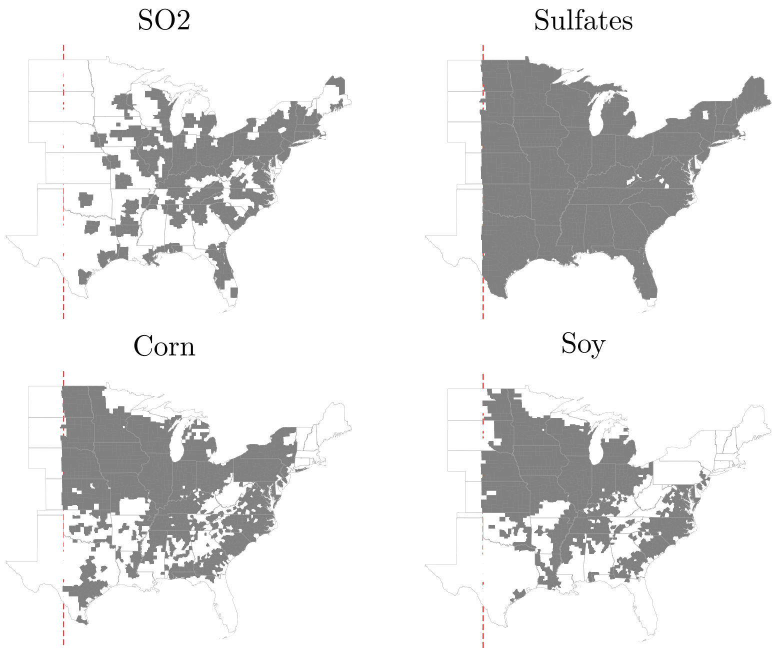
Note: We weight crop regressions by annual county-level acreage. Outcome for corn and soybean is log of crop yield per planted acre. We derive airborne sulfate measures from the APEEP atmospheric transport model using ARP-regulated power plant-level SO2 emissions as inputs. Monitor pollutant measures come from air monitor data we aggregate to the county level. Land Use Regression (LUR) data are from the Center for Air, Climate and Energy Solutions (CACES). See Section VII.A for details.

Figure A-1. Correlation Between Airborne Sulfates and Sulfur Deposition



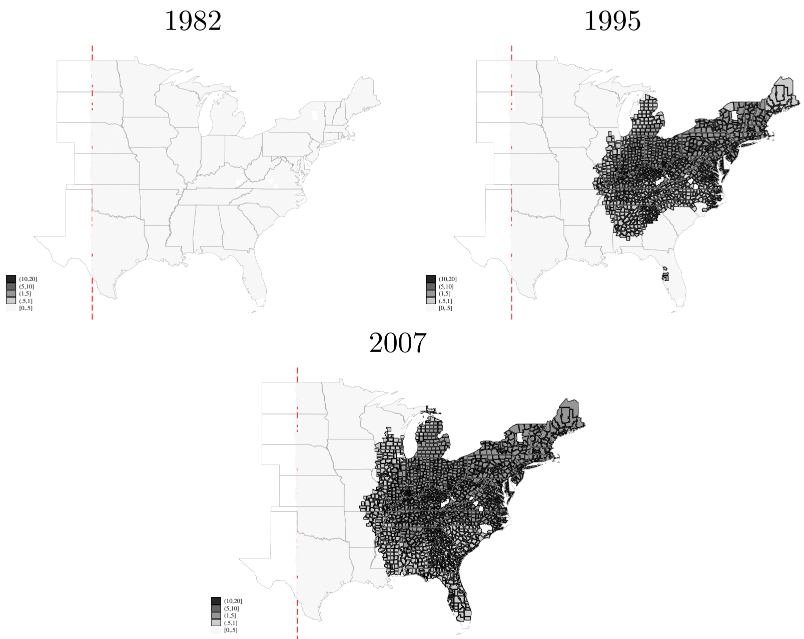
Note: We generate predicted sulfate levels using boiler-level SO2 emissions and the APEEP atmospheric conversion matrix which takes as inputs SO2 and provides as output estimated sulfates, which include sulfate and ammonium sulfate. Sulfur deposition data are from the Clean Air Markets Division, Clean Air Status and Trends Network (CASTNET). Data shows raw values across multiple sensors and multiple years with a simple correlation. We match deposition monitors to atmospheric sulfates using county of monitor.

Figure A-2. Analysis Counties by Outcome



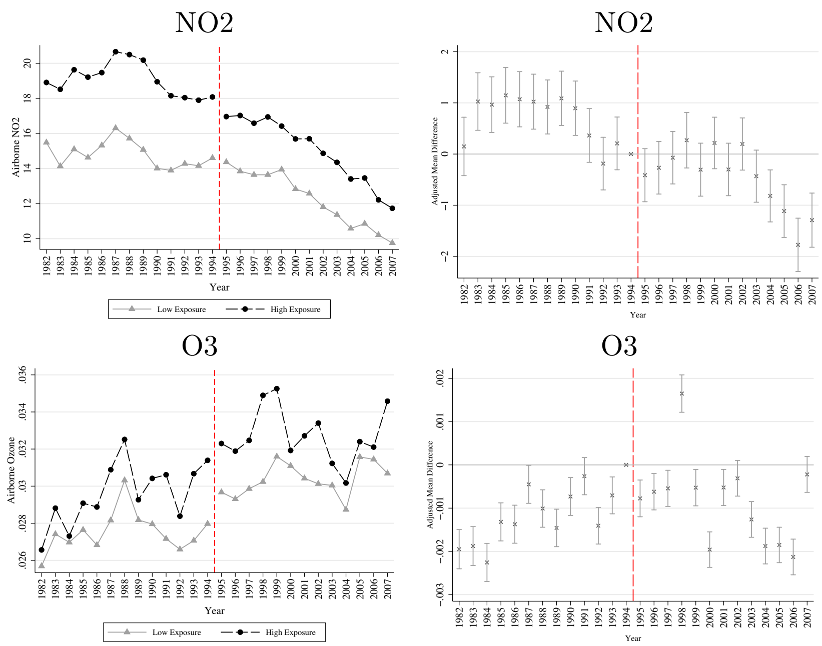
Note: Graphs shade counties used in our main regressions for each noted outcome east of 100 degrees longitude. See Section III for details.

Figure A-3. County-Level Variation in Weighted Number of ARP Plants With Technology Upgrades



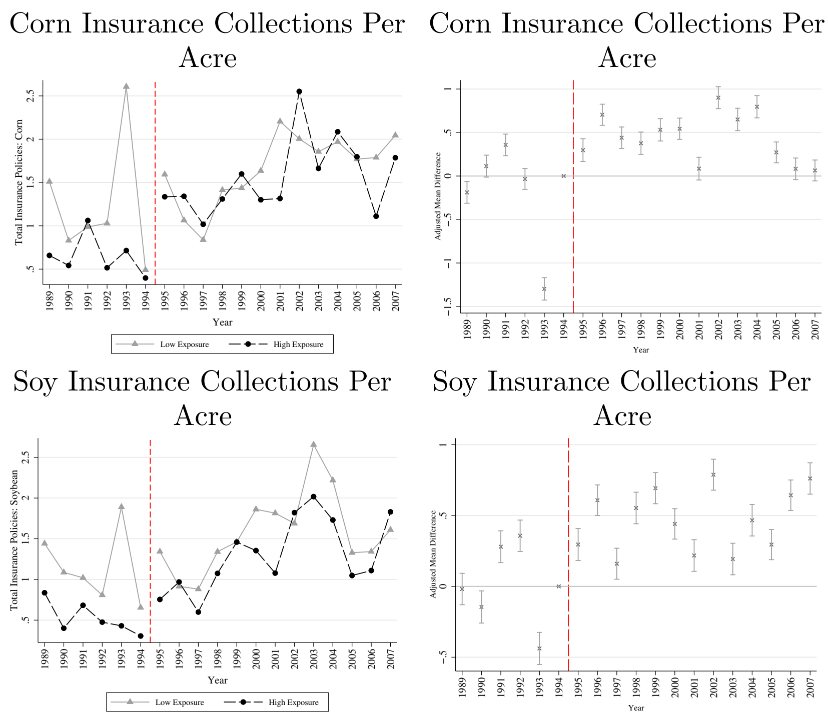
Note:.Our measure of treatment is the number of sulfur control boiler upgrades installed at ARP-treated power plants, weighted by the APEEP atmospheric dispersion matrix for SO2 emissions to ambient sulfates, and multipled by 100,000 for ease of reading. See Section IV for details.

Figure A-4. Trends and Event Studies in Other Pollutants



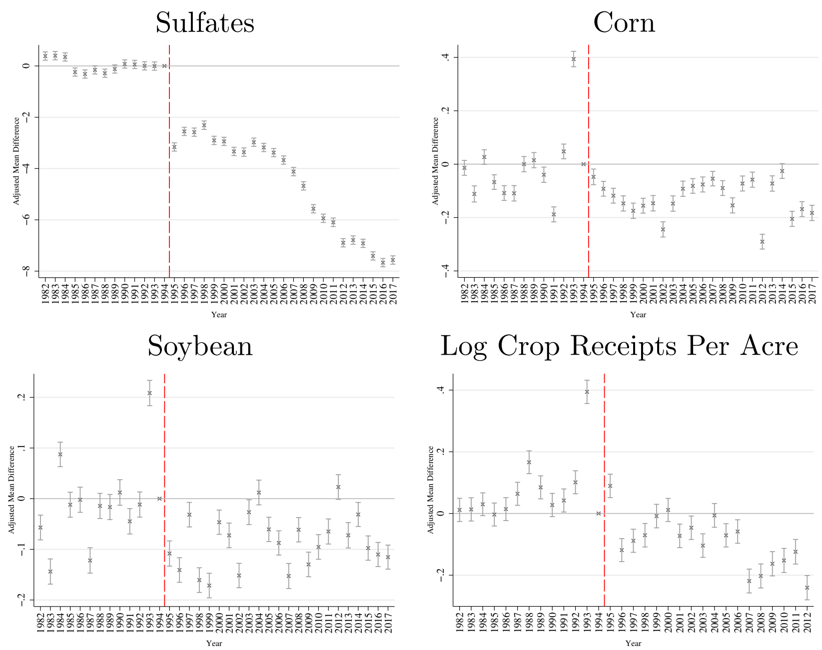
Note: Event studies show the annual marginal effect of an additional unit of our treatment measure as we describe in Section IV. We use 1994, the year prior to the enforcement of the ARP, as baseline for comparison, and treatment levels in 1995 as our measure of marginal treatment intensity. All estimates include 95% confidence intervals, where we cluster standard errors by crop reporting district. Emissions data are from EPA air quality monitors, which we aggregate to the county level.

Figure A-5. Trends and Event Studies in Corn and Soy Indemnity Collections



Note: Trend figures show outcome trends split by above vs. below the median level of treatment intensity in 1995 for all available counties east of the 100th degree meridian. Event studies show the annual marginal effect of an additional unit of our treatment measure as we describe in Section IV. We use 1994, the year prior to the enforcement of the ARP, as baseline for comparison, and treatment levels in 1995 as our measure of marginal treatment intensity. All estimates include 95% confidence intervals, where we cluster standard errors by crop reporting district. Insurance indemnities are from the USDA REIS data.

Figure A-6. Extended Outcomes



Note: Event studies show the annual marginal effect of an additional unit of our treatment measure as we describe in Section IV. We use 1994, the year prior to the enforcement of the ARP, as baseline for comparison, and treatment levels in 1995 as our measure of marginal treatment intensity. All estimates include 95% confidence intervals, where we cluster standard errors by crop reporting district. We derive atmospheric sulfate projections using the APEEP transport model. Corn and soybean outcomes are log of yield per planted acre from the USDA NASS. Crop receipts are from BEA data and are divided by total crop acreage from the Census of Agriculture. We linearly impute between-COA crop acreage at the county-level.

Sulfur as an Input and the Marginal Product

Despite its importance in the growth process, prior to the ARP testing yielded little gains from the use of sulfur fertilizers, potentially because the sulfur deposition vector provided sufficient baseline levels. Morrison (2009) notes research in the 1970s and 80s showed little gains to application of additional sulfur, suggesting sulfur as an input had a low marginal product. Figure B-1 illustrates a basic model for the marginal productivity of sulfur. If, after sufficient ground sulfur, additional application yields no gains, the marginal productivity of sulfur eventually zero and yields are unchanged even with additional application. After the ARP, the sulfur flow decreased due to lower deposition, pushing the marginal product up into a region of positive gains.

Appendix B1. Sulfur Deficiencies and Agricultural Productivity Before the Acid Rain Program

Agricultural science suggests both the stock and flow of sulfur are important. Crops draw soil sulfur, which needs replenishment to maintain high growth yields. Sulfur loss can also occur through water drainage and irrigation, which can be more of a problem in high drainage soils. Productive regions may start with large amounts of ground sulfur, but absent replenishment, could lose productivity over time due to sulfur deficiencies. Such deficiencies appear as stunted growth and yellowed leaves due to a lack of chlorophyll coloring (Sawyer, 2004; Stevens et al., 2002).

While there is no consensus regarding the association between the ARP and sulfur deficiencies, a 2007 North Carolina State University report from the College of Agricultural and Life Sciences, *SoilFacts: Sulfur Fertilization of North Carolina Crops*, specifically notes, "Today [sulfur] deficiency may be more of a concern due to several factors that farmers may not have considered: 1) tighter air quality standards for atmospheric emissions mean less sulfur falls onto the landscape [...]".[34] Through this channel, in the absence of adaptive behavior, ARP-associated reductions in soil-level sulfur flows may lead to reduced output.

Research from the 1970s and 1980s found little benefit to using sulfur fertilizer (Morrison, 2009). By the mid-2000s, experiments suggested a newly-found positive relationship between additional sulfur and yields for most crops studied (Camberato, Maloney and Casteel, 2012), presenting a shift from prior findings that sulfur levels were sufficiently high without additional fertilizers (Sawyer et al., 2009). In addition to the ARP, a number of industry changes could explain shifts in baseline sulfur flows. Adoption of newer fertilizer and pesticide technologies, both with decreased sulfur content compared to older versions, removed a common flow of ground sulfur over time. Field burning, now less common, was another

[34] Extension report E07-50255 , available online at `http://www.soil.ncsu.edu/publications/Soilfacts/AG-439-63W.pdf`.

potential mechanism for returning sulfur to the soil for the following season.[35]

Sulfur flow also came in the form of acid raid and general sulfuric deposition, which decreased substantially with the CAAA. As of yet, there is little work on how the CAAA, and specifically the ARP, affected agricultural through this channel. The EPA considered the effect the program had via benefits of O3 reductions, and estimated gains in crop yields between 1990 and 2010 valued at approximately $7.5 billion due to reductions in O3 (see the Appendix of EPA (1999)). In a follow-up 2008 report, the EPA further discussed theoretical effects of sulfur and oxides of nitrogen on plants, but did not expand models to the assessment of the ARP due to a lack of valuation studies linking said pollutants to the productivity of agricultural land (EPA, 2008). Extension literature began writing of a potential link between the ARP and sulfur deficiencies during the late 2000s. The following quotes (from reports by the Purdue University Department of Agronomy, the Cornell University Cooperative Extension, and North Carolina State University) show a recent move to the hypothesis of a potential link between the ARP and reduced sulfur:

> Sulfur deficiency of corn and other crops may be becoming more prevalent because less [sulphur] is deposited from the troposphere to the soil due to reductions in power plant [sulphur] emissions. ("Sulfur Deficiency in Corn", 2012)[36]
>
> Since the Clean Air Act was passed in 1970, emissions of sulfur dioxide have decreased dramatically resulting in reduced sulfur deposition in many parts of the state. ("Sulfur for Field Crops", 2007))[37]
>
> There are several factors that have resulted in the increasing number of cases where sulfur is being diagnosed as deficient or limiting in young corn plants. First, there is the fact that we have had an extended period of frequent and intense rainfall events starting in the fall of 2002 and continuing through the spring of 2003. Since sulfur is a mobile nutrient and is water soluble, this sulfur in the upper soil profile (top 2 to 4 inches) has been leached into the lower rooting zone. The reduction in sulfur emissions brought about by the clean air act means that these same rainfall events are not replacing the sulfur leached [...] ("Sulfur Deficiency Symptoms in Emerging Corn, 2003)[38]
>
> Yellow striping on corn leaves is more prevalent this year than in the past, possibly because of sulfur deficiency in the soil, says a Purdue Extension soil fertility specialist.

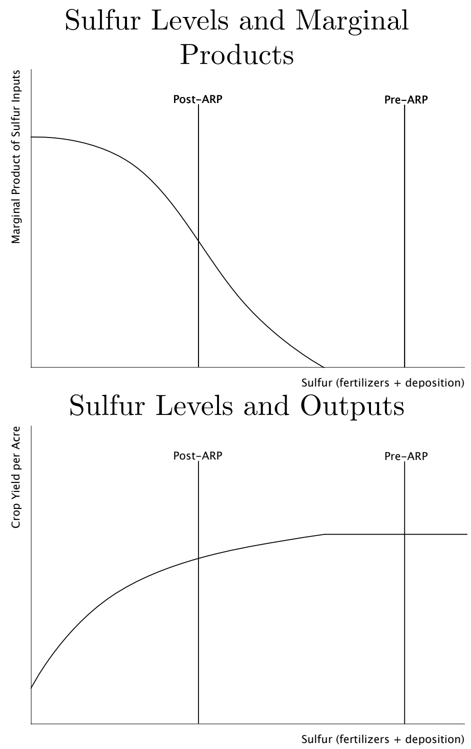
[35] "The Skinny of Sulfur", Agronomy Insider, 3/05/2015.
[36] Camberato, Maloney and Casteel (2012)
[37] Place et al. (2007)
[38] `http://www.ces.ncsu.edu/plymouth/cropsci/docs/sulfur.html`.

> Yellow, green-yellow or yellow-white striping on the leaves of corn plants can indicate a variety of nutrient deficiencies or other damage, said Jim Camberato. Analysis of soil and tissue samples shows that many cases of striping are due to sulfur deficiency.
>
> "We used to get quite a bit of sulfur from rainfall. The power plants would burn coal that had sulfur in it, so sulfur would be deposited in rainfall or absorbed directly from the air by the soil," Camberato said. "But over the last 20-25 years, these emissions have been reduced, so perhaps now the amounts in rainfall and atmosphere deposition are low enough that plants are not getting enough that way anymore." ("Soil fertility specialist says yellow striping in corn may be linked to sulfur deficiency", 2016)

Appendix B2. Trends in Agriculture Around the Time of the ARP

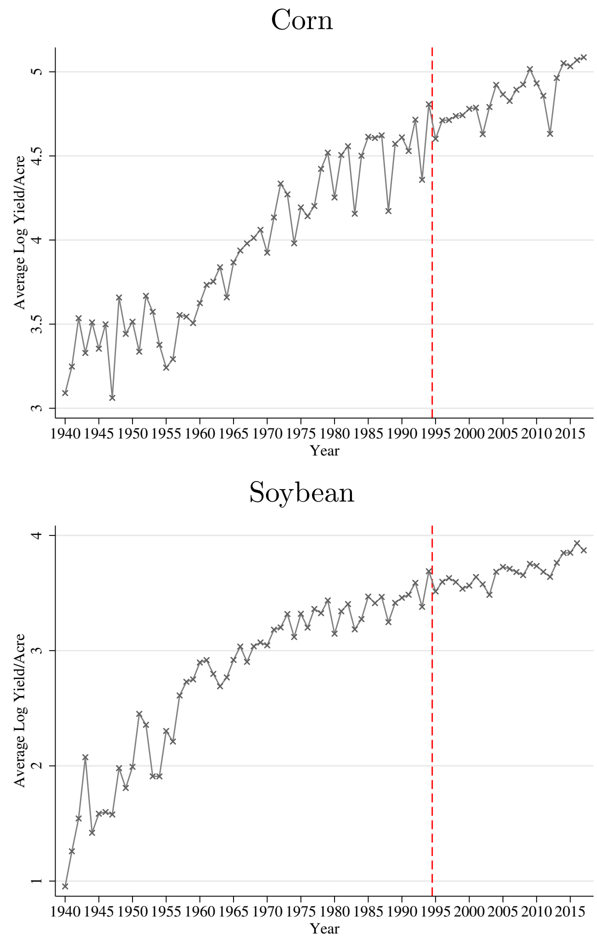
Figure B-2 shows the long-run trend in both corn and soy output across time — in both cases, yields per acre have been regularly increasing. Around the time of the ARP, productivity and prices were volatile both nationally and globally. Figure B-3 shows the global price of corn and soybean across time (in 2015 dollars). Weather drove supply losses and price spikes in the 1990s, as did sharp changes in demand on global markets. China left the corn export market in 1994, leading to speculative price increases. By early 2000, prices had returned to 1994 levels (Stevens, 1999). Our research design controls for these confounders to the extent they affect all areas in a similar fashion over time. There was a drought in 1991 and a combination of freezes, unusual rainfall, a Midwestern flood, a drought, and insects in 1993 (Kliesen, 1994; Lott, 1994). A high-production year followed in 1994, but yields fell again in 1995 due to heat waves and late planting seasons. Starting in 1996, yields stabilized, followed by a number of consistently high-yield years (Stevens, 1999).

Figure B-1. Potential Model of Sulfur Inputs



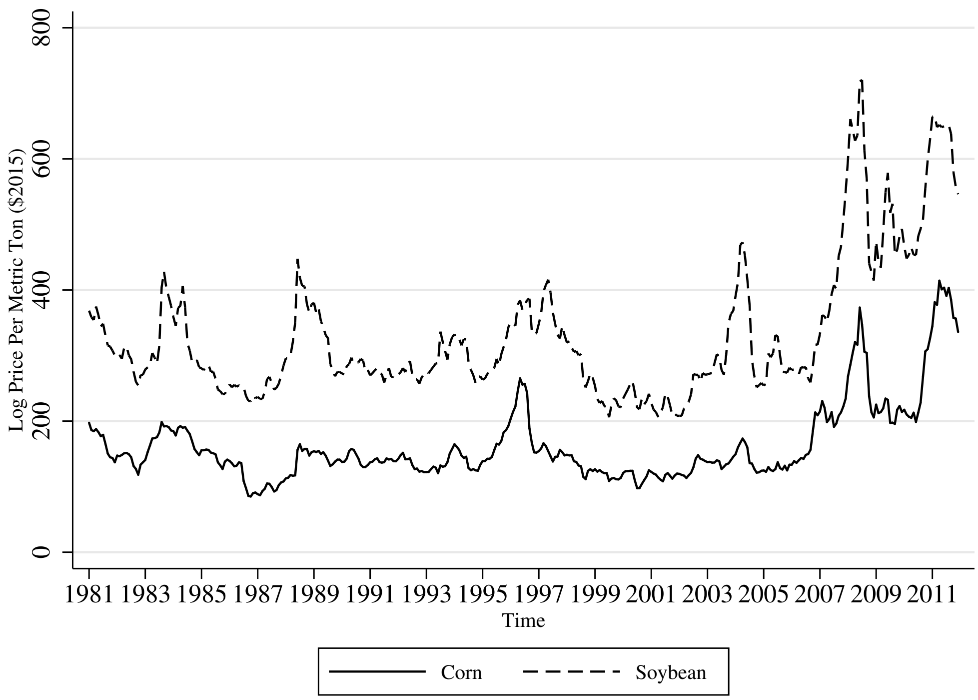
Note: Panel A shows potential relationship between the marginal product of sulfur inputs and sulfur levels from both applied fertilizers and provision via deposition. Panel B shows potential relationship between the output and sulfur levels from both applied fertilizers and provision via deposition. "Pre-ARP" and "Post-ARP" present potential levels corresponding with pre- and post-regulatory soil sulfur levels in a field.

Figure B-2. Historical Log Annual Crop Yield



Note: Historic crop data are in log yield per planted acre. Data come from the U.S. Department of Agriculture's National Agricultural Statistical Service.

FIGURE B-3. HISTORICAL GLOBAL PRICES FOR CORN AND SOY



Note: Global price data come from the International Monetary Fund historic primary commodity data and are inflated to 2015 dollars.

Cost Calculations

Our primary independent variable is airborne sulfates as predicted using the APEEP atmospheric transport model. This includes both SO4 and (NH4)2SO4. To convert this to a measure of ground deposition of SO4, we use data from the EPA Clean Air Markets Division, Clean Air Status and Trends Network (CASTNET) Total Deposition data. We merge ground deposition monitors to air sulfate measures using monitor county information. We then run the following regression, which includes year fixed effects, county fixed effects, and a county-specific linear year trend:

$$SO4 = \beta sulfates + \delta_{year} + \lambda^1_{county} + \lambda^2_{county} Xtrend.$$

We find $\beta = 0.6835$, which implies each additional $\mu g/m^3$ of airborne sulfates correlates with an additional 0.68 pounds of ground SO4 deposition.

To convert this reduced SO4 to reduced crop yields, we use data on how much sulfur each crop removes from the soil — our assumption is that removing S deposition is equivalent to preventing crop take-up of the required sulfur. The Purdue University Soil Fertility Update (July 11, 2017) notes that soybean removes about 0.17 pounds of sulfur per bushels of grain, and corn grain is around 0.05 pounds per bushel. This suggests that each $\mu g/m^3$ of airborne sulfates lost reduces yields per acre by:

$$0.68/0.05 = 13.6 \text{ corn bushels per acre}$$
$$0.68/0.17 = 4 \text{ soybean bushels per acre}$$

To calculate replacement costs, we use data on fertilizer use and price from the Economic Research Service in the United States Department of Agriculture. While they do not have direct data on pure sulfur costs, they do track ammonium sulfate, which is 24% sulfur. We assume to replace a pound of sulfur, producers must purchase 4.17 (1/0.24) pounds of ammonium sulfate. To find average cost per county to replace lost sulfur, we multiply the price of ammonium sulfate by the lost sulfur per acre by the number of acres for each relevant crop. This provides us with an approximate county-level measure of the replacement cost of lost sulfur.

To calculate lost crop receipts, we first repeat our primary reduced form regressions using levels of corn and soybean yields per acre. We find a per-unit reduction of 3.99 corn bushels per acre and 1.61 soybean bushels per acre. As pricing data are often in tons, we convert our bushel measure to tons: data suggest approximately 40 bushels per ton for corn and 37 bushels per ton for soybean. This implies the average county lost approximately 0.04 tons of corn yield per acre and 0.02 tons of soybean yield per acre. To obtain total lost revenues, we multiply these values by the price per ton in a given year and the number of acres in a given county-year.