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Effects of Acid Rain Regulations on Production of Eastern Coals of Varying Sulfur Content

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Abstract: We analyze the effects of the EPA's Acid Rain Program on county-level production of coals of varying sulfur content in the Appalachian and Illinois basins, controlling for Powder River Basin production, proximity of power plants to mines, and scrubber installation. Using a thirty-year panel data set, we find that during the Acid Rain Program coal sulfur content positively affected mine closure and negatively affected production in most coal-producing counties, with the greatest effect from 1995-2000. Estimated effects of power plant flue gas desulfurization equipment installation are substantial, and depend on coal sulfur content, scrubber unit size, and distance from the mines. The estimated elasticity of coal mine output to sulfur allowance price varies widely by coal sulfur content and is negative only for mines producing coals above the 77th percentile in sulfur content. Our results complement previous studies of regulatory effectiveness, limiting the degree to which reductions in acid rain may be attributed to market rather than regulatory factors.

1. Introduction

Over the past thirty years coal's share of U.S. electric energy generation declined from nearly 57% to less than 40%, with profound but complex implications for coal production. Electric power plants are the coal industry's principal customers, accounting for 93% of all coal consumption in the United States in 2013 (EIA 2014d). As figure 1 illustrates, Appalachian coal production has declined steadily since 1995, when Phase 1 of the EPA's Acid Rain Program began. Illinois Basin coal production (encompassing counties in Indiana, Illinois, and western Kentucky) declined slowly but steadily for thirty years. This decline in coal's electricity market share has coincided with the imposition of stricter air-quality regulations, particularly on sulfur dioxide (SO_2) emissions from coal-fired power plants. Many residents of Eastern coal-producing states consequently believe that the U.S. Environmental Protection Agency has been waging a "war on coal," though some academic researchers attribute the decline in Eastern coal production to technical rather than regulatory factors.

[Insert figure 1 about here]

The effects of the air quality regulations on coal production nationwide has not been uniformly negative. While overall Eastern coal production declined by 22% between 1990 and 2008, production of low-sulfur Western coal increased by 70% over the same period (EIA 2014a). Clean air regulations may have encouraged the increasing penetration of low-sulfur Western coals into Eastern markets, but technological and market forces have played their part as well. Ellerman and Montero (1998), observing that many unregulated power plants reduced their emissions voluntarily by switching to Wyoming coal between 1985 and 1993, concluded that economic forces were much more important than clean air regulations in motivating the move to Western coal.

Ellerman and Montero's study influenced subsequent researchers, who have found their conclusions persuasive in part because the resource and productivity differences between the Eastern and Western basins are so large. (See the critical survey of the issue in Schmalansee and Stavins, 2013.) Wyoming's Powder River Basin (PRB) coal mines are nearly ten times as productive as Appalachian mines on a tonnage basis (EIA 2014a), and their production costs are much lower. Furthermore, the cost of long-haul rail transport fell substantially after 1980 due to deregulation and technological innovation in the railroads. Operators of power plants east of the Mississippi adapted their plants to burn PRB coal more easily than many people had thought possible. In recent years, market forces have continued to favor cleaner fuels, as shale gas production has lowered natural gas prices, dramatically increased gas production, and further discouraged use of coal to produce electricity. The question of whether (and how much) to blame market forces versus regulation for the decline of Eastern coal production is still open.

The previous literature has examined the effect of clean air regulations using data on power plant emissions, and on the eastward movement of Powder River Basin coal. We take a different approach, concentrating instead on county-level coal production within Eastern coal basins. Specifically, we examine county-level data on coal production within the Illinois and Appalachian basins from 1983-2012, taking into account variation in both sulfur content of coal mines in each county and installation of emissions control equipment in nearby power plants. This county-level "micro" approach has some advantages over studies such as Ellerman and Montero (1998) that focused on "macro" trends of Western versus Eastern coal production. Differences in productivity and transport cost are less pronounced within the Illinois and Appalachian basins than between the Eastern basins and the Powder River Basin, and within the Eastern basins these production cost differences do not generally favor the coals of lower sulfur content. Consequently, it is easier to identify the effect of clean air regulations on coal production, as fewer confounding factors affect the analysis.

If the shift to low-sulfur coal (and consequent reduction in acidic precipitation) was primarily driven by the lower cost of Western coals rather than Clean Air Act regulations, we would expect little variation in impact of regulations on production of Eastern coals of different sulfur content. On the contrary, our results indicate that clean air regulations had a significant differential impact on coal mining in the Appalachian and Illinois basins, depending on the coal's sulfur content. We present evidence that sulfur content positively affected mine closure in all regulatory phases after 1995. We also find evidence of a greater impact on production of coals of higher sulfur content over the entire period, with the greatest effect occurring from 1995-2000. We estimate that clean air regulations were associated with reduced output in at least 86% of coal-producing counties in both Eastern basins during all regulatory periods. Estimated effects of power plant flue gas desulfurization equipment installation on coal production are very substantial, particularly in the Ohio River Valley, and depend on coal sulfur content, scrubber unit size, and distance from the mines. Finally, in separate estimates examining the relationship between coal mine output and the price of sulfur emissions allowances, and we find that the cross-price elasticity ranges from -0.5 to +1.0 depending on sulfur content, with a negative elasticity appearing only for counties whose mines are above the 77th percentile in sulfur content.

2. Background

Congress passed Clean Air Act legislation in 1963 and 1970, and added significant amendments to the 1970 Clean Air Act in 1977 and 1990. We focus on the consequences of the 1990 amendments, specifically the EPA's implementation of those amendments in its Acid Rain Program (ARP) and successors. Our analysis distinguishes three distinct regulatory periods: Phase 1 (1995-1999), Phase 2 (2000-2007), and the period we term "Post-2008," extending from 2009 to the end of our data set in 2012. During Phase 1, the EPA required reduced SO_2 emissions from fossil electric generating units in 110 power plants, mostly older units, coal-fired, and lacking in pollution control equipment (Lange and Bellas, 2007). In Phase 2, the EPA widened its reach and tightened its standards, implementing a national emissions cap affecting 3200 units in nearly all US fossil-fuels plants (see Ellerman et al., 2000).

Accompanying the emissions caps was an SO_2 emissions trading program, authorized under Title IV of the 1990 Clean Air Act Amendments, as described by Schmalensee and Stavins (2013). This trading program functioned effectively from 1995 through 2007, but it declined in relevance after the D.C. Circuit Court's ruling in *State of North Carolina vs. EPA* (2008), which vacated the EPA's Clean Air Interstate Rule (CAIR) and led to the formulation of the current Cross-State Air Pollution Rule (CSAPR). During this Post-2008 period, regulators' increasing reliance on state-level emissions caps and command-and-control regulatory methods to meet National Ambient Air Quality Standards caused average allowance prices to plunge from almost \$400 in 2008, to \$70 in 2009, to under \$3 by 2011 (EIA, 2011). Technically, generators must still obtain allowances in order to emit $SO_{2,}$ but this requirement is non-binding, as available allowances provide for more emissions than are allowed under other regulations.

To comply with acid rain regulations, electric utilities have employed two principal strategies: fuel-switching and installing emissions scrubber units. Fuel-switching involves substitution away from coals containing high amounts of sulfur and toward coals with lower sulfur content and natural gas. Scrubbers (also known as flue-gas desulfurization, or FGD, equipment) typically remove about 90% of all sulfur dioxide from a plant's emissions, allowing it to comply with regulations regardless of the sulfur content of the fuel it burns.

As of 2012 there were 335 scrubber units in operation (US EIA 2014c), with an additional 67 units planned, retired, or standby. Figure 2 indicates the dates of installation of FGD units, clearly showing their relationship to major Clean Air Act regulatory initiatives in 1977, 1990-1995, and 2010. Scrubbers are expensive and highly capital-intensive, and therefore financially risky for their owners, but they are politically popular because of their perceived ability to protect high-sulfur mining jobs, as noted by Hoag (1995), among others. Lile and Burtraw (1998) document actions taken by state legislatures and regulators to encourage scrubber installation following passage of the 1990 Clean Air Act Amendments. In particular, the high-sulfur coal mining states of Tennessee, West Virginia, Kentucky, Ohio, Indiana, and Illinois passed laws and crafted regulations designed to allow early and more certain recovery of scrubber costs, with the (usually explicit) intent to mitigate the effects of the Acid Rain Program on local coal mines. Cicala (2015) provides evidence that coal-fired power plants subject to rate-of-return regulation were more likely to install scrubbers than divested plants facing a competitive wholesale electric power market. Frey (2013) found that large plants that can take advantage of economies of scale are more likely to install scrubbers, but her empirical results confirm that federal and state air quality regulations were the most important factor driving the wide adoption of scrubber technology since 1978.

[Insert Figure 2 about here]

Over this period, these regulatory attempts to encourage scrubber installation faced increasingly strong and contrary market headwinds favoring fuel switching. Productivity in low-sulfur coal mines increased after 1980, most obviously in the Powder River Basin (PRB) of Wyoming, and low-sulfur coal prices fell. Carlson et al. (2000) provide evidence that these changes, plus technological advances in equipment and methods for burning low-sulfur coals, halved marginal abatement costs from fuel-switching between 1985 and 2000. Technological improvements and deregulation in the rail transport system also favored fuel-switching over FGD installation, as documented by Schmalansee and Stavins (2013) and Ellerman and Montero (1998), among others. Busse and Keohane (2007) provide evidence that railroads used monopoly power to capture some of the rents created from increased PRB coal mining productivity over this period. Gerking and Hamilton (2009) provide evidence that railroads are strategic price discriminators, implying that, despite railroad monopoly power, PRB coal reaches as wide a geographic area as it would have in a competitive rail market.

This literature on fuel-switching in coal-fired power plants has until now focused on the dramatic interregional substitution of low-sulfur Western coal for Eastern coals of higher sulfur content. But Illinois and especially Appalachian coals exhibit considerable sub-regional variation in sulfur content as well, and the differential effects of SO_2 regulations on these various regions within the Eastern coalfields is much less well studied. Hoag (1995) used state-level data and a simple regression model to examine the differential impacts of the 1970 and 1977 Clean Air Act legislation, with mixed and marginally significant results. Hoag and Reed (2002) apparently aggregated quarterly county-level employment data to perform time-series regressions that indicate significant negative employment impacts of the 1977 Clean Air Act legislation on mining of high-sulfur West Kentucky coal, while finding no significant effects on East Kentucky coal. Recently, Betz et al. (2015) assumed a negative relationship between Appalachian coal sulfur content and mining intensity to justify the use of the former as an econometric instrument for the latter. The current paper contributes to this literature by using county-level panel data to quantify local variation in coal production associated with air quality policy changes, taking into account the sulfur content of coal deposits, the distance between mines and power plants, and the use of scrubbers.

3. Data

Historical coal mine production data (1983-2012) are available from the Energy Information Administration (US EIA 2014a). We collected detailed mine-level data from states in the Appalachian (Pennsylvania, West Virginia, Ohio, eastern Kentucky, Maryland, Tennessee, Georgia) and Illinois (Illinois, Indiana, western Kentucky) basins. Because the individual mines in our data set produced for an average of only 4.82 years each, we aggregated our data to the county level. Sulfur (percent by weight) and heat content (mmBtu/ton) data come from the USGS Coal Quality database, which contains over 13,000 samples of coal and associated rocks (Bragg et al, 1998). Using ArcGIS Kriging, we interpolated a raster from these borehole points. ArcGIS's 'Extract Values to Points' tool produces county-level estimates of sulfur content, from which we calculated figures for sulfur content in units of pounds per million Btu. The geographical distribution of sulfur content in the Appalachian and Illinois coalfields is shown in figure 3. Higher sulfur content is generally found in coals throughout the Illinois Basin and Ohio, along the Ohio River, and to a somewhat lesser extent in parts of Pennsylvania, northern West Virginia, Tennessee, and Alabama.

[Insert Figure 3 about here]

We distinguish four time periods in our analysis: Pre-Regulation[1] (1983-1994), Phase 1 (1995-1999), Phase 2 (2000-2008), and the 'Post-2008' period (2009-2012). Historical coal price data comes from the EIA, and natural gas price data come from US Bureau of Labor Statistics' PPI index. The PPI is used instead of other natural gas prices such as Henry Hub because it is an index of different U.S. natural gas prices, it has a longer history than other prices, and because it does not need to be deflated. Coal prices come from the EIA's data base of historical coal prices. The price of SO_2 emissions permits come from the annual EPA allowance auction results (US EPA 2014).

We include a variable measuring the amount of Powder River Basin coal production in our regressions. This variable is highly collinear with a simple time trend, as a glance at figure 1 will confirm. If included alone in our regressions, either the PRB or time trend variable generates a negative and significant coefficient. Neither is statistically significant when both are included, and results for other variables are not much affected by the choice. Because most of the literature (e.g., Ellerman and Montero, 1998; Gerking and Hamilton, 2008) concludes that growth in PRB production drove much of the reduction in Eastern coal production, and that PRB market penetration was driven in turn by high PRB productivity and declining rail transport rates, and because each Eastern county's production is small relative to the

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1 There were clean-air regulations in place prior to 1995, but these lacked the focus on sulfur emissions of the EPA's Acid Rain Program, Phase I of which began in 1995.

market for PRB coal, we chose to include the PRB variable as an exogenous variable in lieu of a time trend. Conclusions about the causal nature of this variable from our regressions, however, should be made with caution. The policy dummy variables also control for time trends to some extent, as discussed below.

3.1 Megawatt Demand and Geographic Distance

Demand for coal is influenced by the geographic distance between the purchasing plant and the producing mine as well as the capacity of the purchasing plant. Transportation costs increase with distance, so other things equal, a plant will demand more coal from nearby mines. Plant capacity is also heterogeneous, which will also affect demand.

The EIA (Form 923, Schedule 5) publishes mine-plant contract information (US EIA 2014c), including specific tonnage, BTU, ash, and sulfur content for each contract. While the contract data are only available from 2008 onwards, they do contain useful information that characterize the relationships between mines and plants. In the Illinois and Appalachian basins, mines generally have multiple contracts with a single plant, with varying coal characteristics. From 2008-2013, 16% of mines sold to only one plant. On average, each mine served 15.99 power plants, though the distribution of this variable is highly skewed, and a few mines served more than 100 plants. Eastern coal mines that have one or more contracts to serve a given power plant are located within 350 miles of that plant in about 89% of all cases.

Each mine faces a demand curve determined by the geographic proximity of coal-fired power plants and the demand for electricity production from those plants. We therefore constructed a county-specific coal demand variable that takes both power plant capacity and distance into account. Using rail network data, we calculated the rail distance from every regional coal-fired power plant to every regional coal-producing county. In counties where the location of the mines is unknown, we calculated a simple geographic center. In counties where mine location is known, we used a mean-center calculation based on existing mine locations within the county. In describing demand from individual power plants, we had the choice of using its energy production measured in megawatt-hours (MWh), or potential energy production based on megawatts (MW) of plant nameplate capacity. We chose not to use the former measure because of the endogenous nature of energy production. However, a large, new, and efficient plant is more likely to be dispatched than an older, smaller, and less efficient one, and hence will demand more coal, so we created a weight for each unit's capacity by regressing its capacity factor on its age and capacity:

$$CF_i = \beta_0 + \beta_1 * A_i + \beta_2 * C_i + \varepsilon_{\mathrm{i},} \tag{1}$$

Where:

CF_i = Plant i's Capacity Factor
A_i = Plant i's Age
C_i = Plant i's Capacity

We then characterized each unit by its capacity, weighted by its predicted capacity factor, which we calculated using the estimated regression coefficients shown in table 1 multiplied by its age and size.

[Insert Table 1 about here]

To gauge the importance of scrubbers in determining a plant's demand for higher-sulfur coal, we developed two separate demand variables, one for scrubbed and a separate one for non-scrubbed capacity, using the following equation:

$$MWDemand_{its} = \sum WeightedCapacity_{its}/Raildistance_i \quad (2)$$

where the summation is over time, and

i = specific county
t = year
s = scrubber installation
WeightedCapacity = generation unit nameplate capacity * predicted capacity factor
Raildistance = distance between generation unit and mine along rail network.

In a regression on county coal production, the expected sign of a county's MW Demand coefficient is positive: both increasing capacity and decreasing transport distance should increase the marketability of the produced coal. Table 2 displays summary statistics for variables used in the estimation.

[Insert Table 2 about here]

4. Empirical Model

With mine production aggregated to the county level, 18% of the county-years in this study had no production. Because the decision to produce and the quantity of production are related, we employ a two-stage Heckman sample selection model.

4.1 Probit

The first stage of the Heckman selection model uses a probit regression to estimate the probability p_{it} that a county's coal mines produce in a given year. The probit regressors include the county's sulfur content interacted with the policy time period, total MW/distance for both scrubbed and non-scrubbed plants, and total PRB production. Because natural gas can be used as a substitute for coal in electricity production, the relative price ratio of natural gas to a national average of coal prices is also included[2].

[Insert Table 3 here]

2 Results are insensitive to alternative measures of coal prices: the correlation between the series we use and any other bituminous price series is .99 or greater.

Results shown in Table 3 indicate strong relationship between the probability of mine shutdowns and sulfur content. To illustrate, if all other variables are held at mean levels, a one standard deviation increase of sulfur content reduces the probability of producing in the Post-2008 period by an estimated 14%. The negative and significant coefficient on PRB production is consistent with fuel-switching from Eastern to Western coals. The significant and positive coefficient on the scrubbed MW Demand variable indicates that scrubbers in coal plant boilers may have reduced the incidence of mine closures, as was intended by the state legislators and regulators who formulated policies to encourage scrubber installation.

4.2 Estimation of Coal Demand

In the second stage of the Heckman selection model, we regressed the log of coal productopm in county i in year t on policy variables, our measure of distance-attenuated megawatt demand, price, and the inverse Mills ratio generated from the probit estimation. These relationships are modeled as:

$$\begin{aligned}\ln(y_{it}) = {} & \beta_0 + \beta_1(P1_t) + \beta_2(P2_t) + \beta_3(PC_t) + \beta_4(SC_i * P1_t) + \beta_5(SC_i * P2_t) + \\ & \beta_6(SC_i * PC_t) + \beta_7(TotMWD_{it}) + \beta_8(SC_i * ScbMWD_{it} * P1_t) + \beta_9(SC_i * ScbMWD_{it} * \\ & P2_t) + \beta_9(SC_i * ScbMWD_{it} * PC_t) + \beta_{10}(\ln(TotPRB_t)) + \beta_{11}(PriceRatio_t) + u_{it}\end{aligned} \tag{3}$$

where

y_{it}	Logged production (tons) of mine county *i* in year *t* in tons
SC_i	Sulfur content (lbs/mmBtu) at mine county
$P1_t$	1/0 variable, 1 for the period in which ARP Phase 1 was in place (1995-1999)
$P2_t$	1/0 variable, 1 for the period in which ARP Phase 2 was in place (2000-2008)
PC_t	1/0 variable, 1 for the period after the 2008 US Circuit Court ruling (2009-2012)
$TotMWD_{it}$	Total MW Demand in year *t* / Miles from mine county *i*
$ScbMWD_{it}$	Total FGD-installed MW Demand in year *t* / Miles from mine county *i*
$\ln(TotPRB_t)$	Logged total PRB coal production
$PriceRatio_t$	Natural gas/coal price ratio

Regression results reported in table 4 show statistically significant relationships of the expected signs between coal production and all but one of the explanatory variables.[3] The coefficient on Powder River Basin production is both negative and significant, indicating a nearly one-for-one substitution of PRB production for study-area coal production. The inverse Mills ratio coefficient is positive and significant, indicating the expected positive relationship between mine activity and output. Perhaps surprisingly, the addition of county-level fixed effects causes very little change in coefficients of any variables except distance-adjusted MW Demand. This result suggests that our MW-Demand variable is effective in capturing relevant county-specific effects. The lack of significance of the MW-Demand variable in the

3 An alternative specification using a Tobit model produced qualitatively similar results.

fixed-effects results may simply reflect the tendency for power plants to be located near the coalfields, a tendency that is largely picked up by the county fixed effects.

[Insert Table 4 about here]

Although the three policy period binary variables have positive and significant coefficients, interacting sulfur content with the policy variables yields negative and significant coefficients, so the estimated net effect of sulfur regulations on coal production was negative for most counties for most regulatory time periods, as shown in figure 4. Colors in figure 4 correspond to the value $\beta_1(P1_t) + \beta_2(P2_t) + \beta_3(PC_t) + \beta_4(SC_i * P1_t) + \beta_5(SC_i * P2_t) + \beta_6(SC_i * PC_t)$, a log difference expressed as a percentage. This number may be interpreted as a "pure sulfur regulation effect," net of the effects of both scrubber installation and Powder River Basin coal production. In Phase 1 ($P1$=1, $P2$=PC=0), all 188 coal-producing counties show an estimated decrease in coal production associated with the policy change. The estimated effect on coal production is negative in Phase 2 ($P2$=1, $P1$=PC=0) for the 168 counties (89%) whose coals contain at least 0.78 lbs/mmBtu of sulfur; in the Post-2008 period (PC=1) the 161 counties (86%) whose coals contain more than 0.93 lbs/mmBtu are estimated to have lost production as a consequence of the regulations. The biggest "losers" from regulations in each case are concentrated along the Ohio River and in the Illinois Basin, while the "winners" are in southeastern West Virginia, western Virginia, and eastern Pennsylvania.

The installation of scrubbers in coal plants is also associated with increases in high-sulfur coal production, as indicated by the positive and significant coefficient on the interaction variable of scrubbed capacity, regulatory regime, and sulfur content. Thus, the higher the sulfur content in a county's coals, the larger the effect of scrubbed capacity on coal production, and the more scrubbed capacity in a mine's neighborhood, the greater the marginal ameliorative effect on its high-sulfur coal production loss. The magnitude of the scrubber effect is largest in Phase 1, when only the highest emitters were regulated and the technology of fuel-switching was less well-developed. The geographic impact of scrubbers is illustrated in figure 5, in which the shading indicates the value $\beta_8(SC_i * ScbMWD_{it} * P1_t) + \beta_9(SC_i * ScbMWD_{it} * P2_t) + \beta_9(SC_i * ScbMWD_{it} * PC_t)$, a log difference expressed as a percentage. Effects are large, and are near 100% in the Ohio River Valley, where coals tend to be high in sulfur content and both the number and size of installed scrubber units are high.

Figure 6 combines the two effects shown in figures 4 and 5, and colors correspond to values of $\beta_1(P1_t) + \beta_2(P2_t) + \beta_3(PC_t) + \beta_4(SC_i * P1_t) + \beta_5(SC_i * P2_t) + \beta_6(SC_i * PC_t) + \beta_7(TotMWD_{it}) + \beta_8(SC_i * ScbMWD_{it} * P1_t) + \beta_9(SC_i * ScbMWD_{it} * P2_t) + \beta_9(SC_i * ScbMWD_{it} * PC_t)$, again expressed as a percentage change. Overall, compared to the "pure sulfur effects" shown in figure 4, the introduction of scrubbers increases production in all counties, particularly for Phase 1, and for counties in Ohio, western Kentucky, and Alabama. These effects are less pronounced for later phases of regulation.

[Insert Figures 4-7 about here]

5. Sulfur Price Elasticity

We also examine the relationship between allowance permit pricing and coal production. Twenty years' worth of allowance trading data (1993-2012) are available; however, we examine effects only in the years 1993-2008, as allowance availability became a non-binding constraint on power plant operations after 2008. To measure the sulfur price elasticity of coal production, we regress logged production values on allowance prices and relevant policy and other control variables, including county fixed effects.

$$\ln(y_{it}) = \beta_0 + \beta_1(AP_t) + \beta_2(SC_i * AP_t) + \beta_3(P1_t) + \beta_4(P2_t) + \beta_5(SC_i * P1_t) + \beta_6(SC_i * P2_t) + \beta_7(TotMWD_{it}) + \beta_8(SC_i * ScbMWD_{it} * P1_t) + \beta_9(SC_i * ScbMWD_{it} * P2_t) + \beta_{10}(PriceRatio_t) + \beta_{11}(\ln(TotPRB_t)) + u_{it}, \quad (4)$$

where:

y_{it}	Logged production (tons) of mine county *i* in year *t* in tons
AP_t	Sulfur Allowance Prices in year *t*
SC_i	Sulfur content (lbs/mmBtu) at mine county *i*
$P1_t$	1/0 variable, 1 for years in which ARP Phase 1 was in place (1995-1999)
$P2_t$	1/0 variable, 1 for years in which ARP Phase 2 was in place (2000-2008)
$TotMWD_{it}$	Total MW Demand in year *t* / Miles from mine county *i*
$ScbMWD_{it}$	Total FGD-installed MW Demand in year *t* / Miles from mine county *i*
$PriceRatio_t$	Natural gas/coal price ratio
$\ln(TotPRB_t)$	Logged total PRB coal production.

Fixed-effects regression results are presented in table 5, along with pooled OLS results for comparison. During the modeled years of sulfur permit trading (1993-2008), the elasticity should depend on the sulfur content of the county's coals. The allowance price coefficient β_1 may be interpreted as the sulfur allowance price elasticity of production for coals with zero sulfur content. Its estimate is positive, significant, and near one in the fixed-effects model, indicating that allowances and low-sulfur coal are substitutes. The estimated coefficient β_2 is negative for the interaction-term between sulfur content and allowance price, indicating that the elasticity of substitution between low-sulfur coal and allowance permits declines with increasing sulfur content, or in other words, that coal sulfur content and SO_2 allowance permits are complements. Using results from the county-level fixed effects model, the overall allowance-price elasticity of coal production is negative for the 43 of 188 (23%) counties whose coals contain more than 2.45 lb/mmBtu of sulfur. Within our data set, the allowance price elasticity estimates range from -1.0 to +0.5 for the highest and lowest sulfur-content counties respectively.

[Insert Table 5 about here]

This relatively high sulfur threshold requirement for complementarity is perhaps surprising. However, much of the discussion of the Acid Rain Program in the literature (see especially Bohi and Burtraw, 1996, and Schmalensee and Stavins 2013) emphasizes that the sulfur allowance market was affected by many factors that tended to divorce it from contemporaneous coal production. Many allowances were purchased and banked for later use, and the price spike of 2006 was largely attributed to disruptions in rail transport from the PRB region, which would have increased the demand for Eastern coal of all types.

6. Conclusions

It is difficult to disentangle the effects of clean air policy from the effects of technological change and market competition, but doing so is of great importance for policy evaluation. Effective environmental regulation will usually be destructive to polluting industries. The perception of regulatory effectiveness matters for determining the political environment in which regulatory policy is made, because an effective regulation is worth fighting about, both for those concerned with environmental quality and for those whose livelihood depends on the polluting industries. If we believe that market forces rather than environmental regulation will determine the future state of the environment then we have little incentive to maintain the current regulatory structure.

In this paper, we have presented evidence of the effectiveness of environmental regulation in changing patterns of production in the Eastern coal industry, an industry that produces a product that is undoubtedly both useful and environmentally harmful. We use a fixed-effects model that corrects for sample selectivity bias on county-level panel data for the period 1983-2012. We control for market forces in the form of natural gas prices (which we find have little or no effect over our period of study), and Powder River Basin coal production (which has a strongly negative relationship to Eastern coal production). Taking advantage of cross-sectional variation in sulfur content within Eastern coalfields and variation in mine proximity to coal-fired power plants, we quantify various aspects of the negative relationship between the sulfur content of Eastern coals and their production during each of the three phases of sulfur dioxide regulation.

We find evidence that, after controlling for PRB production and gas prices, coal production in all counties in the Appalachian and Illinois basins was harmed during Phase 1 of the EPA's Acid Rain Program, though as many as 14% of the counties may have seen an increase in production as a result of later phases of regulation. In a separate regression, we find that (from 1995 to 2008) increases in allowance prices were associated with reduced production for about 23% of the highest-sulfur coals, but are associated with positive or zero effects for the remainder. We also find strong evidence that installing flue gas scrubbers in power plants effectively encourages production from high-sulfur mines, as was the intent of coal-state regulators and legislators who implemented policies designed to encourage their installation.

The study has limitations. We make no serious attempt to estimate the causal effect of PRB coal production on Eastern coal production, as our PRB production variable is highly trended and is therefore collinear with other trended variables, such as technological change and economic growth. The regulatory periods we pick are based on landmark changes in regulation, but their effects may have been anticipated and they may have lingered, so we draw no conclusions about the specific effects of specific policies. Although our study takes into account the spatial structure of county-level coal markets, more sophisticated modeling methods might be employed. We also make no attempt to explore the local employment or income effects of the estimated changes in production, leaving such considerations to a future study.

Despite these limitations, these results fill a gap in the policy literature. While many previous studies have alluded to changes in coal production associated with Clean Air Act regulations, this is the first, and the most fine-grained, study attempting to quantify these effects on coal production while controlling for some market forces. We are entering an era in which new market forces, most obviously the increase in shale gas and oil production, and new regulations related to climate change are reshaping the energy industries of North America and the world. A continuing effort is needed to improve our understanding of the effects of those regulations and market forces, for good and ill, on industrial structure and personal well-being at both the local and global level.

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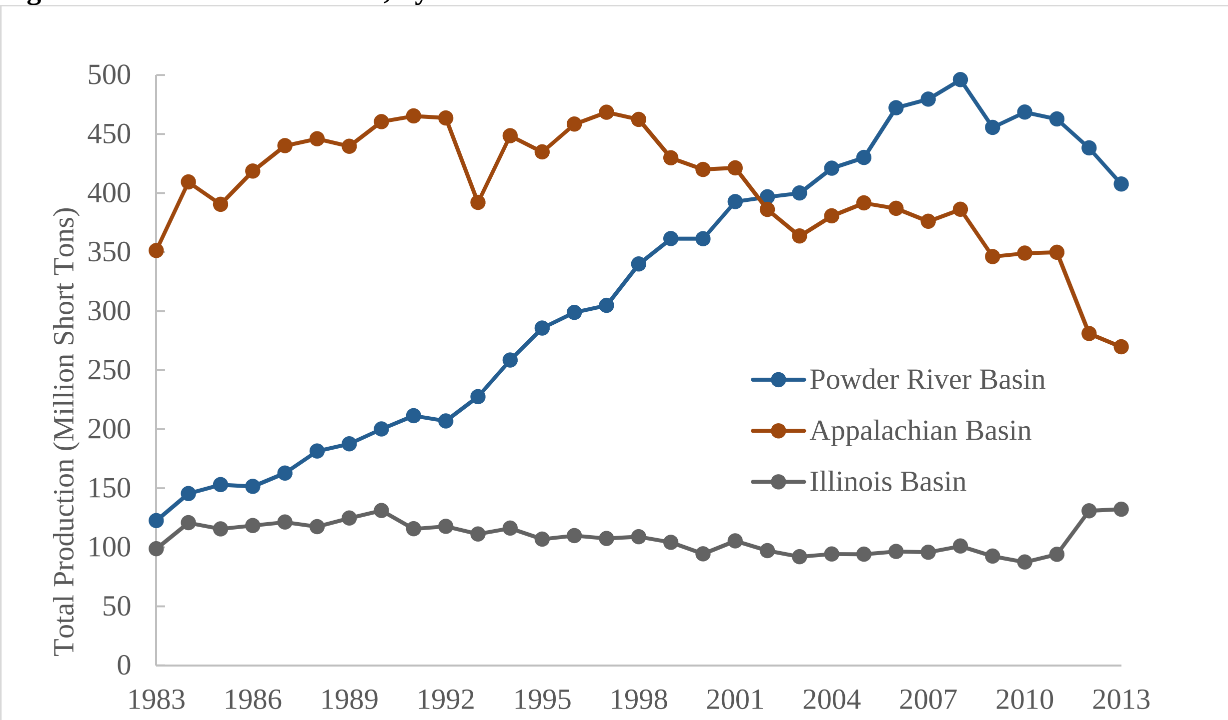
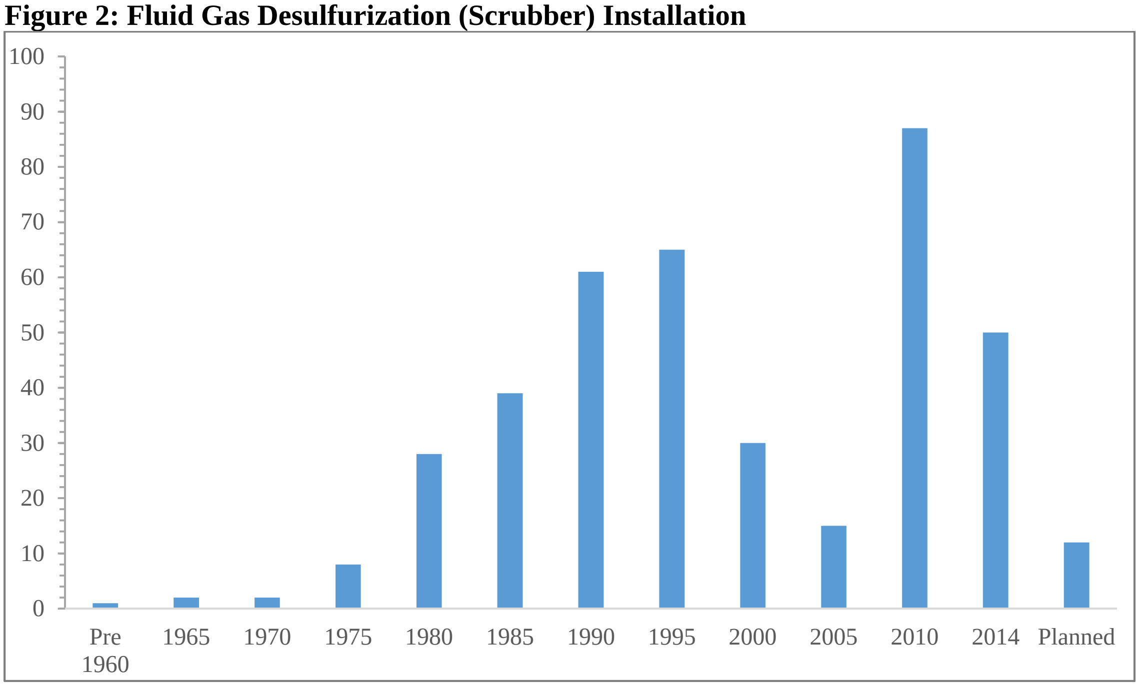
Tables and Figures

Figure 1: Total Coal Produced, by Basin:



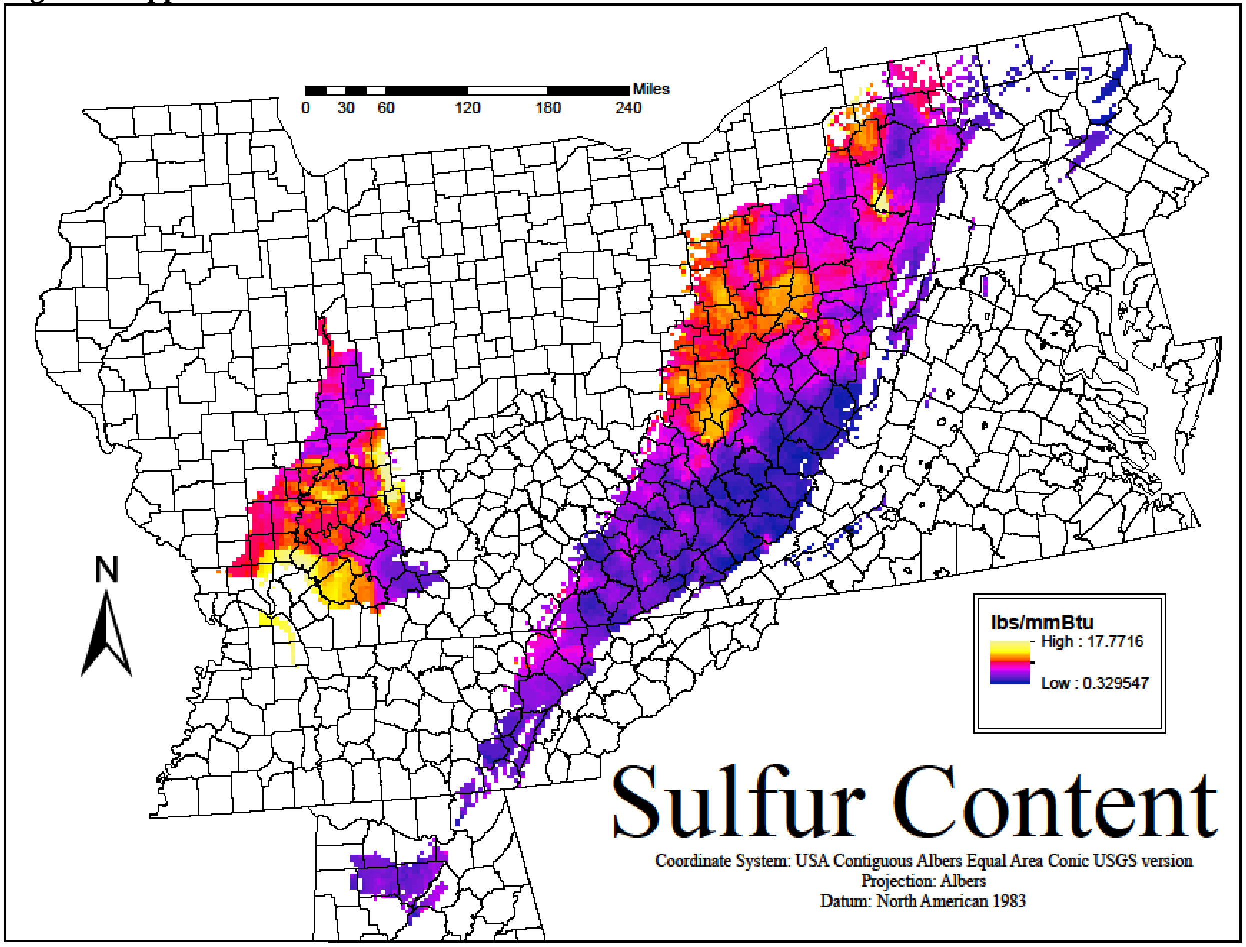
Source: EIA

Figure 2: Fluid Gas Desulfurization (Scrubber) Installation



Source: EIA Form 860 (EIA 2014b)

Figure 3: Appalachian and Illinois Basin Coal Sulfur Content



Source: Bragg et al. (1998)

Figure 4: Estimated Effects of Clean Air Act Policy on Coal Production, Ignoring Effects of Scrubbers and PRB Production

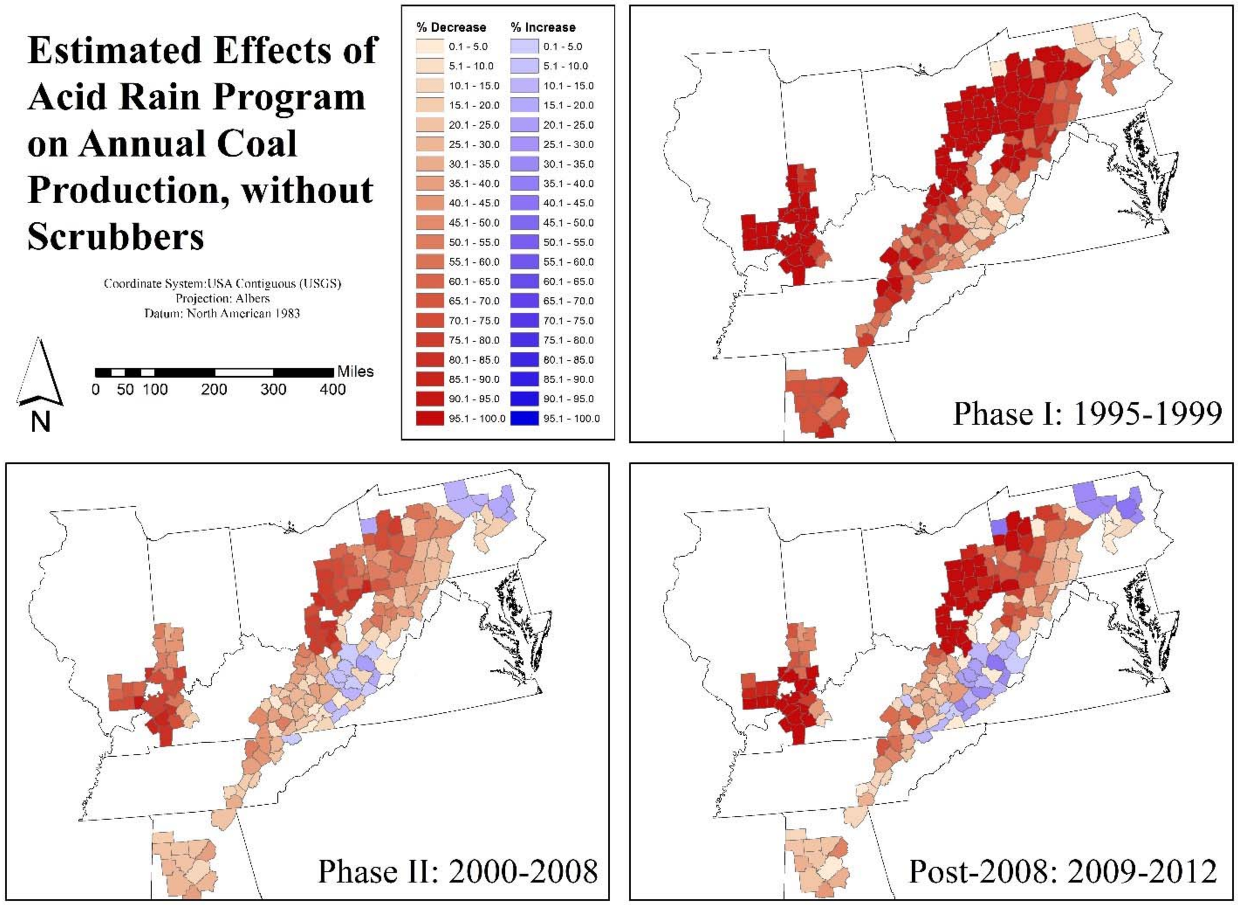


Figure 5: Estimated Percentage Increase of Coal Production Due to Scrubbers

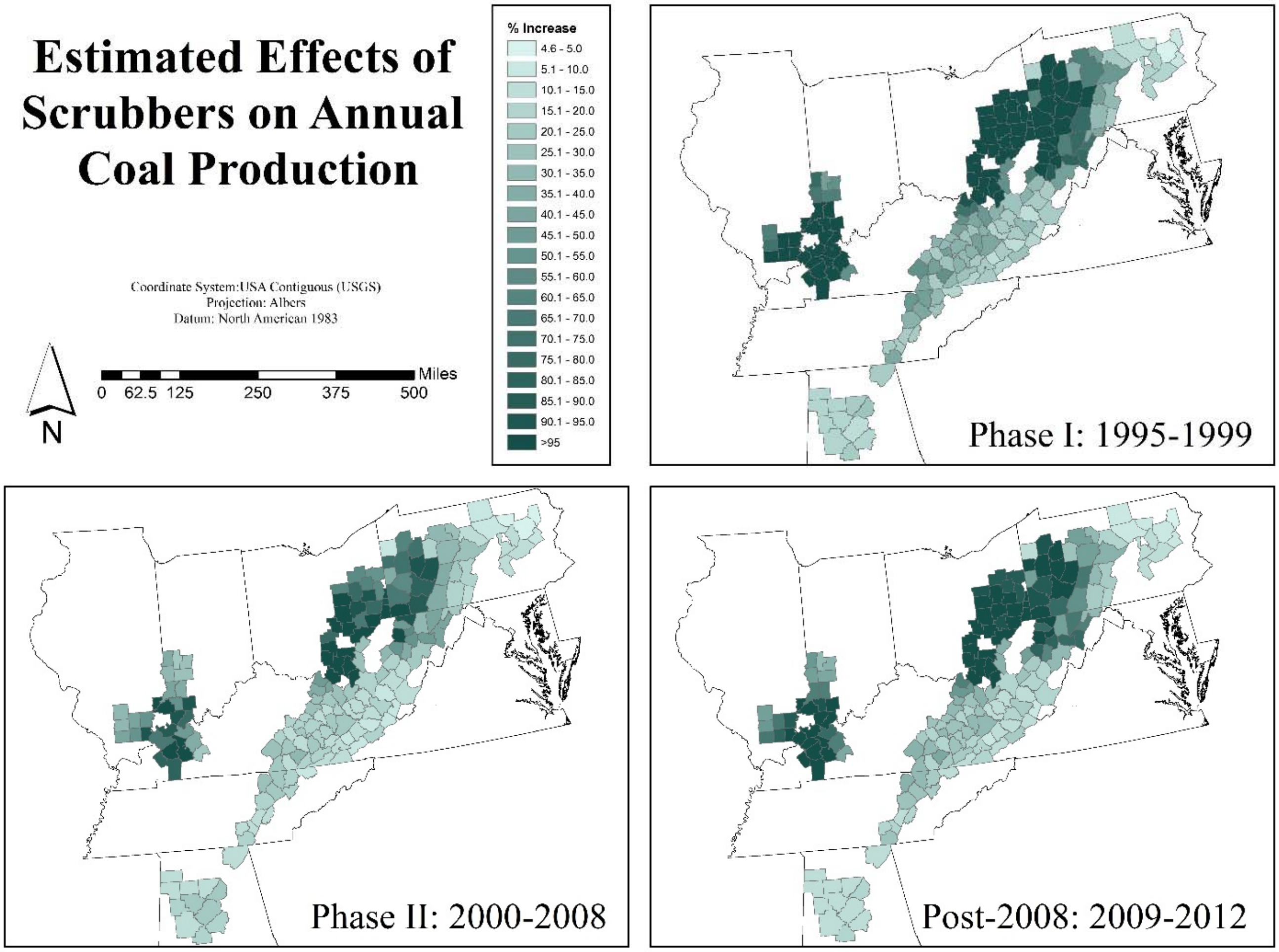


Figure 6: Estimated Overall Effects of CAA Policy and Scrubbers on Coal Production

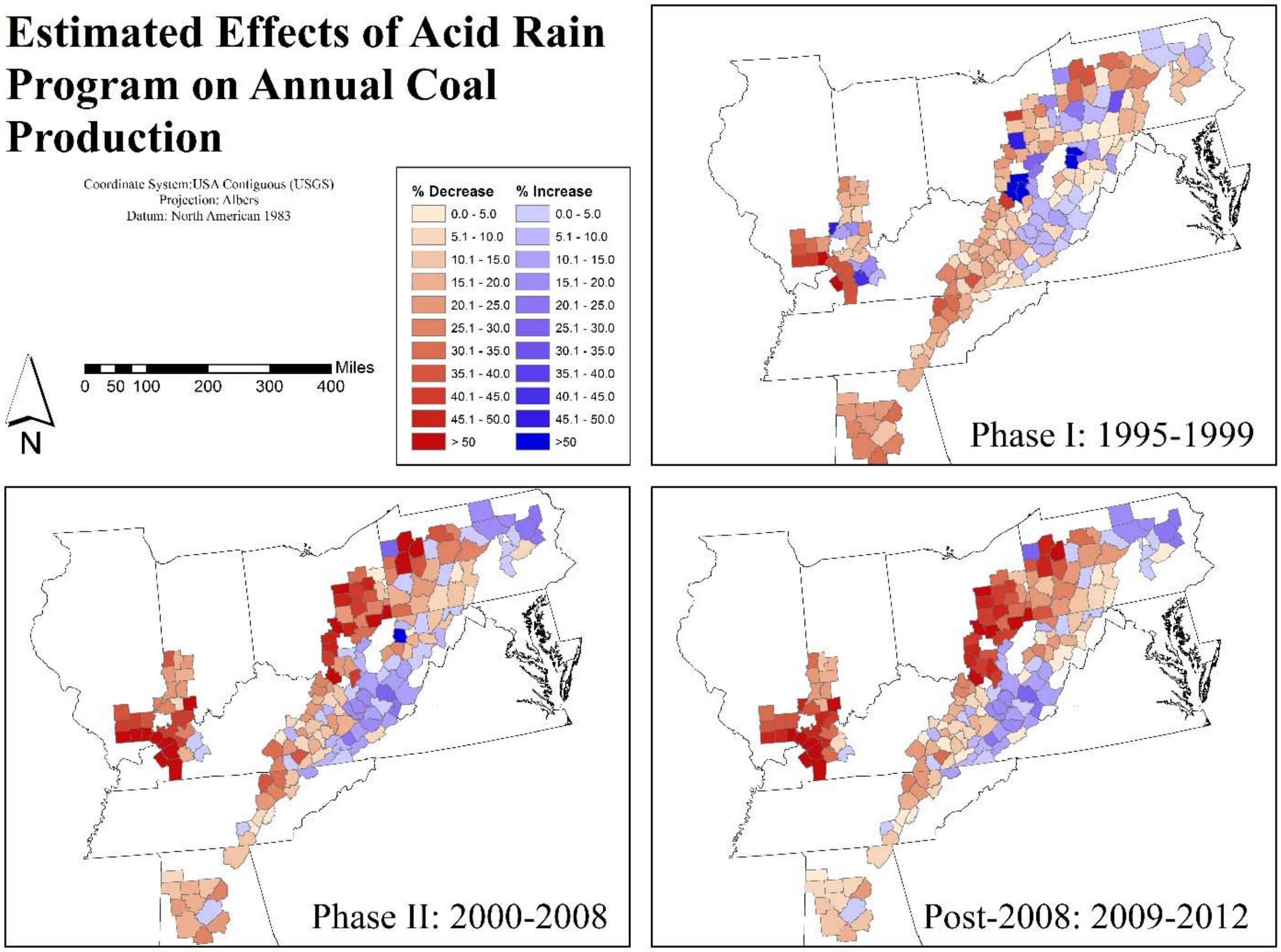


Table 1: Capacity Weight Regression Results

Dependent Variable: Coal Plant Capacity Factor

Independent Variables	OLS
Boiler Age	-0.00316***
	(0.00018929)
Nameplate Capacity	0.00012546***
	(0.0000036)
Constant	0.52763***
	(-0.00715)
Observations	3964

Standard errors in parentheses
*** $p<0.01$, ** $p<0.05$, * $p<0.1$

Table 2: Summary Statistics

Variable	Obs	Mean	Std. Dev.	Min	Max
Total Coal Produced	5640	2,736,747	4,824,727	0	42,700,000
ln(Total Coal Produced)	4610	13.70	2.07	3.40	17.57
Scrubbed MW Demand	5640	82.44	61.92	14.15	572.79
Total MW Demand	5640	314.24	99.46	127.58	707.84
Sulfur Content (lbs/mmBtu)	5640	1.78	0.92	0.48	4.63
Sulfur Content*ScrubbedMWD*Phase1	5640	25.73	78.11	0	662.98
Sulfur Content*ScrubbedMWD*Phase2	5640	55.23	122.82	0	1,465.42
Sulfur Content*ScrubbedMWD*Post2008	5640	47.98	162.90	0	1,782.83
Natural Gas Price / Coal Price	5640	5.60	3.63	2.23	14.22
Total PRB Production	5640	315.75	120.82	122.47	495.96

Table 3: Probit Results - Marginal Effects

Dependent Variable: One if County Produces Coal, Zero Otherwise

Independent Variables	Probit
Sulfur Content * Phase 1	-0.364***
	(0.0581)
Sulfur Content * Phase 2	-0.516***
	(0.0739)
S.Content * Post-2008	-0.573***
	(0.107)
Total MW Demand / Distance	0.00111
	(0.00129)
Sulfur Content * Scrubbed MW Demand / Distance	0.00122***
	(0.000414)
Natural Gas Price / Coal Price	0.0209
	(0.0174)
PRB Production	-0.00302***
	(0.000602)
Constant	2.742***
	(0.42)
Observations	5,640
Number of Counties	188

Standard errors in parentheses

*** $p<0.01$, ** $p<0.05$, * $p<0.1$

Table 4: Regression Results

Dependent Variable: ln(Total County Production)

Independent Variables	OLS	County Fixed Effects
Phase 1	0.256**	0.205
	(0.126)	(0.127)
Phase 2	0.477***	0.406**
	(0.158)	(0.161)
Post-2008	0.399**	0.340*
	(0.172)	(0.175)
Sulfur Content * Phase 1	-0.565***	-0.542***
	(0.108)	(0.108)
Sulfur Content * Phase 2	-0.609***	-0.569***
	(0.115)	(0.117)
Sulfur Content * Post-2008	-0.431**	-0.404**
	(0.181)	(0.182)
Total Distance-Adjusted MW Demand	0.00389***	0.00121
	(0.00101)	(0.00184)
Sulfur Content*ScrubMWD*Phase 1	0.00406***	0.00400***
	(0.000726)	(0.000724)
Sulfur Content *ScrubMWD*Phase 2	0.00251***	0.00242***
	(0.000456)	(0.000458)
Sulfur Content *ScrubMWD*Post-2008	0.000941**	0.000946**
	(0.000442)	(0.000444)
ln(Total PRB Production)	-0.937***	-0.819***
	(0.128)	(0.149)
Relative Natural Gas/Coal Prices	-0.00254	-0.00405
	(0.0132)	(0.0131)
Inverse Mills Ratio	1.525***	1.351**
	(0.539)	(0.547)
Constant	17.31***	17.87***
	(0.604)	(0.594)
Observations	4,610	4,610
Number of Counties	188	188

Standard errors in parentheses

*** p<0.01, ** p<0.05, * p<0.1

Table 5: Elasticity Model

Dependent Variable: ln(Total County Production)

Independent Variables	County Fixed Effects	OLS
ln(Allowance Price)	0.998***	0.627***
	(0.285)	(0.231)
Sulfur Content*ln(Allowance Price)	-0.407***	-0.217***
	(0.119)	(0.0794)
ARP Phase 1	0.694	0.374
	(0.547)	(0.527)
ARP Phase 2	0.513	0.485
	(0.688)	(0.687)
Sulfur Content * Phase 1	-0.845**	-0.662*
	(0.363)	(0.349)
Sulfur Content * Phase 2	-0.638**	-0.599**
	(0.278)	(0.276)
Total Distance-Adjusted MW Demand	-0.00692	0.0159***
	(0.0204)	(0.00427)
Sulfur Content *ScrubMWD*Phase1	0.00414*	0.00363
	(0.00238)	(0.00234)
Sulfur Content *ScrubMWD*Phase2	0.000753	0.000138
	(0.00134)	(0.00130)
Relative NatGas/Coal Prices	-0.0371	-0.0455
	(0.0450)	(0.0443)
ln(Total PRB Production)	-1.831*	-1.803*
	(0.970)	(0.963)
Constant	22.63***	15.49***
	(7.566)	(4.982)
Observations	3,008	3,008
Number of Counties	188	188

Standard errors in parentheses

*** p<0.01, ** p<0.05, * p<0.1