Who Gained from Environmental Regulation?: The 1990 Clean Air Act*

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Abstract

Title IV of the 1990 Clean Air Act Amendments introduced a cap-and-trade system for sulfur dioxide emissions from large coal-fired electric power plants in the United States. This paper shows that one of the consequences of the new policy was to enrich the railroads that transport coal eastward from the Powder River Basin in Wyoming – the country's largest deposit of low-sulfur coal.

The suddenness of the policy shift, and the fact that in its first phase it only covered a subset of power plants, allow us to identify the effect of the new policy on delivered coal prices. We find compelling evidence that the two railroads serving the PRB exercised market power in the form of price discrimination among power plants.

After Title IV took effect, the delivered price of PRB coal rose at western plants, and fell at plants located further away. These estimation of results allows for unobserved heterogeneity among short-term contracts at the plant level, and controls for changes in railroad costs and in minemouth coal prices over time.

The observed changes are consistent with a strategy of railroads lowering marginal prices to expand market share, while recouping the revenue thus lost through a fixed fee, much as a simple theoretical model shows would be optimal.

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1 Introduction

Title IV of the 1990 Clean Air Act Amendments introduced a novel cap-and-trade program for sulfur dioxide emissions from large coal-fired electric power plants in the United States. This paper analyzes the effects of that regulatory change on the market for low-sulfur coal. Because burning low-sulfur coal saves utilities the expense of buying allowances or of installing and running pollution control equipment, the regulation makes low-sulfur coal more desirable relative to high-sulfur coal than it was before the regulation. In particular, the new sulfur dioxide allowance market raised demand for low-sulfur coal from the Powder River Basin in Wyoming (henceforth the "PRB"), the most important deposit of low-sulfur coal in the United States.

The suddenness of the policy shift, and the fact that its first phase covered only a subset of power plants, allow us to identify the effect of the new policy on delivered coal prices. We find evidence that the two railroads carrying low-sulfur coal east from the PRB practiced price discrimination among power plants. Much as theory predicts, the railroads charged nearby power plants higher delivered prices, relative to cost, than what more distant plants paid. The effect of the new regulation was to exacerbate this discrimination, increasing prices even more for nearby plants while lowering them further away. Moreover, this discriminatory pricing appears to have enabled the two railroads to benefit substantially from the environmental regulation.

Notably, all coal from the PRB must be carried on one of two railroads: Burlington Northern Santa Fe (BNSF) and Union Pacific (UP). Indeed, coal from the PRB represents the rail industry's largest single freight source (Watson 1998). While the railroads are overseen by government regulators, some slack surely exists. Moreover, several coal mines in the PRB are "captive shippers" to one railroad or the other, and some power plants are located on rail lines served by only one of these two railroads.

We first use a simple theoretical model of pricing with market power to illustrate the effect of Title IV regulation in a perfectly competitive market compared to a market with market power. We then tackle the question empirically, using detailed data on coal deliveries to power plants, along with information on minemouth coal prices and on power plant characteristics. We start by examining how Title IV affected the geographic market share of low-sulfur coal. Phase I of the tradeable permits program, from 1995 to 1999, coincided with a dramatic expansion in the geographic extent of low-sulfur coal from the Powder River Basin in Wyoming. Such an expansion is just what one would expect, given the sharp increase in demand due to Title IV.

The heart of our paper is an empirical analysis of delivered coal prices before and after Title IV took effect. Our results suggest that the two railroads that carry coal east from the PRB altered their price schedules in such a way that the delivered price of PRB coal increased over much of its delivery range, but fell at the extensive margin. In particular, our empirical results estimate that delivered coal prices – net of the price of coal at the minemouth – rose by approximately three to four dollars per ton regardless of distance. At the same time, estimated transportation rates fell by two to five mills per ton-mile. These results allow for unobserved heterogeneity among short-term contracts at the plant level. The same results hold for a model which controls for contemporaneous deliveries to plants that were not affected by the new regulation.

Hence the railroads appear to have altered their price schedules in response to the Title IV regulation. Simple calculations show that their gains were significant. Moreover, our findings suggest that the ability of railroads to spatially price discriminate may have led to *lower* costs of complying with Title IV regulation via fuel-switching than would have been predicted on the basis of pre-Title IV prices for low-sulfur coal.

In a broad sense, of course, many parties gained from the Title IV regulation. At the most basic level, members of society benefited from cleaner air (Burtraw et al., 1998). And because utilities were allocated tradeable allowances for free, those power plants that could reduce emissions relatively cheaply stood to gain from the regulation. In this paper, we focus on the potential gains from the regulation due to the increase in the value of low-sulfur coal – gains that might have accrued to the mines that extract this coal, nearby power plants that burn it, or the railroads that transport it. These gains were potentially large; but they have drawn less attention than the benefits from clean air or the grandfathering of allowances.

In the next section, we provide brief overviews of the regulatory regimes governing railroad transportation and sulfur dioxide emissions, which provide the motivation and the context for questions about regulatory rents from low-sulfur coal. Section 3 develops a simple theoretical framework for thinking about the price premium for low-sulfur coal induced by emissions regulation. After discussing the data in Section 4 , we present a series of maps in Section 5 to analyze the expansion over time of the geographic range of low-sulfur coal from the Powder River Basin. Section 6 presents our empirical results, using detailed data on coal deliveries to investigate how Title IV affected the delivered prices of low-sulfur coal from the PRB. Section 7 concludes.

2 The regulatory context

2.1 Regulation of railroad transport

Historically, railroads have been obligated to serve all customers, at a reasonable price, equally, and to safely deliver passengers and freight.[1] From an economist's perspective it is clear that determining a fair and equal rate system that serves all customers may well be a challenge. On the supply side, the underlying cost structure of a railroad is large fixed costs associated with the route network and relatively small marginal costs associated with any particular shipper's load. On the demand side, there are differences in the inherent profitability of routes depending on distances, volumes of traffic, and shipper outside options.

The current regulatory framework under which railroads operate was established by the Railroad Revitalization and Regulatory Reform (4R) Act of 1976 and the Staggers Rail Act of 1980. The 4R Act freed railroads from rate regulation where they had no monopoly, and allowed a railroad without "market dominance" to move its rates around without regulatory approval as long as those rates remained within a "zone of reasonableness." The Staggers Act went even further. It allowed railroads without market dominance to set whatever rates they chose, and established guidelines that allowed rates to be 170-190 percent of variable costs without being evidence of market dominance. The Act also permitted railroads to establish contract rates with their shippers to a greater extent than was previously allowed.

While railroad regulation constrains the railroads' ability to exercise market power, evidence from rate cases suggests that they are still able to do so. At least one formal complaint has been brought against railroads over the transportation rates for PRB coal: a rate case initiated by the public utility of San Antonio, objecting to an increase in transportation rates charged by Burlington Northern. In a decision favorable to the railroads, the ICC found that even if railroads set the maximum rates allowable under the guidelines for market dominance, that they would not earn a sufficient rate of return on coal routes. The railroads argued that second best, or Ramsey prices, required increases on coal rates. That the utility found it worthwhile to lodge a formal complaint, and that the regulatory body allowed the railroad ample scope for rate-setting, both provide evidence that railroads are able to exercise some degree of market power.

The threat of entry (itself subject to regulatory approval) also constrains the degree of market

[1] This section draws heavily from Keeler (1983).

power the railroads may wield. Meanwhile, in 1998 the Dakota, Minnesota & Eastern Railroad petitioned the Surface Transportation Board for approval to construct a 280-mile spur connecting the PRB with the existing DM&E line in Wasta, South Dakota. Their application was initially approved in 2001, but as of the spring of 2004 remained held up by legal roadblocks thrown up by its opponents, who include ranchers and Native Americans living along the proposed route (and less visibly, one may suppose, UP and BNSF) (Gallagher 2004).

2.2 Regulation of sulfur dioxide emissions

Burning coal to produce electricity produces sulfur dioxide (SO_2) as a byproduct, because coal contains sulfur. Propelled into the atmosphere by tall stacks, SO_2 returns to earth as sulfuric acid in precipitation, and thus is a primary component of acid rain. In downwind urban areas, SO_2 contributes to respiratory ailments and morbidity.

Title IV of the 1990 Clean Air Act Amendments introduced a novel market-based policy to control SO2 emissions from existing fossil-fueled electric generating units.[2] Each generating unit in the program is allocated permits, or "allowances," which allow it to emit a certain amount of sulfur dioxide in a given year. A unit that emits more sulfur dioxide than is covered by its permit allocation can buy permits from other generating units. A generator that emits less sulfur dioxide than its allocation, either by using low sulfur coal or removing sulfur dioxide from its flue gases with a "scrubber", may sell its surplus permits, or bank them for future use or sale.

Phase I of the allowance trading program started in 1995 and lasted through 1999. It applied directly to the 263 largest, dirtiest existing generating units, located at 110 power plants – those units that had been "grandfathered" out of earlier federal legislation of 1970 and 1977, which had focused exclusively on new sources of pollution.[3] These units are known as "Table A" units, after the table of the legislation that listed them. Just over one hundred additional units participated in the program voluntarily for all five years of Phase I.[4] Phase II of the program started in 2000 and extended the market to essentially every fossil-fired power plant of reasonable size. Compliance with the program has been perfect, largely due to the presence of a "truing-up" period in the first few months of each year (in which utilities had time to buy allowances needed to cover the previous year's emissions) and the threat of a $2000-per-ton fine for violations. During Phase I, allowance prices ranged between a low of $70 and a high of $210, with an average of $134.[5]

[2] The level of regulation is the generating unit: i.e., an electricity-generating turbine powered by steam from an associated boiler. A typical power plant houses several such units, often built at different times, burning different fuel, and subject to different emissions regulations.

For a comprehensive analysis of the Acid Rain Program and its performance during Phase I, see Ellerman et al. (2000).

[3] Under the Clean Air Act Amendments of 1970, new generating units (those built after August 17, 1971) were subject to New Source Performance Standards which imposed a maximum allowable rate of SO_2 emissions of 1.2 pounds SO_2 per million Btus.

In the second phase of federal regulation, under the Clean Air Act Amendments of 1977, new sources (constructed after September 1978) were required not only to meet the prior emissions rate, but also to do so by removing between 70 and 90 percent of SO_2 emissions from their flue gases. This requirement was deliberately designed to mandate the use of scrubbers and hence maintain demand for high-sulfur coal.

[4] For a description of the voluntary "substitution and compensation" program, and a fascinating analysis of the selection problem it created, see Montero (1999).

[5] The average allowance price is for August 1994-December 1999 and is computed from price data compiled by Cantor Fitzgerald EBS and Fieldston Publications and made available by the EPA. During this period, the allowance price (as recorded by Cantor Fitzgerald) ranged from a low of $69 in March 1996 to a high of $212 in May 1999.

For details on the allocation of allowances, see Joskow and Schmalensee (1998).

3 Regulation, market power, and the price of low-sulfur coal

Our goal in this section is to provide theoretical background for the empirical analysis at the heart of the paper. That analysis will analyze coal price data; but to recognize patterns and draw inferences from that data, we must have a model of pricing in mind.

We present three key results.[6] First, if low-sulfur coal is abundant and competitively supplied, its price will not change as a result of environmental regulation. Second, an *unconstrained* monopolist of low-sulfur coal would price discriminate among plants by their location, charging higher delivered prices to nearby ("captive") plants than to plants further away (which have better substitutes). In response to environmental regulation that raised demand for low-sulfur coal, such a monopolist would raise its delivered prices everywhere by the same amount in order to fully capture the additional surplus.

Finally, we show that a railroad with *constrained* market power would, under certain (fairly plausible) conditions, respond to environmental regulation by raising its delivered prices to nearby plants while lowering them on the extensive margin. Again, we show that such a pricing policy can be interpreted in terms of a two-part tariff, with the railroad raising its "fixed fee" and lowering its rate per unit of distance.

3.1 A simple model of horizontal differentiation due to transportation

Coal is a low-value commodity: transportation costs represent a large fraction of its delivered price. The relative prices for low- versus high-sulfur coal that a particular power plant faces, therefore, depend on the plant's location relative to sources of those coals. Much of the low-sulfur coal mined in the United States comes from the Powder River Basin (PRB) in eastern Wyoming and southeastern Montana. Coal from southern Illinois and Indiana has much higher sulfur content. Hence a power plant in western Missouri will find low-sulfur coal relatively much cheaper than an otherwise identical power plant along the lower Ohio River.[7]

Our framework is a very simple and straightforward model of horizontal product differentiation in the style of Hotelling (1929). Suppose that there are two sources of coal, located at the endpoints of a line. Without loss of generality, normalize the length of the line to be 1; and suppose that there is a unit population of coal consumers ("power plants") with unit demand distributed uniformly and continuously along the line. Let the coal from the western endpoint (denoted 0) be "low-sulfur coal"; let coal from the eastern endpoint 1 be "high-sulfur coal." Coal from a given origin is assumed to have a constant level of sulfur, resulting in emissions rates of $m_0 < m_1$ for origins 0 and 1, respectively. The costs of transportation per unit of distance is assumed to be constant, and are given by t_0 and t_1 for the origins 0 and 1 respectively. For simplicity, since our interest is in transportation, we assume that the unit costs of extraction are zero at both origins.

We consider two means of reducing emissions: switching from high-sulfur coal to low-sulfur coal; and installing a scrubber.[8] The cost of coal-switching depends on the relative delivered prices of high- and low-sulfur coal, and hence varies with a plant's geographic location. We assume that each plant faces a known scrubbing cost, which differs among plants. For ease of modeling, we also suppose that the emissions rate from a plant that installs a scrubber is the same as that from low-sulfur coal. In this simple model of unit demand and unit output, each plant's average cost of

[6]Our discussion is deliberately intuitive rather than formal; we refer the interested reader to a companion paper (Keohane and Busse (2004)) for a more detailed discussion.

[7]Figure 7 below provides a map of major coal districts and power plants.

[8]Everything carries through to the more general model in which the alternative abatement methods include low-sulfur coal from another source.

scrubbing is constant. The choice is not how much to scrub, but whether or not to scrub.[9]

3.2 The price premium under perfect competition

As a benchmark, consider a "baseline scenario" with perfect competition among coal mines at each end point and among railroads, and unlimited supplies of both types of coal. In this case, prior to regulation on emissions, coal prices settle to long-run average costs. That is, delivered prices just cover the costs of extraction and transportation. The geographic boundary between low- and high-sulfur coal (denoted b_0°) is the point at which the delivered coal prices are equal; the plant on the margin is indifferent between the two coals. Formally, given our assumptions,

$$b^\circ = \frac{t_1}{t_0 + t_1}.$$

This baseline model is illustrated by Figure 1.

Now suppose that a tradeable permits system for SO_2 emissions is introduced. We assume that the regulation is binding, meaning that the total number of pollution allowances is less than emissions would be in the absence of regulation. Hence, in aggregate, power plants must reduce their emissions. A power plant that continues to burn high-sulfur coal without installing a scrubber must now hold enough allowances to cover its emissions; because allowances are scarce, they will have a positive price. Let z° denote the market-clearing permit price in equilibrium; it is determined by the stringency of the cap on emissions, the relative sulfur contents of the fuels, and the availability of other abatement options – *e.g.,* the costs of installing scrubbers.

The regulation makes low-sulfur coal more attractive than it was before. Plants east of b_0° will switch to low-sulfur coal if the delivered price of low-sulfur coal is less than the *total* cost of high-sulfur coal, which is the sum of its delivered price *plus* the excess cost of allowances needed to cover the higher emissions. The latter allowance cost is $z^\circ (m_1 - m_0)$. Hence the boundary between low- and high-sulfur coal shifts eastward, towards origin 1:

$$b_R^\circ = \frac{t_1 + z^\circ (m_1 - m_0)}{t_0 + t_1},$$

where the subscript R denotes the effect of environmental regulation.

Note at the new boundary the delivered price of low-sulfur coal is higher than that of high-sulfur coal, by an amount equal to $z^\circ(m_1 - m_0)$. This "sulfur premium," however, is driven by horizontal differentiation in where plants are located.[10] In particular, *the delivered price of coal is everywhere unaffected by the regulation*: price equals average cost.[11] What does change is the demand for low-sulfur coal: it increases, extending the geographic range of low-sulfur coal eastward.

[9] These assumptions also allow us to ignore the different between fixed and variable costs of scrubbing. In reality, of course, the marginal costs of scrubbing are likely to be increasing. Moreover, scrubbers can and do achieve much lower emissions rates than that arising from the lowest-sulfur coal. Our assumptions greatly simplify the analysis, however, without affecting the qualitative results.

[10] That the size of the premium depends on the permit price does not contradict this claim: the permit price and the boundary are jointly determined and depend on the stringency of regulation, the emissions rates of different fuels, and the underlying costs of extracting and transporting coal.

[11] Of course, the "net" cost to power plants of burning low-sulfur coal – taking the cost of emissions permits into account – increases under environmental regulation, by zm_0. But that increase in price is not captured by the coal mines or railroads.

3.3 Optimal pricing with market power in transportation

Now suppose that transportation out of origin 0 is controlled by a monopolist.[12] (We continue to assume that high-sulfur coal from origin 1 is competitively supplied, and that the mining industry at origin 0 is competitive as well.) While the assumption of unconstrained market power is unrealistic, this model allows us to build intuition for the pricing strategy when market power is limited.

The profit-maximizing policy is to perfectly price-discriminate among power plants, according to their location. The monopolist charges each plant its full willingness-to-pay by setting the price at location x equal to the price of (competitively supplied) coal from origin 1:

$$p^*(x) = t_1 \cdot (1 - x). \tag{1}$$

Intuitively, the monopolist prices along a "demand curve" for low-sulfur coal that traces out the delivered cost of high-sulfur coal.

The monopolist delivers coal according to this price schedule out to the location where price equals average cost; to go any further would incur losses. Hence the boundary b is given by

$$p^*(b) = t_0 b \quad \Rightarrow \quad b^* = \frac{t_1}{t_0 + t_1}.$$

Under this pricing scheme, the monopolist extracts the entire surplus associated with low-sulfur coal (Figure 2). Note that the location of the low-sulfur coal boundary is the same as it would be under perfect competition (just as, in a standard model of monopoly output, the quantity produced under perfect price discrimination equals that under perfect competition).

This optimal price schedule can be described by an equivalent *two-part tariff* – a device that will be particularly useful in the empirical analysis to come. Let r denote the "fixed fee" in a two-part tariff, with ρ the markup of the per-mile transportation rate over the variable cost. The delivered per-ton price of coal from origin 0 to location x can be written as the unit cost of transportation, plus the railroad's fixed fee, plus the the per-mile markup:

$$p(x) = t_0 x + r + \rho x. \tag{2}$$

Setting the fixed fee $r^* = t_1$ and the variable margin $\rho^* = -(t_0 + t_1)$ yields the optimal price schedule $p^*(x)$ given by equation (1). In this case, the two-part tariff implied by optimal pricing combines a large fixed fee with a *subsidy* (i.e., a negative rate per unit of distance) on transportation cost.

Now suppose a tradeable permits system is introduced. The policy induces a parallel shift in the demand curve for low-sulfur coal. Each plant's willingness-to-pay for low-sulfur coal (relative to high-sulfur coal) increases by $z^* (m_1 - m_0)$, or the permit price times the difference in sulfur contents in the two types of coal. The monopolist's optimal response is to raise delivered prices everywhere by the same amount, capturing the entire surplus.[13]

The new price is given by

$$\begin{aligned} p_R^*(x) &= t_1 \cdot (1 - x) + z^* (m_1 - m_0) \\ &= t_0 x + r_R^* + \rho^* x, \end{aligned} \tag{3}$$

[12] For simplicity of exposition we consider a lone monopolist. Our results extend in obvious ways to Cournot duopolies or other specifications of market power.

[13] Note that there must be some available alternative abatement measure for a monopoly solution to exist. Otherwise, the monopolist faces a perfectly inelastic demand curve for low-sulfur coal, and could charge an infinite price.

where the variable markup ρ^* is unchanged and the fixed fee $r_R^* = t_1 + z^*(m_1 - m_0)$. In other words, in response to environmental regulation the monopolist raises the "fixed fee" by just enough to capture the full rise in demand for low-sulfur coal, without affecting the per-mile rate. Note that in contrast to the perfect-competition case, the price of low-sulfur coal *at every location* increases by the fixed amount $z^*(m_1 - m_0)$.

As was the case absent environmental regulation, the low-sulfur coal boundary under perfect price discrimination is identical to the boundary under perfect competition. Indeed, the permit price is also identical to the perfectly competitive permit price: that is, $z^* = z^\circ$.[14] It is the change in the fixed fee, and hence in delivered prices, that distinguishes this monopoly case from the perfect-competition case.

3.4 Constrained (linear) pricing

Regulatory constraints in the real world may prevent railroads from exercising perfect price discrimination. We now turn to the case in which the railroad has market power, but its ability to price-discriminate is limited (for antitrust reasons, for example).[15] For simplicity, we consider the polar case in which the railroad is required to charge a linear tariff equal to a constant transportation rate regardless of distance. We again ask: What is the effect of environmental regulation on the relative price and geographic extent of low-sulfur coal? The answer turns out to depend in an intuitive way on the slope of the aggregate marginal abatement cost function, and thus on the costs of scrubbing and of alternative sources of low-sulfur coal.[16]

To see why, begin by considering the case in which there is no environmental regulation. Because it has market power, but is prevented from perfectly price discriminating, the railroad will charge a positive markup over the marginal cost of transportation. Some plants for whom the delivered *cost* of low-sulfur coal is lower than that of high-sulfur coal will nonetheless face a higher *price* for low-sulfur coal. These plants will buy high-sulfur coal even though they would have bought low-sulfur coal under either perfect competition or perfect price discrimination. The transportation rate will be greater and the aggregate usage of low-sulfur coal less than under perfect competition. This result clearly echoes the standard monopoly pricing result. Figure 3 illustrates the model in this case.

Now suppose that a tradeable permit system is introduced. To develop intuition, we imagine that after the regulation is imposed the railroad is temporarily forbidden from changing its rates, and the market is allowed to reach an equilibrium. (For the sake of this thought experiment, we assume that the power plants freely adjust to changes in regulation and transportation rates.) We then ask: starting from that point, would the monopolist prefer to raise or lower its transportation rate?

[14] The key to the argument is that the decisions by plants whether or not to install scrubbers – the alternative means of abatement – are *identical* under the cases of perfect competition and perfect price discrimination. To see this, note that the cost of buying high-sulfur coal and installing a scrubber is necessarily always greater than the cost of buying high-sulfur coal; and the latter cost is unaffected by market power in transportation from origin 0. Hence the costs of high-sulfur coal, and therefore of scrubbing, are unchanged everywhere.

The only possible exception to this argument would be for plants located west of the low-sulfur coal boundary that can install scrubbers more cheaply (in average-cost terms) than buying allowances. Such plants would prefer to buy high-sulfur coal and scrub it than to pay the full markup charged by the monopolist. In equilibrium, however, such a condition cannot hold; and moreover such a condition does not appear to hold in actuality, given that permit prices are much lower than typical average scrubbing costs.

[15] Formal proof of the claims in this section can be found in the Appendix.

[16] To be precise, by "aggregate marginal abatement cost function" we have in mind the aggregate marginal cost function of all abatement *other than* low-sulfur coal from origin 0. We return to this point shortly.

For a fixed transportation rate, regulation will increase demand for low-sulfur coal. Hence regulation increases the railroad's profits, even without a change in rates, because some plants switch from high- to low-sulfur coal. Just as in the case of perfect competition (or perfect price discrimination), the boundary between low- and high-sulfur coal will shift eastward.

Because regulation changes the demand for low-sulfur coal, however, it also alters the optimal transportation rate. Whether raising the rate increases the monopolist's profits depends on how the demand for low-sulfur coal responds. An increase in the relative price of low-sulfur coal has two effects on plant-level choices: some plants that were burning low-sulfur coal switch to other forms of abatement (e.g., scrubbing), while other plants switch to high-sulfur coal. Because total emissions are fixed by the number of permits, any increase in high-sulfur coal must lead to a corresponding increase in demand for permits, driving the permit price up. This increase in the permit price raises the incentive to reduce emissions. In doing so, it *mitigates* the effect of the relative price increase on the demand for low-sulfur coal: by pushing permit prices up, the rise in the relative price raises the willingness-to-pay for low-sulfur coal. Although the net cost of burning low-sulfur coal must still rise relative to the cost of high-sulfur coal, the rising permit price partially offsets the effect. In other words, the endogenous response of permit prices dampens the response of demand to a rise the relative price of low-sulfur coal.

The size of this dampening effect depends on how fast permit prices rise as plants shift away from low-sulfur coal. The more rapidly permit prices rise, the more they will cushion the impact of rising low-sulfur coal prices. In turn, the response of permit prices hinges on the slope of the marginal abatement cost function. Suppose that the marginal cost function is steep: marginal abatement costs rise rapidly with abatement.[17] As plants shift away from low-sulfur coal in this case, the permit price will rise sharply, raising the value of low-sulfur coal. (Recall that the permit price in equilibrium must equal the aggregate marginal abatement cost.) Hence the decrease in low sulfur coal use will relatively minor. In this case, the firm can increase its transportation rate without greatly diminishing demand.

If the aggregate marginal cost function is relatively flat, on the other hand, permit prices will be much less sensitive to a shift away from low-sulfur coal. Raising the transportation rate in this case erodes market share considerably, because the cushioning effect of permit prices is much reduced. (In the limit, a perfectly flat marginal cost function would produce a constant permit price, and the offsetting effect would disappear entirely.) The monopolist's best response to regulation in this case is to charge a lower transportation rate and extend her geographic reach eastward.

It remains to consider the determinants of the slope of the marginal abatement cost function. In the simple model we have developed so far, with only two sources of coal, the "marginal abatement cost function" corresponds to the marginal cost of scrubbing. This will be flatter, the more homogeneous are scrubbing costs among plants. In the real world, however, there are multiple sources of coal, with a range of sulfur contents. Other sources of low-sulfur coal exist, aside from the Powder River Basin (although with less potential for exercise of market power); and in the aggregate much abatement can be achieved by switching from a high-sulfur coal to a coal with intermediate sulfur content. Hence in general, the slope of the aggregate marginal abatement cost function depends not only on the dispersion of scrubbing costs, but also on the availability of lower-sulfur (not necessarily *low*-sulfur) coal. The wider is the range of alternative sources of low-sulfur coal – the greater the number of substitutes for PRB coal, in other words – the flatter will be the marginal abatement cost function.

Finally, note that in this model, railroad regulation reduces efficiency and exacerbates the

[17] In the Appendix, we make precise the definition of "flat" and "steep." We show there that the key condition can be expressed in terms of the elasticity of the permit price with respect to the consumption of low-sulfur coal.

costs of environmental regulation. Under the constraint on pricing, less low-sulfur coal from 0 is consumed than would be efficient. To meet the overall emissions cap, more resources will be spent on alternative forms of abatement – *i.e.,* scrubbers or other sources of low-sulfur coal. The permit price will be higher than it would have been under the two-part tariff.

3.5 Summary of the theoretical model

We can use the theoretical discussion above to construct a simple model of the price and geographic extent of low-sulfur coal, meant to motivate the subsequent empirical analysis. For the time being, we continue to assume for simplicity that all coal is identical aside from its sulfur content, and that sulfur contents are constant for coal from each origin. (We will relax these assumptions in the empirical analysis.)

While we have focused on the polar cases of perfect price discrimination and constant linear prices for expositional purposes, neither case is likely to hold in the real world. Railroads are constrained in their ability to price discriminate, by explicit regulation, the availability of substitutes, and the threat of entry. On the other hand, they negotiate transportation rates separately for different plants, giving them more pricing flexibility than under a linear pricing model.

Hence a plausible model of pricing is one intermediate between the two polar cases. For example, suppose that the railroad is prevented from charging an explicit fixed fee, but is able to choose from among a (small) set of transportation rates. Then the optimal schedule will impose higher rates per mile for nearby plants than for more distant ones, even if marginal costs are constant. Under suitable conditions on the distribution of plants and the number of different transportation rates, the overall schedule of delivered prices will rise with distance, but with a slope less than any of the individual per-mile rates. A regression line of delivered price on distance will thus yield both a positive slope and a positive intercept (corresponding to the implicit "fixed fee" from the imperfectly replicated two-part tariff scheme). Figure 4 provides an illustration.

In this intermediate case, the intuition from the two extreme models can be applied to predict the response to environmental regulation through tradeable permits. The key result from the linear-pricing model is that whether the railroads raise or lower their transportation rate under environmental regulation depends on the relationship between the price of low-sulfur coal and the price of allowances, mediated by the substitutability between low-sulfur and high-sulfur coal. In the intermediate case of a finite number of linear prices, an increase in the price of low-sulfur coal for plants near the low-sulfur coal origin will have a negligible effect on high-sulfur coal consumption and hence on permit prices. By the logic of the model above, the railroads' optimal response to regulation is to raise delivered coal prices for nearby plants.

More distant plants face a lower cost for high-sulfur coal. Thus they are more likely to substitute away from low-sulfur coal if the price rises. For these plants near the extensive boundary, the analysis of the previous section applies exactly as before. Whether the railroads raise or lower their transportation rates at the extensive margin, therefore, depends on the slope of the marginal abatement cost function.

Whether the marginal abatement cost function is "flat" or "steep" is, in principle, an empirical question. Work by Keohane (2003), taking into account the prices of coals from a range of origins at the level of individual power plants as well as the costs of scrubbing, suggests that the marginal abatement cost function for Title IV plants was flat. Figure 5 illustrates a typical annual estimate of the short-run marginal abatement cost function for Title IV plants. Hence our model suggests that in response to the introduction of tradeable allowances for sulfur dioxide, railroads should have raised the delivered price of low-sulfur coal from the PRB to nearby plants, and lowered it to plants on the extensive margin.

The expected effect of environmental regulation on the overall pattern of delivered prices, therefore, will be to *raise* the implicit fixed fee (as in the case of perfect price discrimination) and to *lower* the transportation rate (as in the linear pricing model). This corresponds to a simple intuition: when demand for low-sulfur coal increases due to the introduction of tradeable allowances, a railroad with market power will raise prices on nearby plants (which have fewer substitutes for PRB coal) while simultaneously lowering prices on more distant plants (which could shift to high-sulfur coal more easily and hence have more elastic demand).

4 Data

We use three types of data: records of coal deliveries to power plants, plant-level information about coal transportation, and industry surveys of minemouth prices. Data on coal deliveries are taken from Form 423 of the Federal Energy Regulatory Commission (FERC), the "Monthly Report of Cost and Quality of Fuels for Electric Power Plants." The form must be filed by electric generating units with capacity of at least 50 megawatts.[18] The form records all monthly fuel deliveries received by each plant in each month. We use data on coal deliveries from 1972, the advent of federal sulfur dioxide regulation, until 1999, the end of Phase I of Title IV. We restrict our attention to deliveries on the "spot market," defined as delivery contracts under 1 year in duration. For each delivery, we know the price of the coal (in cents per million Btus); the quantity delivered; selected characteristics of the coal, including its heat, sulfur, and ash contents[19]; the coal district, state, and county where the coal was mined; and the nature of the coal contract.[20] Starting in 1983, the mine or mining company is specified as well.

We shall focus in this paper on what FERC categorizes as "spot market" deliveries: deliveries under short-term contracts less than one year in length. These deliveries are much more likely to be sensitive to changes in policy regimes than are deliveries under long-term contracts, and thus present a cleaner test of the effect of the allowance market. Following FERC, we shall use the term "spot market" below for convenience, but in the estimation we shall treat all deliveries from a given source in a given year as belonging to the same underlying short-term contract.

Figure 6 plots the delivered spot-market prices of PRB coal to Title IV plants (*i.e.,* plants that during the last half of the 1990s were regulated by Phase I of Title IV) over time, from 1983 (the earliest observation in the dataset) to 1999 (the last year of Phase I of Title IV). Two points stand out. First, coal deliveries were much sparser in the 1980s. On average, there were 116 deliveries of spot-market PRB coal to Title IV plants each year from 1983 to 1988. Spot PRB deliveries jumped to 249 in 1989, 408 in 1990, and an average of nearly 600 annually thereafter.

Second, prices fell steadily throughout the first several years, and then flattened out abruptly in the late 1980s and afterward – coinciding with the surge in deliveries. Because we are interested here in the effects of Title IV, in the latter half of the 1990s, it seems prudent to drop the early period in our analysis, when the market appears to have been fundamentally different. Because we also lack cost data before October 1987, we choose that as our starting point.[21] Finally, note that

[18] More specifically, "The form is completed by each electric power producer for each of its electric generating plants with total steam turbine electric generating capacity and/or combined-cycle (gas turbine with associated steam turbine) generating capacity of 50 or more megawatts. Fuel received for use in gas turbine or internal combustion units that are not associated with a combined-cycle operation is not reported."

[19] Coal prices can also vary with other characteristics: moisture content, grindability, and content of some other specific elements like nitrogen and chlorine. Form 423, however, does not collect data on these characteristics.

[20] A coal district is a decades-old designation by the Bureau of Mines to delineate deposits of coal. There are 24 coal districts in the U.S., 15 of which have substantial commercial significance. The definition appears to depends both on the properties of the coal and its location relative to major transportation routes.

[21] Separate regressions that include the early period (not reported) bear out this concern. In particular, those

there appears to be a distinct upward shift in prices in the second half of 1994, in the run-up to Title IV. While this simple plot is only illustrative, the regressions in Section 6 demonstrate that the apparent price increase does indeed represent a phenomenon in the data.

Transportation data come from several sources. Actual distances by rail between power plants and the Powder River Basin were compiled from state-level maps and railroad atlases, along with the Platt's Coal Map produced by Financial Times Energy.[22] By "actual," we mean the distance traveled by rail – not the distance "as a crow flies." These distances are supplemented with data supplied by Platt on the transportation options available to each plant – *i.e.,* whether the plant is served by barge or rail, and if the latter, by which railroads.

To account for changes in the (variable) costs of railroad transportation, we use the Railroad Cost Adjustment Factor computed monthly by the Surface Transportation Board. The measure we use, which is used by the STB in assessing railroad rates, is essentially an index of input prices (fuel, labor, and so on) deflated by a measure of productivity. Thus it represents an index of the real cost of hauling one ton of coal one mile. The series runs from fall 1987 through the end of 2002.

Although this is an index rather than a direct measure of cost, we can effectively control for the latter and even recover an estimate of the cost in the base year, if we are willing to assume that the margin over variable cost is constant over time. Suppose (for simplicity) that the "true" price schedule (at time t) is given by

$$p_t = \bar{p} + v_t d + \tau d,$$

where p is the delivered price, $\bar{p}$ is a "fixed fee" in a two-part tariff, d is distance, v_t is variable cost at time t, and τ is the margin over variable cost. We lack data on v, however, and instead run the following regression:

$$p_t = \beta_0 + \beta_1 \tilde{v}_t d + \beta_2 d + \varepsilon_t,$$

where $\tilde{v} = \left(\frac{v_t}{v_1}\right)$ is a cost index calculated relative to the base period 1. At $t = 1$, $\tilde{v} = 1$ by construction and hence $\hat{\beta}_1 + \hat{\beta}_2 = v_1 + \tau$ in expectation, with $E\left(\hat{\beta}_0\right) = \bar{p}$. At $t = s > 1$, in expectation $\hat{\beta}_1 \tilde{v}_s + \hat{\beta}_2 = v_s + \tau$. Substituting for $\hat{\beta}_2$ and solving yields $\hat{\beta}_1 = \frac{v_s - v_1}{\tilde{v}_s - 1} = v_1$ in expectation.

Finally, data on minemouth coal prices come from *Coal Outlook*, an industry newsletter published by Financial Times Energy. The price data represent the spot prices that the coal companies report receiving for coal at the minemouth; they are collected from bimonthly surveys with coal company staff. For PRB coal two series are gathered: for coal with 8400 Btus/lb heat content, and for coal with 8800 Btus/lb. Table 1 reports the distribution of price, sulfur content, and Btus for our data. (Note that the distributions in these tables are *not* the distribution of price or sulfur content for actual purchases, but the distribution within the mine price data reported by Coal Outlook.)

The mine price data are plotted in Figure 7. FOB prices for PRB coal with heat content of 8400 Btu/lb were roughly \$3.50 per ton from 1990-1993. Prices rose to \$4.00 per ton in early 1994, where they remained for most of 1994 and the first half of 1995. They then fell gradually from

regressions make the effect of Title IV appear much greater. If a trend variable is included to account for the steady fall in prices during the 1980s, Title IV appears to have a large effect in reversing the trend and keeping prices above where they would otherwise have been. On the other hand, if no trend is included, the *negative* effect of Title IV is exaggerated, simply because prices were lower during the entire 1990s. These problems can be solved by separating the data into three periods – early, middle, and Title IV. Indeed, we did exactly that But once that is done, there is little apparent reason to keep the early period in the regression at all. (The results reported in the paper are very similar to results from such a three-part regression.)

[22] For details on this transportation data, see Keohane (2002).

Table 1: Distribution of PRB mine prices

Heat content	Mean	10th Percentile	Median	90th Percentile	Observations
Mine prices in \$/ton					
8400 Btus/lb	3.66	3.15	3.72	4.02	129
8800 Btus/lb	4.77	4.15	4.75	5.27	129

mid-1995, reaching \$3 in mid-1997. Prices fluctuated around \$3.50 for the rest of the period until 1999. The pattern is echoed almost exactly, although at a higher price, for coal with a higher heat content (8800 Btu/lb).

The pattern illustrated in Figure 7 is suggestive. The advent of the allowance market, and the corresponding increase in the demand for low-sulfur coal, did not lead to any lasting increase in the minemouth price of PRB coal. If the coal mines were able to capture rents from the regulation, they did so through advances in extraction technology, not through increases in coal prices. The railroads, meanwhile, stood to gain from any increase in delivered prices or in the geographic extent of PRB coal.

5 The geographic extent of low-sulfur coal

The models in Section 3 underscore the importance of geography in driving the coals chosen by power plants and in determining the rents from low-sulfur coal. In the United States, most of the coal used as fuel for electricity generation is concentrated in three major deposits: the PRB; the Illinois Basin in southern Illinois and Indiana and northwestern Kentucky; and Central Appalachia, just south of the confluence of the Big Sandy and Ohio Rivers. (Figure 8 shows coal deposits by type throughout the US, and Figure 9 shows the three regions that are primary sources of fuel.) There is substantial regional variation in the characteristics of the coal. Coal from the Illinois Basin has a high heat content, around 11,250 Btus per pound, and also a high sulfur content, ranging from 2.1 to 7.5 pounds of SO_2 per million Btus (mmBtus). Coal from the PRB has a much lower sulfur content, from 0.38 to 0.98 lbs SO_2/mmBtus, but also a lower heat content, around 8600 Btus/lb. Appalachian coal also has a high heat content, 12,300 Btus/lb., and varies substantially in terms of sulfur content, 0.95 - 3.1 lbs SO_2/mmBtus.

Coal-fired power plants are distributed throughout the country, but are concentrated in the Midwest and particularly along the major river systems of the Mississippi and Ohio Rivers and the shores of the Great Lakes. This historical pattern of distribution was determined by the abundant water to run in cooling systems, the bituminous coal deposits in the Illinois Basin and Appalachia, and the growth of population in the Midwest. Figure 9 also shows the distribution of power plants under the two regulatory regimes considered here: the uniform emissions rate ceiling under the New Source Performance Standards ("NSPS-D") of the 1970s, and the tradeable allowance system of Title IV.[23]

As a qualitative means of assessing the impact of Title IV, we present a series of maps to

[23]Sulfur dioxide regulation targets generating *units*, not plants. Our coal delivery data, however, is at the plant level. Hence we shall use the term "Title IV plant" to refer to a plant that includes at least one generating unit regulated by "Title IV"; and similarly with NSPS-D regulation.

illustrate the changes over time in the geographic range of PRB coal.[24] Our measure of geographic range is the *cumulative percentage of PRB coal*. By "cumulative percentage" at a given location in a given year, we mean the total amount of PRB coal delivered in that year to all plants *west* of that location, divided by the total amount of all coal delivered to the same set of plants in that year.[25] We can then identify geographic ranges corresponding to ranges of those percentage measures: *e.g.,* 50-60% or 70-80%.[26]

The panels in Figure 10 display these ranges for Title IV plants in three years: 1990, 1995, and 1999. (Recall that Phase I of the tradeable-allowances program began in 1995.). The shaded bands represent various cumulative percentage ranges of PRB coal, with darker regions correspond to higher percentages. The circles on the maps indicate the locations of Title IV power plants. Black (filled) circles denote plants which bought over half of their coal from the PRB in the specified year; half- filled circles mark plants that purchased positive but smaller amounts of PRB coal; and white circles represent plants that did not buy any PRB coal at all.

The change from 1990 to 1999 is dramatic. In 1990, the *maximum* cumulative percentage was less than 50%: that is, no single plant even received more than half of its coal from the PRB. East of the Mississippi River, the cumulative percentage falls below 30%; the 10% line does not even reach into Indiana. By 1995, the first year of the tradeable allowances program, PRB coal has expanded eastward considerably. Roughly 60% of all coal deliveries west of the Mississippi are now PRB coal. The median line (the 50% cutoff) now cuts through Illinois and Mississippi, just about where the 20% line had crossed five years earlier.

By 1999, five years into allowance trading, the extensive range of PRB coal has shifted even further: the median line reaches into Indiana and Alabama. More notable is the increased *intensity* of PRB coal consumption. West of the Mississippi, roughly eighty percent of all coal is PRB coal. The westernmost plants in Minnesota, Iowa, and western Missouri now consume PRB coal almost exclusively.

A natural "control group" for comparison is the set of power plants that were not covered by the new regulation. The regulatory regime for these units was *constant* throughout the decade of the 1990s: hence patterns of PRB coal consumption among this set of plants are driven by factors other than the allowance trading program. The results are shown in panels a-c of Figure 11.

One is struck first by the much higher fraction of PRB coal in NSPS-D plants, relative to the fractions observed for Title IV. Even in 1990, the cumulative percentage of PRB coal never fell below 40% for NSPS-D plants. And already in 1990, the westernmost plants derived over 80% of their coal from the PRB. Over the region where the cumulative percentage for Title IV was only 10% in 1990 (westward from Illinois and Mississippi), the cumulative percentage for NSPS-D plants in the same year was 60%.

While the extent of PRB coal is greater than it was for Title IV plants, however, the *expansion*

[24] These maps echo an earlier effort, with necessarily less complete data, by Denny Ellerman and his colleagues; see Ellerman *et al.* (2000).

[25] An ideal measure of the geographic extent, in the simplified world of the horizontal-differentiation models studied above, would be the "Hotelling boundary" of low-sulfur coal from the PRB. Such a sharp boundary, however, does not exist in the real world. Power plants contain several different units, some of which may have scrubbers or be covered by different regulations. Moreover, there is considerable underlying variation among plants in their access to other coal sources, their contractual obligations at the time of the regulation, and their technical ability to adapt their boilers to PRB coal.

[26] For purposes of illustration we have chosen the easternmost point for each percentage. That is, the line for the 70-80% range, say, extends to the easternmost plant for which the cumulative percentage of PRB coal is between 70 and 80 percent. There may well be plants to the west of that plant for which the cumulative percentage is lower. Indeed, because of underlying variation among power plants, the share of PRB coal at the *plant* level does not fall monotonically as we move eastward.

of that extent appears to be less dramatic. The NSPS-D ranges shift out considerably from 1990 to 1995, with the 70% line moving from the eastern Plains to the Mississippi River; the 60% and 50% lines shift out accordingly. Even relative to these shifts, however, the expansion of PRB coal among Title IV plants from 1990 to 1995 is notable. In 1990, no Title IV plants were consuming more than 50% PRB coal; by 1995, the 70% line is almost as far east for Title IV plants as for NSPS-D plants.

From 1995 to 1999, the cumulative share of PRB coal at NSPS-D plants shifts eastward again, although less dramatically than earlier in the decade. This eastward movement is overtaken by the changes among Title IV plants, however – at least at the high end of PRB shares. Although the 70% for Title IV lags behind that for NSPS-D, the 80% line is much further east: at the Mississippi for Title IV, but still in the Great Plains for NSPS-D.

These maps show that the introduction of a tradeable-allowances program coincided with a dramatic eastward expansion in the range of PRB coal. Moreover, the spread of low-sulfur coal appears to have been more rapid for plants that were subject to the new regulatory regime. Thus is it plausible that Title IV regulation had real effects on fuel choice by power plants. These changes in the patterns of coal consumption suggest that coal mines or railroads had an *opportunity* to capture the rents generated by environmental regulation. Whether or not they were able to do so is the focus of the next section.

6 The effect of Title IV on delivered coal prices

This section examines data on coal deliveries to explore how delivered coal prices changed as a result of the tradeable permit regime for SO_2. We use a series of regressions to estimate the implicit price schedule for transporting coal eastward from the PRB, and to uncover changes in that price schedule that coincided with the Title IV trading program. We employ two distinct tests. First, we compare prices before and after Title IV took effect, and analyze how the observed price changes vary with distance from the PRB. Second, we control for coal prices at plants that were not regulated by the new regime, in order to compare prices after Title IV at newly regulated plants with contemporaneous prices at plants outside of the trading program.

Our main results show that the "net railhead price" of PRB coal – the "zero-distance" price of a ton of coal with average characteristics – rose substantially under Title IV. At the same time, the implicit transportation rate per ton-mile fell. In other words, viewing the price schedule as a linear function of distance, the intercept rose while the slope declined. The net effect was that delivered coal prices rose for the plants closest to the PRB, while they fell for plants further away. These findings remain when we allow for unobserved heterogeneity at the level of short-term contracts. The results are consistent with the railroads pursuing a strategy of lowering the transportation rate to increase market share, but recouping the resulting loss of revenue with an increase in the implicit fixed component of the price.

6.1 Econometric framework

In keeping with the interpretation of the railroads' pricing schedules as implicitly replicating a two-part tariff, we model the delivered price to a given power plant as a linear function of the distance by railroad from the plant to the Powder River Basin. The dependent variable is the delivered price of coal, *net* of the contemporaneous minemouth price. We shall focus on the intercept term, which (as we explain below) has the interpretation of a "net railhead price"; on the coefficient on distance, which represents the transportation rate per ton-mile; and particularly on the interactions of each of those variables with a dummy variable that equals 1 during the Phase I period of Title

IV regulation. These estimated effects of Title IV on delivered coal prices are the focus of our analysis.

In the simple theoretical model, every plant was identical, and coal characteristics were constant. Thus in the empirical model, we control for a number of other variables: key characteristics of the coal (its sulfur, heat, and ash content); the size of the purchase, to account for volume discounts; and the other transportation options of the plant (namely, how many rail lines it is served by, and whether or not it is served by barge – both measures interacted with rail distance.) We include interactions between the Title IV dummy and the coal characteristics, to allow their implicit prices to vary with the regime. We also include monthly dummy variables to allow for seasonal effects.

While we focus on the effect of regulation on the "net railhead price" and transportation rate, the change in the coefficient on sulfur content under Title IV is also of considerable interest. After 1995, plants incurred an additional marginal cost of burning coal equal to the price of an allowance per ton of SO_2 emitted. This allowance price ranged between \$70 and \$210. The implicit price on sulfur content under Title IV should be of the same magnitude, and negative (since higher-sulfur coal corresponds to greater emissions of SO_2).

Let p_{ijt} denote the delivered price of coal net of the minemouth price (in dollars per ton) at time t under contract i to plant j. Our basic regression equation is the following:

$$\begin{aligned} p_{ijt} \quad = \quad & \beta_{00} + \beta_{01} TIV_t + \gamma_{00} \cdot DIST_j + \gamma_{01} \cdot DIST_j \cdot TIV_t + \psi \cdot DIST_j \cdot COSTINDX_t \\ & + \mathbf{x}_{ijt} \boldsymbol{\beta} + \mathbf{z}_j \boldsymbol{\gamma} + \text{month dummies} + \eta_{ijt}. \end{aligned} \tag{4}$$

Two variables (and their interactions) are of primary interest. $DIST_j$ is the rail distance (in miles) from the PRB to the power plant. TIV_t is a dummy variable that equals 1 after Title IV took effect. (We include the second half of 1994 in the regulatory period to account for lag time between when coal is delivered and when it is burned.[27]) We control for variable cost by including the cost index discussed above times the rail distance. As discussed above, $\hat{\psi}$ is then an estimate of the average variable cost in the base year (1990), leaving $\hat{\gamma}_{00}$ as an estimate of the price-cost margin.

The vector $\mathbf{x}_{ijt}$ includes time-varying characteristics of the delivery, including the SO_2 content of the coal as well as other characteristics and the size of the purchase. These characteristics are interacted with TIV_t as well, to allow the implicit prices of coal characteristics (in particular, SO_2 content) to vary with the policy regime.[28] Plant-level characteristics (the nameplate capacity of the plant and its transportation options) are contained in $\mathbf{z}_j$, which is constant across time. We include month dummies to allow for seasonal effects in coal prices.

The dependent variable is the delivered price of coal minus the contemporaneous minemouth price of coal, expressed in 1995 dollars per ton.[29] We measure sulfur content in terms of the SO_2 emissions (in tons) that would be released from burning a ton of coal.[30] Thus regression coefficients on this variable can be interpreted as implicit prices in dollars per ton of SO_2. Rail

[27] Coal can only be stored for a limited period of time before it is used because it can absorb moisture and the surface can weather, impairing combustion. Under many contracts, excess weathering or moisture can be grounds for rejecting a shipment.

[28] Because we are interested in the implicit prices of SO_2 (in particular) before and after the start of the allowances program, we include the delivery characteristics interacted with $(1 - TIV_i)$ and TIV_j, rather than including them "whole" along with an interaction term with TIV_j.

[29] Form 423 reports the data in nominal cents/mmBtus; we use the reported heat content of the coal to convert the price into dollars per ton, and then deflate all dollars values using the intermediate-goods Producer Price Index.

[30] One ton of sulfur in coal produces somewhat less than two tons of sulfur dioxide in the flue gases: the molecular weight of SO_2 is twice that of S, but of course the coal is not perfectly combusted. There are variations in the exact output of SO_2 per ton of S in the coal, depending on the heat content of the coal burned and on the characteristics of the boiler. To convert reported sulfur content (in percent by weight) into SO_2 emissions, we used benchmark emissions factors that would apply to the most common boilers, adjusting for the heat content of the coal.

distances are measured in miles, giving their coefficients the interpretation of rates per ton-mile. We also normalize several variables (SO_2, ash, and heat contents; quantity; and nameplate capacity) by subtracting their grand means. Doing so aids interpretation: The constant term β_{00} thus represents the "net railhead price" of an average shipment of coal to a plant served by one rail line and also by barge. By "net railhead price," we mean the delivered price (net of minemouth price) minus the portion attributable to distance. Since the minemouth price that is received by the coal mine itself has been subtracted off, the constant term estimates the implicit fixed charge (per ton but not varying with distance) collected by the railroad. The coefficient β_{01} thus measures the change in the net railhead price after Title IV. If the cost index variable were excluded, γ_{00} would represent the rate per ton-mile; with the cost index included, γ_{00} represents the *margin* the railroad earns above its costs, and γ_{01} measures the change in the margin after the new policy took effect.

The full sample comprises all spot-market deliveries of PRB coal reported on Form 423 from January 1990 to December 2000 to plants that were served by railroad, and for which we have necessary data. Table 2 presents summary statistics.

6.2 Results

We present our results in three subsections. The first contains the results from estimating equation 4 via OLS. We then allow for correlation between deliveries under the same contract. A final subsection discusses the results and their interpretation.

6.2.1 OLS

Comparisons among Phase I plants before and after Title IV Table 3 presents the results obtained from estimating equation 4 by OLS for all plants that received PRB coal between 1990 and 2000. Table 3 contains three columns. Column 1 is a benchmark regression which includes only the distance, cost, and coal characteristics. The first two rows present results on how delivered prices vary with distance. The cost index that is a component of the *"Real cost index * RR distance"* variable reported in the second row tracks nominal changes in railroad costs and has a 1990 base year. Since the dependent variable is measured in real 1995 dollars, we deflate this cost index by the price index used to deflate the dependent variable; the remaining index reflects changes in real costs. The estimated coefficient of 0.005 can be interpreted, as described in section 4, as indicating that costs accounted for 5 mills (0.5 cents) per ton-mile of the delivered price in 1990 and for an amount that varies quarter-by-quarter in proportion to the cost index. The coefficient on the *"RR distance"* variable reported in the first column indicates that the railroads earned a margin of 2 mills per ton-mile above the costs.

Finally, the positive and significant constant term indicates that, even after subtracting the minemouth price, and accounting for distance, cost, coal and plant characteristics, and seasonal effects, there is a \$4.08 per ton component of delivered price unaccounted for. We term this the "net railhead price" (where "net" indicates "net of contemporaneous minemouth price"). Since we report our coal characteristics as deviations from means, this net railhead price can be understood as the zero distance price for coal of average characteristics, or as the implicit "fixed fee" or "per ton" (as opposed to "per ton-mile") component of delivered coal prices.

It is important to understand that this is an implied fixed fee. We do not observe railroad tariffs that are broken out explicitly into fixed fees and per ton-mile fees. What we observe is delivered per ton prices as reported on Form 423. The contracts themselves are confidential, and what we have gleaned anecdotally about their form suggests that the fees that are specified as independent of distance are not as large as what we estimate here. Therefore, our "net railhead price" should

Table 2: Summary statistics

Variable	Mean	Standard deviation	Minimum	Maximum
TABLE A PLANTS				
Pre-Title IV	$N = 493$			
Coal price (1995 $/ton)	19.814	4.853	11.787	34.895
RR distance to PRB (miles)	1202.254	299.127	716	1711
Plant served by multiple RRs	0.211	0.408	0	1
Plant captive to one RR	0.706	0.456	0	1
Namecap capacity of plant (GWe)	1.175	0.705	0.212	3.340
SO_2 content (tons per ton coal)	0.006	0.002	0.003	0.009
Heat content (btus/lb)	8632.7	170.376	8249	8954
Ash content (% by weight)	5.060	1.043	4.1	25.58
Quantity (000 tons)	47.599	47.245	0.1	246
Post-Title IV	$N = 908$			
Coal price (1995 $/ton)	16.526	2.476	11.208	37.824
RR distance to PRB (miles)	1164.314	236.593	716	1699
Plant served by multiple RRs	0.262	0.440	0	1
Plant captive to one RR	0.554	0.497	0	1
Namecap capacity of plant (GWe)	1.121	0.760	0.141	3.340
SO_2 content (tons per ton coal)	0.005	0.001	0.003	0.010
Heat content (btus/lb)	8625.305	214.165	7969	9003
Ash content (% by weight)	5.200	0.555	3.1	7.08
Quantity (000 tons)	63.803	59.621	0.1	497
ALL PLANTS				
Pre-Title IV	$N = 1938$			
Coal price (1995 $/ton)	18.780	5.379	7.375	80.678
RR distance to PRB (miles)	1172.698	362.856	348	1881
Plant served by multiple RRs	0.301	0.459	0	1
Plant captive to one RR	0.618	0.486	0	1
Namecap capacity of plant (GWe)	1.115	0.833	0.088	3.564
SO_2 content (tons per ton coal)	0.006	0.001	0.003	0.010
Heat content (btus/lb)	8599.603	205.245	7382	9406
Ash content (% by weight)	5.049	0.802	3.6	25.58
Quantity (000 tons)	60.402	67.036	0.1	526
Post-Title IV	$N = 4299$			
Coal price (1995 $/ton)	17.428	4.640	6.843	44.148
RR distance to PRB (miles)	1211.124	339.025	320	2248
Plant served by multiple RRs	0.213	0.409	0	1
Plant captive to one RR	0.677	0.468	0	1
Namecap capacity of plant (GWe)	1.195	0.910	0.116	3.564
SO_2 content (tons per ton coal)	0.006	0.001	0.003	0.010
Heat content (btus/lb)	8609.896	199.832	7969	9374
Ash content (% by weight)	5.187	0.550	0.56	10.67
Quantity (000 tons)	72.958	81.982	0.1	1297.312

Table 3: Results from OLS estimation: Spot deliveries to all plants

Dependent variable: Delivered coal price net of minemouth price (1995 $/ton)	(1)	(2)	(3)
RR distance (miles)	0.002 **	0.005 **	0.005 **
	(0.001)	(0.001)	(0.001)
Real cost index * RR distance	0.005 **	0.004 **	0.004 **
	(0.001)	(0.001)	(0.001)
Title IV		2.486 **	1.873 **
		(0.595)	(0.664)
Title IV * RR distance		-0.002 **	-0.002 **
		(0.001)	(0.001)
SO_2 content[b] (tons per ton coal)	336.831 **	199.698	189.665
	(97.727)	(106.053)	(108.061)
Title IV * SO_2 content[b]		148.577	129.367
		(81.733)	(88.731)
Heat content[b] (Btus/lb)	0.005 **	0.004 **	0.004 **
	(0.001)	(0.001)	(0.001)
Ash content[b] (% by weight))	-0.180	0.125	0.107
	(0.176)	(0.189)	(0.177)
Quantity[b] (000 tons)	-0.000	0.002	0.003
	(0.001)	(0.004)	(0.004)
Nameplate capacity of plant[b] (GWe)	0.631 **	0.427 *	0.463 **
	(0.100)	(0.168)	(0.163)
Plant served by multiple railroads * RR distance	0.000 (0.000)	0.000 (0.000)	0.000 (0.000)
Plant captive of single railroad (no barge) * RR distance	0.002 ** (0.000)	0.002 ** (0.000)	0.002 ** (0.000)
Table A unit			-2.254 *
			(0.932)
Table A * RR distance			0.002 **
			(0.001)
Table A * Title IV			4.894 **
			(1.452)
Table A * Title IV * RR distance			-0.005 **
			(0.001)
Table A * Title IV * SO_2 content[b]			84.707
			(127.989)
Constant	4.081 **	2.438 **	2.804 **
	(0.341)	(0.467)	(0.501)
Observations	6237	6237	6237
R-squared	0.55	0.55	0.56

Notes: * significant at 5 % level ** at 1 % level
[a] Denotes variables expressed as deviations from grand means.
Specification also includes month dummies and Title IV interactions with heat content, ash content, quantity, and nameplate capacity.

be understood as the intercept of a predicted location-price "schedule" which is actually the result of individual negotiations between railroads and plants at different locations.

Considering now the other covariates in the regression, the results in all three columns of the table indicate that prices are higher for coal with higher heat content, as one would expect. Ash content and delivery size, however, do not have a statistically significant effects on price. Plants that have a single railroad delivery option (no other railroads and no barge service) pay significantly higher prices. The results in all three columns of Table 3 indicate that such plants pay 2 mills (0.2 cents) more per ton-mile in delivered price than do plants with more transportation options. Larger capacity plants, somewhat unexpectedly, also pay higher prices for coal. The coefficient in the first column indicates that a 100 megawatt increase in plant capacity (about 10% of the average plant size) is associated with a 6.3 cent per ton increase in delivered price, a result that is not economically large despite its statistical significance. This result would be less surprising if it were the case for purchases under long-term contract, where large buyers might pay a premium to guarantee supply, but this is a less compelling story in for the spot market transactions that make up the estimation sample. The estimated parameter on the sulfur content of coal is positive and significant, suggesting that in the absence of an incentive to reduce SO_2 emissions, PRB coal with higher sulfur content is more valuable – presumably because of other unobserved characteristics correlated with sulfur content.[31]

Column 2 adds the indicator for transactions that occurred after Title IV took effect.[32] Before Title IV, the railroads charged a net railhead price of $2.44 per ton and a 5 mill per ton-mile markup over costs. After Title IV, the predicted per ton price doubles, rising by $2.47, while the predicted markup falls by 2 mills per ton-mile.

The combined effect of these two changes was to raise prices for plants close to the PRB and lower them for plants further away. For the estimates in column 2, the "breakeven" distance at which delivered prices were unaffected was 1040 miles. Closer in, price went up; further away, price went down. (For comparison, the mean delivery distance in the sample for Phase I plants during Title IV was 1213 miles, and the median was 1292 miles.) While the differences may appear to be a matter of pennies per ton, they translate into substantial amounts of money per delivery: the average delivery of PRB coal during the Title IV period was over 70,000 tons.

Comparisons among Phase I plants before and after Title IV Table 3 shows that the same results emerge when we include in the estimation sample deliveries to plants that were not brought under the tradeable-permits regime during Phase I.[33] Including these plants allows us to estimate the effect of Title IV not only by doing a pre versus post comparison of the price paid by Phase I firms, but also to compare the effect of the advent of regulation on the affected (Phase I) and unaffected firms. This is analogous to a difference-in-differences specification.

In the final column, the specification distinguishes between power plants with units that were directly regulated by the allowance market (the "Table A" plants) and those that were not. This allows us to test whether the regulatory regime itself explains the shift in the price schedule.

[31] Although both the federal NSPS-D regime and most state-level regulations impose limits on SO_2 emissions rates, *all* PRB coal satisfies those standards. Hence there is no marginal incentive *within* PRB coal to pay more for lower sulfur.

[32] As described above, the Title IV indicator equals one for all transactions occuring in July 1994 or later to account for the fact that power plants likely make their purchases in the second half of 1994 anticipating the commencement of the regulatory period in January 1995. The results presented here change very little if the Title IV period is defined as beginning in October 1994 instead.

[33] For this specification, we drop observations after December 1999, when the trading program expanded to include all sizeable power plants.

The coefficient estimates for the coal and plant characteristic control variables are little changed from column 2. Figure 12 may be helpful in interpreting the remaining results. The figure plots the price schedule predicted by the coefficients in column 3 for Table A and non-Table A plants both before and after Title IV takes effect. (Again, since the covariates are deviations from their grand means, these schedules represent the prices for coal of average characteristics delivered to plants of average characteristics at different distances. The dependent variable is net of minemouth prices, so the actual delivered prices at these locations would be about $4-5 higher than what is plotted here.)

As the graph shows, the effect of Title IV is to flatten the price schedule, raising prices within about 1025 miles of the PRB and lowering prices at greater distances. This effect is larger for Table A plants than for non-Table A plants. For non-Table A plants, after Title IV per ton-mile prices are lower by two mills (0.2 cents) and per ton prices higher by $1.87 than they were pre-Title IV. For Table A plants after Title IV, per ton-mile rates are lower by an *additional* 5 mills and per ton prices higher by an additional $4.89.

The close correspondence with the earlier regressions gives compelling confirmation of the results. That the railroads appear to have been able to charge different prices *at the same point in time* to plants under different policy regimes supports the claim that they were able to price discriminate in their exercise of market power. Such a degree of price discrimination is hardly implausible. In particular, there is no plausible scope for plants to arbitrage price differences away through resale. Coal delivered to power plants by rail is typically expelled from specialized hydraulic railcars onto a vast coal pile, whence it travels by conveyor belt into adjacent boilers. Loading the coal back into trucks for transport to nearby power plants would cost far more than the differences in delivered coal prices; and one may assume that the railroads themselves would be unwilling to redirect coal shipments themselves in order to erode their own profit margins.

6.2.2 Random effects

Delivery contracts negotiated among power plants, coal mines, and railroads are likely to vary in ways unobservable to the econometrician: a plant manager may be a strong negotiator, the timing of a particular contract may prove particularly advantageous to the buyer or the railroad, and so on. These effects will likely be constant across deliveries under a given contract. To account for such unobserved heterogeneity, while allowing estimation of the effects of time-invariant plant characteristics (e.g., distance from the PRB), we utilize a random-effects specification. We utilize the same regression equation specified in equation 4, but separate out η_{ijt} into two terms, u_{ij} and ε_{ijt}.

$$\begin{aligned} p_{ijt} &= \beta_{00} + \beta_{01} TIV_t + \gamma_{00} \cdot DIST_j + \gamma_{01} \cdot DIST_j \cdot TIV_t + \psi \cdot DIST_j \cdot COSTINDX_t \\ &\quad + \mathbf{x}_{ijt}\boldsymbol{\beta} + \mathbf{z}_j\boldsymbol{\gamma} + \text{month dummies} + u_{ij} + \varepsilon_{ijt}. \end{aligned} \tag{5}$$

Thus u_{ij} is a *contract*-specific random effect with zero mean and variance σ_u^2. (Recall that the "spot market" deliveries analyzed in this paper are defined as contracts of less than one year in length. Hence the random effects correspond to plant-source-year triples. Since we count July 1994 as the start of Title IV, we treat January-June 1994 and July-December 1994 as separate "years" in the random effect plant-source-year triples.) The residual ε_{ijt} is taken to represent random variation in delivered prices at the level of the individual delivery, and is assumed to be i.i.d. with zero mean and variance σ^2.

The random effect results are reported in Table 4, whose three columns echo the specifications of Table 3. In many ways, the results are very similar to the results of the OLS specifications. The cost of railroad transportation is estimated to be 4-5 mills per ton-mile in the base year of

Table 4: Random effects estimation results: Spot deliveries to all plants

Dependent variable: Delivered coal price net of minemouth price (1995 $/ton)	(1)	(2)	(3)
RR distance (miles)	0.002 **	0.005 **	0.004 **
	(0.001)	(0.001)	(0.001)
Real cost index x RR distance	0.005 **	0.004 **	0.004 **
	(0.001)	(0.001)	(0.001)
Title IV		1.843 *	1.262
		(0.730)	(0.786)
Title IV * RR distance		-0.002 **	-0.001
		(0.001)	(0.000)
SO_2 content[b] (tons per ton coal)	108.171	105.011	91.431
	(71.036)	(72.031)	(72.029)
Title IV * SO_2 content[b]		-33.307	-63.371
		(43.353)	(45.725)
Heat content[b] (Btus/lb)	0.003 **	0.002 **	0.002 **
	(0.000)	(0.001)	(0.001)
Ash content[b] (% by weight))	0.019	0.007	0.006
	(0.050)	(0.065)	(0.065)
Quantity[b] (000 tons)	-0.000	-0.000	-0.000
	(0.000)	(0.001)	(0.001)
Nameplate capacity of plant[b] (GWe)	0.635 **	0.708 **	0.766 **
	(0.120)	(0.197)	(0.196)
Plant served by multiple railroads * RR distance	0.000	0.000	0.000
	(0.000)	(0.000)	(0.000)
Plant captive of single railroad (no barge) * RR distance	0.002 **	0.002 **	0.002 **
	(0.000)	(0.000)	(0.000)
Table A unit			-3.123 *
			(1.550)
Table A * RR distance			0.003 **
			(0.001)
Table A * Title IV			3.620
			(2.004)
Table A * Title IV * RR distance			-0.004 *
			(0.002)
Table A * Title IV * SO_2 content[b]			194.280
			(104.477)
Constant	3.987 **	2.725 **	3.332 **
	(0.349)	(0.607)	(0.656)
Observations	6237	6237	6237
Number of contracts (groups)	1505	1505	1505

Notes: * significant at 5 % level ** at 1 % level
[a] denotes variables expressed as deviations from their grand means.
Specification also includes month dummies and Title IV interactions with heat content, ash content, quantity, and nameplate capacity.

1990, and in columns 2 and 3 the railroads are estimated to charge a markup of 5 and 4 mills per ton-mile above that, very similar results to those in Table 3. The covariates also produce similar results: heat content, nameplate capacity, and multiple delivery options are what have statistically significant effects on delivered prices.

The column of most interest is column 3. This is also the specification whose results most differ from the analogous OLS specification. In column 3, Title IV is not estimated to have a statistically significant effect on the price schedules for non-Table A firms (as captured by the coefficients on *"Title IV"* and *"Title IV * RR distance"*; p-values on both coefficients are 0.11. However, Title IV does have a significant effect on Table A firms. Even pre-Title IV, Table A firms face a statistically significantly different price schedule. The coefficient on the *"Table A unit"* dummy variable of -3.123 and on the *"Table A * RR distance"* variable of 0.003 indicates that pre-Title IV Table A firms faced a steeper price schedule than non-Table A firms. After Title IV, the implied per ton fee rose by \$3.62 (p-value 0.071), and the per-ton mile price fell by 4 mills. As with the OLS result, this implies that Title IV raised prices for some plants (those within 885 miles of the PRB), and lowered delivered prices to the most distant plants.

The price schedules predicted by the coefficients of column 3 of Table 4 for Table A and non-Table A plants in the pre- and post-Title IV periods are graphed in Figure 13. (In this figure, the point value of all coefficients are used even though some are of borderline statistical significance.)

6.2.3 Discussion

Earlier in the paper we argue that from the perspective of the coal mines and railroads of the Powder River Basin, the effect of Title IV can be seen as a increase in demand for low-sulfur coal and for transportation of the coal from the PRB to points east. We also argue that railroads have market power in transporting coal from the PRB. At first blush, it may therefore seem surprising that the effect of Title IV is to lower prices over a greater geographic range than prices rise, and generally to lower prices by more where they decrease than the amount by which they rise where they increase. As we argued in section **??**, however, the effect of a cap-and-trade regime would indeed be to flatten the price schedule. More distant customers are predicted to be offered delivered prices that are a lower markup on costs than nearby customers.

In a monopoly setting, the intuition behind this result is very simple. Suppose a price discriminating monopolist faced demand from two separable groups, one with more elastic demand (charged a lower price) and one with less elastic demand (charged a higher price). If the market with more elastic demand were to grow by the addition of buyers who were yet more elastic, the monopolist might indeed make greater profits by lowering the price in the more elastic market even further, and making up the difference on volume.

In the low-sulfur coal market, there is evidence that railroads are doing just this. Even though prices are falling, revenues are going up. Based on the reported price and quantity information in the data set, railroad revenues (calculated as the difference between real delivered price per ton and minemouth price, times delivery quantity) are about double in the post-Title IV period what they were in the pre-Title IV period. While prices are falling over much of the delivery region, quantities approximately triple, making the net change in revenue positive. Revenues are not profits, and we do not have cost information in our data other than the cost index, so we cannot calculate profits directly. However, the cost index falls by more than 30% between 1990 and 1999, which strongly suggests that railroad profits are indeed increasing after Title IV.

There is ample reason to believe that Table A firms might have more elastic demand than other purchasers of low-sulfur coal, and perhaps also more elastic demand after the imposition of Title IV than before. Title IV allows plants three choices for compliance: using low-sulfur coal, scrubbing emissions, and buying permits. The permit option gives Table A plants more flexibility than plants covered by the NSPS-D emissions standard, which should give them weakly more elastic demand for low-sulfur coal than firms regulated by emissions standards. This is particularly salient since allowance prices turned out to be substantially lower than most ex ante forecasts, making allowances an attractive substitute.[34]

Interestingly, this analysis suggests a connection between the exercise of market power by railroads and the relatively low delivered price of PRB coal for distant utilities – primarily those in the Midwest – during Phase I. Our results above suggest that the cost to many utilities of complying with Title IV by switching to low-sulfur PRB coal was lower than one would have predicted either on the basis of prices charged to non-Table A plants, or to Table A plants prior to the regulation. Ellerman and Montero (1998) attribute the observed drop in PRB coal prices to the railroad deregulation, but do not explain the reason for the long lag time from the enactment of the Staggers Act in 1980 and the fall in prices in the mid-1990s. Our analysis points to price discrimination as a key factor. Because railroads are able to price discriminate, they ultimately find it profit maximizing to lower the delivered price of low-sulfur coal as a result of the regulation. While the existence of market power presumably causes welfare losses relative to a perfectly competitive benchmark, the ability to spatially price discriminate leads railroads to lower instead of raise their rates in response to Title IV.[35]

7 Conclusion

The aim of this paper is to understand how the tradeable permits system for SO_2 emissions created by the Clean Air Act Amendments of 1990 affected the market for low-sulfur coal. We present two primary empirical findings. First, low-sulfur coal from the Powder River Basin has penetrated consistently further east over the last fifteen years, consistent with the simple Hotelling model presented. The pattern of eastward movement over time suggests that it was driven at least in part by Title IV.

Second, the advent of Title IV coincided with increases in the price of PRB coal delivered by the two railroads that serve the region. After the allowance trading program took effect, the railhead price of PRB coal rose by two to three dollars per ton – representing an increase of thirty to one hundred percent over the prior railhead price. At the same time, estimated transportation rates fell by two to four mills per ton-mile. The net effect was to increase the price of delivered coal from the PRB for western plants (within approximately 1000 miles), while lowering the price on the extensive margin. The results suggest that railroads are able to price discriminate both geographically and among customers who face different regulatory regimes.

These observed changes are consistent with a strategy of lowering marginal prices to expand market share, while recouping their losses through a fixed fee. Indeed, the prices the railroads charge to carry coal east act "as if" they are levying a two-part tariff in order to capture rents from their market power – much as the theoretical model developed in this paper suggests. If they are not actually able to impose a two-part tariff (due to railroad regulation), they seem to be achieving the functional equivalent of such a price schedule. Hence the railroads appear to have captured a sizeable share of the gains from regulation.

[34]Of course, the price of PRB coal was a significant factor in the lower-than-expected allowance prices. But other factors, such as an overinvestment in scrubbers and expanded low-sulfur coal production in other regions, also contributed significantly.

[35]Mansur (2004) analyzes a similar interaction of environmental regulation and market power in the context of production decisions by generators competing in restructured electricity markets.

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8 Model appendix

In this appendix, we provide proof of the various claims made in Section 3 . We first describe the basic model and summarize the notation. We then make a few preliminary remarks before developing the results.

8.1 The basic model and notation

There are two sources of coal, located at the endpoints of a line of unit length. A unit population of coal consumers ("power plants") with unit demand is distributed uniformly and continuously along the line. Let the coal from the western endpoint (denoted 0) be "low-sulfur coal," with sulfur dioxide emissions of m_0 per unit of output; let coal from the eastern endpoint 1 be "high-sulfur coal" with sulfur dioxide emissions $m_1 > m_0$ per unit of output. Let the marginal extraction cost of the two coals be constant at each origin and denoted c_0 and c_1.[36] Both coals are assumed to be in unlimited supply: i.e., there is neither a short-run capacity constraint on production, nor any positive scarcity rent. Let the marginal costs of transportation ("railroads") from the two sources be constant and given by t_0 and t_1, respectively. As for the case of mining, we assume that there are no capacity constraints on transportation. Finally, denote distance along the line from 0 by d, and let $p_j(d)$ be the delivered price of coal from origin j to point d.

Notation is summarized below:

j indexes origins $\{0, 1\}$

d distance from origin 0

c_j unit extraction cost at origin j

t_j unit transportation cost at origin j

m_j pollution emissions of coal from j, $m_0 < m_1$ by assumption

q total allowable emissions (number of permits)

b boundary between coals from 0 and 1

$p_j(d)$ delivered price of coal from origin j at d

z price of pollution permit

$\lambda(z)$ fraction of plants to right of boundary b that emit at m_0 (either by buying low-sulfur coal elsewhere or by scrubbing); $\lambda' > 0, \lambda'' < 0$ (as seen shortly, these assumptions correspond to positive and increasing marginal costs of abatement.)

r_j fixed fee charged by railroad from origin j, net of extraction cost; assume $r_1 = 0$

ρ_j per-unit-distance fee charged by railroad from origin j, net of transport cost; assume $\rho_1 = 0$.

8.2 Perfect competition

As a benchmark, consider a "baseline scenario" with perfect competition (equivalently, Bertrand competition) among coal mines at each end point and among railroads. In this case, prior to regulation on emissions, coal prices settle to long-run average costs. The "minemouth prices" of coal (the prices of coal at the mine, before the cost of transportation is added in) are $p_0(0) = c_0$

[36] Increasing marginal costs of extraction would complicate the analysis without adding insight. A "marginal user cost" or "Hotelling scarcity rent" ((?)) could be incorporated into the marginal extraction cost without affecting the results, as long as the stocks of low- and high-sulfur coal are large enough that regulation-induced changes in demand will not affect scarcity. In the current context, where coal stores are sufficient for many years at current rates of use, this seems to be a reasonable assumption.

For a treatment of the interaction between geographic dispersion and scarcity rents of mineral resources when this assumption does *not* hold, see (?).

and $p_1(1) = c_1$. Delivered prices are, respectively, $p_0(d) = c_0 + t_0 d$ and $p_1(d) = c_1 + t_1(1-d)$. Equivalently, the fixed fee and net transportation charge are both zero: $r_0 = \rho_0 = 0$.

The plant located at geographic boundary b between low- and high-sulfur coal must be indifferent between burning low- and high-sulfur coal. In the absence of environmental regulation, this implies that the delivered coal prices must be equal:

$$\begin{aligned} c_0 + r_0 + (t_0 + \rho_0) b &= c_1 + t_1(1-b) \\ b_0 &\equiv \frac{c_1 + t_1 - c_0}{t_0 + t_1}. \end{aligned} \tag{6}$$

Now suppose that a tradeable permits system for SO_2 is introduced, with total allowable emissions equal to $q < m_0 \cdot b_{NR}^{PC} + m_1 \cdot \left(1 - b_{NR}^{PC}\right)$, i.e., less than emissions would be in the absence of regulation. Let $z > 0$ denote the price of emissions permits, and let $\lambda(z)$ represent the fraction of plants east of the boundary that adopt alternative forms of abatement. (For ease of exposition, we will refer to alternative forms of abatement as "scrubbing," but they could also include other sources of low-sulfur coal, as discussed in the text.) The function $\lambda()$ reflects the cost of scrubbing and the variation in that cost among plants: it is essentially an inverse marginal cost function. For ease of modeling, we shall suppose that plants with scrubbers can burn high-sulfur coal but emit at rate m_0. Our results extend in obvious ways to the case in which abatement yields another (constant) emissions rate.

Because environmental regulation does not affect the costs of extraction or transportation, it cannot affect the price under perfect competition. After the introduction of regulation, $r_0 = \rho_0 = 0$ as before, and delivered prices remain $p_0(d) = c_0 + t_0 d$ and $p_1(d) = c_1 + t_1(1-d)$.

We can again use an indifference condition to derive the boundary under regulation:

$$b = \frac{(c_1 - c_0) + t_1 - r_0 + (m_1 - m_0) z}{t_0 + \rho_0 + t_1}, \tag{7}$$

which is a function of the permit price z. Total emissions must equal the cap q:

$$b m_0 + (1-b)\left[\lambda(z) m_0 + (1 - \lambda(z))\, m_1\right] = q \tag{8}$$

The permit price z must adjust to satisfy this condition. Solving for $\lambda(z)$ yields $\lambda(z) = 1 - \frac{q - m_0}{(1-b)(m_1 - m_0)}$. By construction, the inverse of the function $\lambda(z)$ is the aggregate marginal abatement cost function. Hence the permit price must satisfy z:

$$z = MC\left(1 - \frac{q - m_0}{(1-b)\,(m_1 - m_0)}\right). \tag{9}$$

This provides an implicit definition of z, since the boundary b is itself a function of the permit price. The indifference condition (7) and condition (9) offer two equations in two unknowns.

Note that differentiating (9) with respect to b yields

$$\frac{\partial z}{\partial b} = MC'\left(1 - \frac{q - m_0}{(1-b)\,(m_1 - m_0)}\right)\left(-\frac{(q - m_0)}{(1-b)^2\,(m_1 - m_0)}\right) < 0. \tag{10}$$

Hence the permit price falls as the boundary extends eastward. This is intuitive, since the demand for permits falls as the share of coal that is low in sulfur rises.

8.3 Monopoly power in transportation

Assume monopoly in transportation out of 0 and perfect competition out of 1. Continue to assume that coal is produced competitively at both origins. The monopoly railroad out of 0 solves $\max_{r_0, \rho_0} R_0 = r_0 b + \frac{1}{2}\rho_0 b^2$, where b (and z, in the case of regulation) satisfy the conditions above, and of course $0 \le b \le 1$.

8.3.1 Unconstrained (first-best) pricing

Claim 1 *In the absence of environmental regulation, the optimal price schedule is a two-part tariff with a fixed fee* $r_0 = (c_1 + t_1 - c_0)$ *and a transportation rate of* $\rho_0 = -(t_0 + t_1)$.

To see this, note that the monopolist's total rent $R = r_0 b + \frac{1}{2}\rho_0 b^2$. Choose any arbitrary values of r_0 and ρ_0 for which the boundary $b > 0$. Then consider the following perturbation: decrease ρ_0 by $\Delta > 0$ and raise r_0 by Δb. The boundary condition (6) will be unaffected; hence the perturbation will not affect the boundary or the permit price. The rent, however, will increase by $\Delta b^2 - \frac{1}{2}\Delta b^2 = \frac{1}{2}\Delta b^2 \geq 0$. Hence the monopolist prefers to raise the fixed fee as much as possible, and reduce the transportation rate accordingly. This holds as long as $b > 0$, *i.e.,* as long as some plants buy low-sulfur coal. Hence the price of coal from 0 at its own origin must be no greater than the price of coal from 1 at the same spot, which is $c_1 + t_1$. This imposes a ceiling on the fixed fee of $r_0^* = c_1 + t_1 - c_0$, which is therefore the optimal fixed fee.

Since (6) must hold, the transportation rate ρ_0 and the boundary b must satisfy $\rho_0 = \frac{c_1 - c_0 + t_1 - r_0}{b} - (t_0 + t_1)$. Since $r_0 = c_1 - c_0 + t_1$, it follows that $\rho_0 = -(t_0 + t_1)$. Under the optimal pricing rule, the monopolist subsidizes transportation in order to extract the full surplus from consumers. Note that the *net* transportation rate is $\rho_0 + t_0 = -t_1$.

Claim 2 *The boundary* b *under a monopolist is the same as under perfect competition.*

Viewing the problem as one of choosing the boundary b, given the values of r_0 and ρ_0 just derived, we have $R = r_0 b + \frac{1}{2}\rho_0 b^2$. Substituting for r_0 and ρ_0 and setting the derivative with respect to b equal to zero yields $c_1 - c_0 + t_1 - (t_0 + t_1)b = 0$, hence $b^*_{NR} = \frac{c_1 - c_0 + t_1}{(t_0 + t_1)}$: exactly the boundary under perfect competition.

Note the boundary in this case is not actually determined directly by the pricing scheme: strictly speaking, all plants are indifferent between the two types of coal. Hence we require that the monopolist be able to deny coal to plants beyond its chosen boundary. (Alternatively, we could assume that indifferent plants abide by the monopolist's wishes; or we could allow the monopolist to raise the transportation rate by ε and lower the fixed fee by $b^*\varepsilon$.)

Note that in this model pure monopoly power has no effect on permit prices or the market share of low-sulfur coal, relative to perfect competition: the only effect is that the monopolist captures the entire rent.

Claim 3 *Under environmental regulation, the monopolist's optimal price schedule can be characterized as a two-part tariff composed of a fixed fee* $r_0 = c_1 + t_1 - c_0 + z^{PC}(m_1 - m_0)$ *(where* z^{PC} *is the permit price under perfect competition) and a transportation subsidy* $\rho_0 = -(t_1 + t_0)$. *The boundary* b *and the permit price are the same as under perfect competition.*

The logic follows the logic above exactly, except that now $z > 0$. That the permit price z is the same as prevails under perfect competition is shown below. Substituting for r_0 and ρ_0 in the monopolist's first-order condition yields $c_1 - c_0 + t_1 + z(m_1 - m_0) - (t_0 + t_1)b = 0$, hence $b^* = \frac{c_1 - c_0 + t_1 + z(m_1 - m_0)}{(t_0 + t_1)}$, which is exactly the boundary under perfect competition.

Because the boundary is the same as under perfect competition, the permit price must be as well. The fixed fee has to be just large enough to achieve this indifference, which implies that

$$
\begin{aligned}
c_0 + r_0 + (t_0 + \rho_0)b + zm_0 &= c_1 + t_1(1 - b) + zm_1 \\
\Rightarrow r_0 &= c_1 - c_0 + t_1 - (t_0 + \rho_0 + t_1)\, b + z(m_1 - m_0) \\
&= c_1 - c_0 + t_1 + z^{PC}(m_1 - m_0)
\end{aligned}
$$

where z^{PC} is found by the two conditions mentioned above, namely:

$$\begin{aligned} b_{REG}^{PC} &= \frac{c_1 - c_0 + t_1}{t_0 + t_1} + \left(\frac{m_1 - m_0}{t_0 + t_1}\right) z^{PC}; \\ z^{PC} &= MC\left(1 - \frac{q - m_0}{(1 - b_{REG}^{PC})(m_1 - m_0)}\right). \end{aligned}$$

8.3.2 Constrained pricing

Suppose now that the railroad is prevented from perfectly price-discriminating. For ease of exposition, we assume that a ceiling $\hat{r}_0$ is imposed on the fixed fee. (In the text, we discuss the polar case in which $\hat{r}_0 = 0$).

Claim 4 *In the absence of environmental regulation, the constrained monopolist sets a transportation rate larger than the first-best rate, with a boundary correspondingly closer to origin* 0*. The boundary condition (6) implies that* $\rho_0 = \frac{c_1 - c_0 + t_1 - \hat{r}_0}{b} - (t_0 + t_1)$*,with* $\partial\rho_0/\partial b = -\frac{c_1 - c_0 + t_1 - \hat{r}_0}{b^2} < 0$.

Again we frame the problem as one of choosing the boundary b. Then $R = \hat{r}_0 b + \frac{1}{2}\rho_0 b^2$, with first-order condition $\partial R/\partial b = \hat{r}_0 + \rho_0 b + \frac{1}{2}b^2\frac{\partial\rho_0}{\partial b} = 0$. Substituting for ρ_0 yields and solving yields

$$b_{NR}^{SB} = \frac{1}{2}\frac{c_1 - c_0 + t_1}{t_0 + t_1} + \frac{1}{2}\frac{\hat{r}_0}{t_0 + t_1} < \frac{c_1 - c_0 + t_1}{t_0 + t_1},$$

noting that $\hat{r}_0 < c_1 - c_0 + t_1$ by the assumption of a binding ceiling on the fixed fee. Hence the boundary is unambiguously closer to 0 under the constraint. By similar reasoning, ρ_0 is larger than it would be in the first-best case. Note that if the monopolist is entirely prevented from imposing a fixed fee, so that $\hat{r}_0 = 0$, $b_{NR}^{SB} = \frac{1}{2}\frac{c_1 - c_0 + t_1}{t_0 + t_1}$ and $\rho_0 = t_0 + t_1 > 0$. The parallels are clear with the standard case of a monopolist facing a linear demand curve and constant marginal cost.

Substituting the equation for the boundary back into the equation for ρ_0 yields

$$\rho_0 = (t_0 + t_1)\left(\frac{c_1 - c_0 + t_1 - 3\hat{r}_0}{c_1 - c_0 + t_1 + \hat{r}_0}\right).$$

Claim 5 *Under environmental regulation, the second-best monopoly boundary is closer to origin* 0 *and the transportation rate is higher than under perfect competition or the monopolist's optimal two-part tariff.*

In the case of environmental regulation, the boundary condition lets us write ρ_0 as a function of b as follows:

$$\rho_0 = \frac{c_1 - c_0 + t_1 - \hat{r}_0 + z(m_1 - m_0)}{b} - (t_0 + t_1),$$

with $\partial\rho_0/\partial b = -\frac{c_1 - c_0 + t_1 - \hat{r}_0 + z(m_1 - m_0)}{b^2} + \frac{\partial z}{\partial b}\frac{(m_1 - m_0)}{b}$.

Viewing the problem as one of choosing the boundary b, the first-order condition is $\partial R/\partial b = \hat{r}_0 + \rho_0 b + \frac{1}{2}b^2\frac{\partial\rho_0}{\partial b} = 0$. Substituting for ρ_0 and $\partial\rho_0/\partial b$ yields

$$\hat{r}_0 + c_1 - c_0 + t_1 - \hat{r}_0 + z(m_1 - m_0) - (t_0 + t_1)b + \frac{1}{2}b^2\frac{\partial\rho_0}{\partial b} = 0$$

$$\frac{1}{2}\left(c_1 - c_0 + t_1 + z(m_1 - m_0)\right) + \frac{1}{2}\hat{r}_0 - (t_0 + t_1)b + \frac{1}{2}\frac{\partial z}{\partial b}(m_1 - m_0)\, b = 0.$$

Note that $\hat{r}_0 < c_1 - c_0 + t_1 + z(m_1 - m_0)$ by the assumption of a binding ceiling on the fixed fee.

Recall that $\frac{\partial z}{\partial b} < 0$. Hence b is unambiguously smaller than it would be under the optimal two-part tariff; likewise, ρ_0 is larger than it would be in the first-best case.

Claim 6 *When the monopolist is constrained in its pricing, the effect of environmental regulation on the boundary and transportation rate depends on the slope of the marginal abatement cost function.*

Rearranging the last line above, we can write the first-order condition as follows:

$$\begin{aligned} b_{REG} &= \frac{1}{2}\frac{\hat{r}_0}{(t_0+t_1)} + \frac{1}{2}\frac{c_1-c_0+t_1}{(t_0+t_1)} + \frac{1}{2}z\frac{(m_1-m_0)}{(t_0+t_1)} + \frac{1}{2}\frac{\partial z}{\partial b}\frac{(m_1-m_0)}{(t_0+t_1)}b_{REG} \\ &= b_{NR} + \frac{1}{2}z\frac{(m_1-m_0)}{(t_0+t_1)} + \frac{1}{2}\frac{\partial z}{\partial b}\frac{(m_1-m_0)}{(t_0+t_1)}b_{REG}. \end{aligned}$$

Hence the boundary $b_{REG} > b_{NR}$ if and only if $\frac{1}{2}z\frac{(m_1-m_0)}{(t_0+t_1)} + \frac{1}{2}\frac{\partial z}{\partial b}\frac{(m_1-m_0)}{(t_0+t_1)}b_{REG} > 0$ – that is, if and only if

$$1 > -\frac{\partial z}{\partial b}\frac{b_{REG}}{z}. \tag{11}$$

The term $-\frac{\partial z}{\partial b}\frac{b_{REG}}{z} > 0$ is the elasticity of the permit price with respect to the low-sulfur coal boundary. In other words, it measures the sensitivity of the permit price to the market share of low-sulfur coal. From equation (10), $\frac{\partial z}{\partial b} < 0$ is proportional to minus the slope of the marginal cost function. Hence when the marginal cost function is flat (MC' is small), $\frac{\partial z}{\partial b}$ is small in magnitude (all else equal) and condition (11) is more likely to apply, all else equal.

Note that the transportation rate ρ_0 after regulation becomes

$$\rho_0 = (t_0+t_1)\left[\frac{c_1-c_0+t_1-3\hat{r}_0}{c_1-c_0+t_1+\hat{r}_0+z(m_1-m_0)} - \frac{\partial z}{\partial b}(m_1-m_0)\left(\frac{c_1-c_0+t_1-\hat{r}_0+z(m_1-m_0)}{c_1-c_0+t_1+\hat{r}_0+z(m_1-m_0)}\right)\right].$$

Figure 1 – Horizontal differentiation in the market for coal: The baseline case of perfect competition.

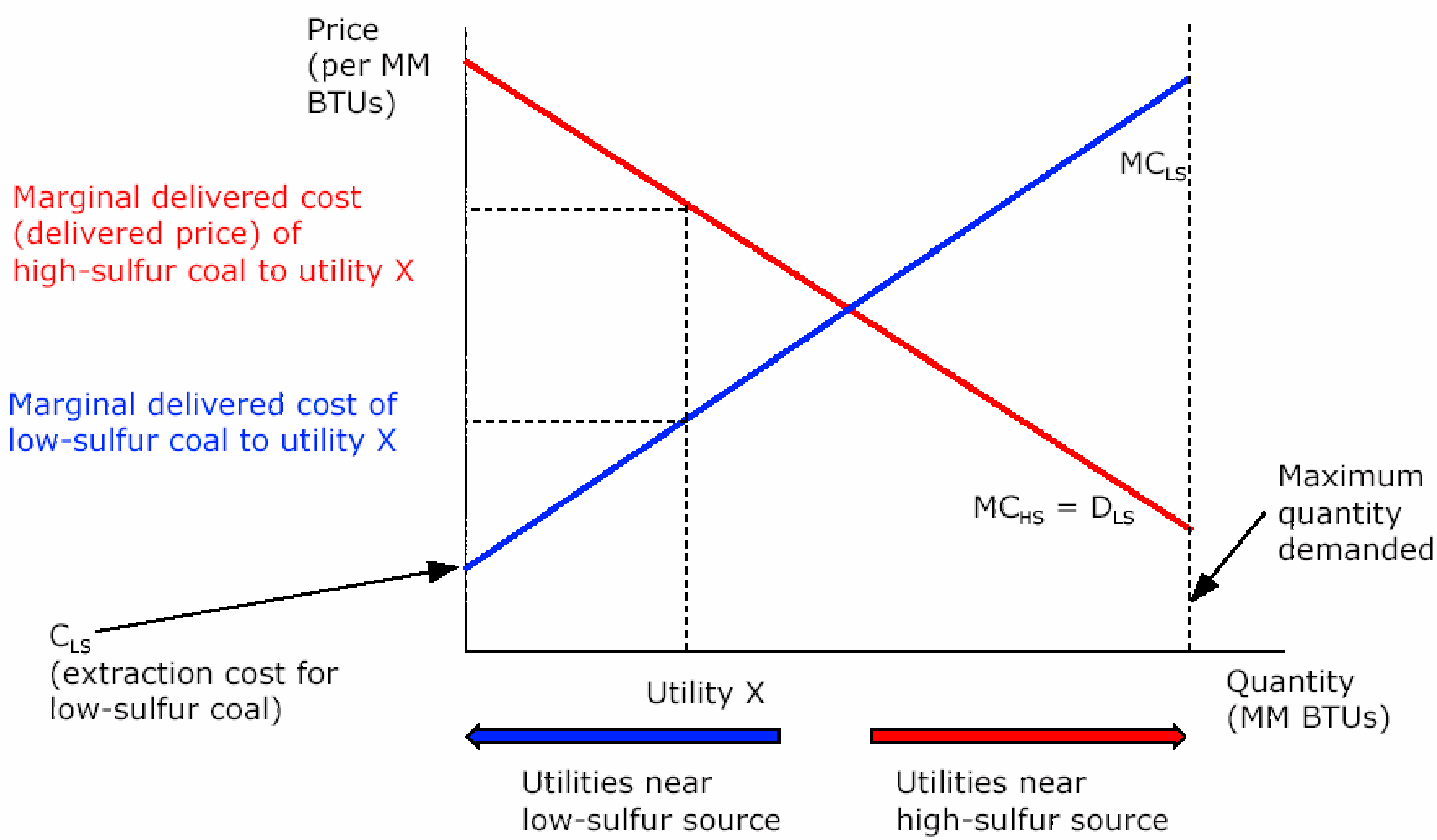


Figure 2 – Perfect price discrimination.

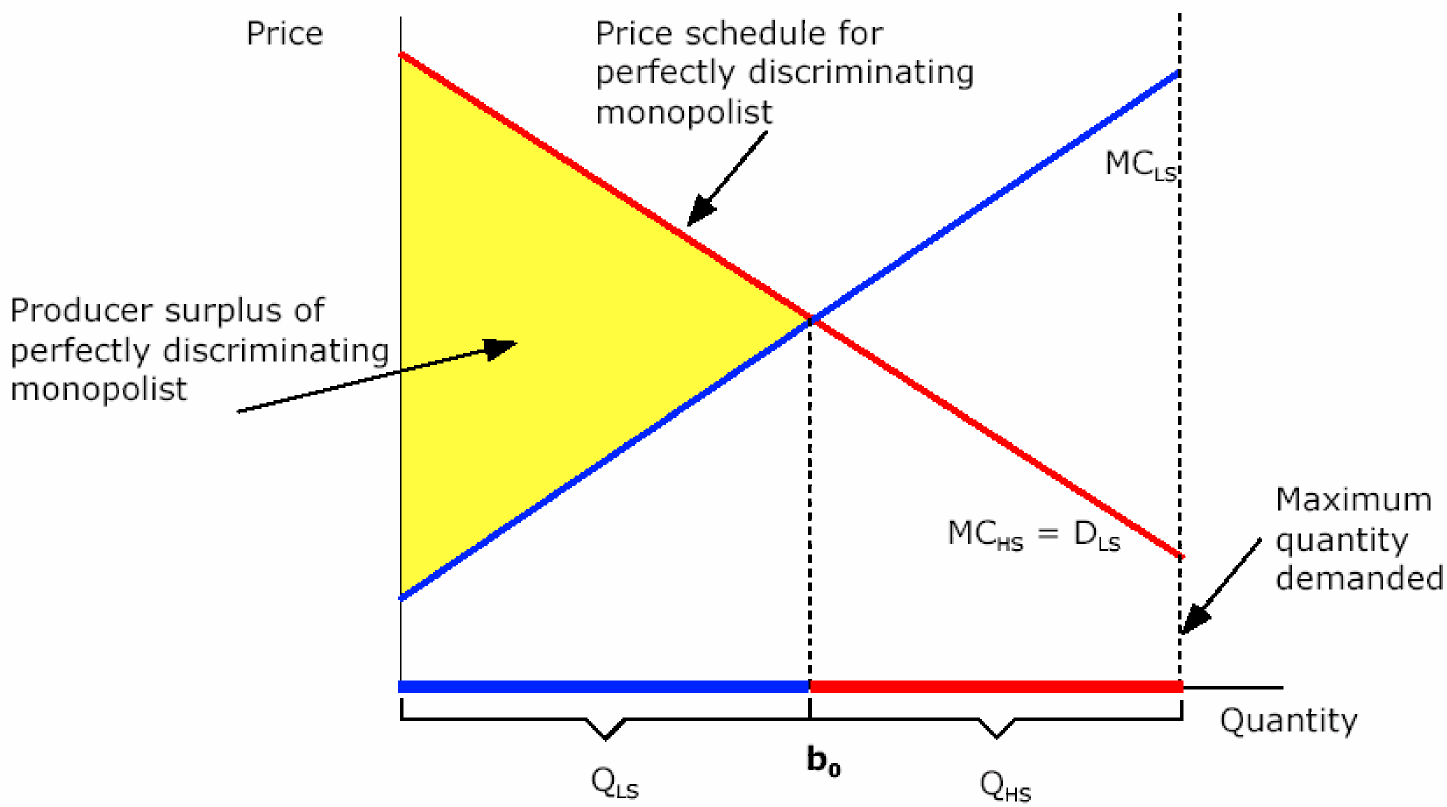


Figure 3 – Constrained market power.

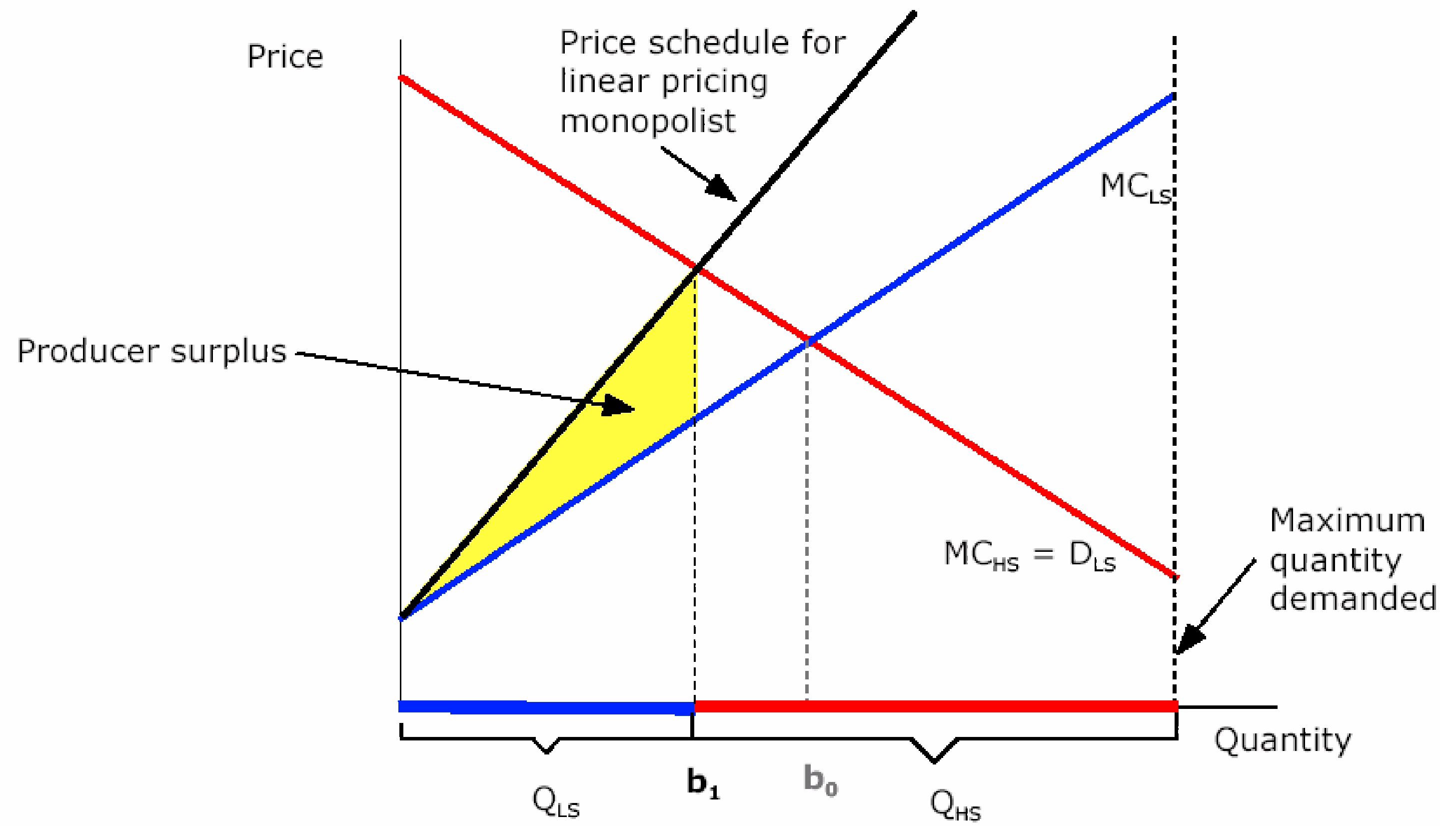


Figure 4 – Effective price schedule for a monopolist with limited ability to discriminate.

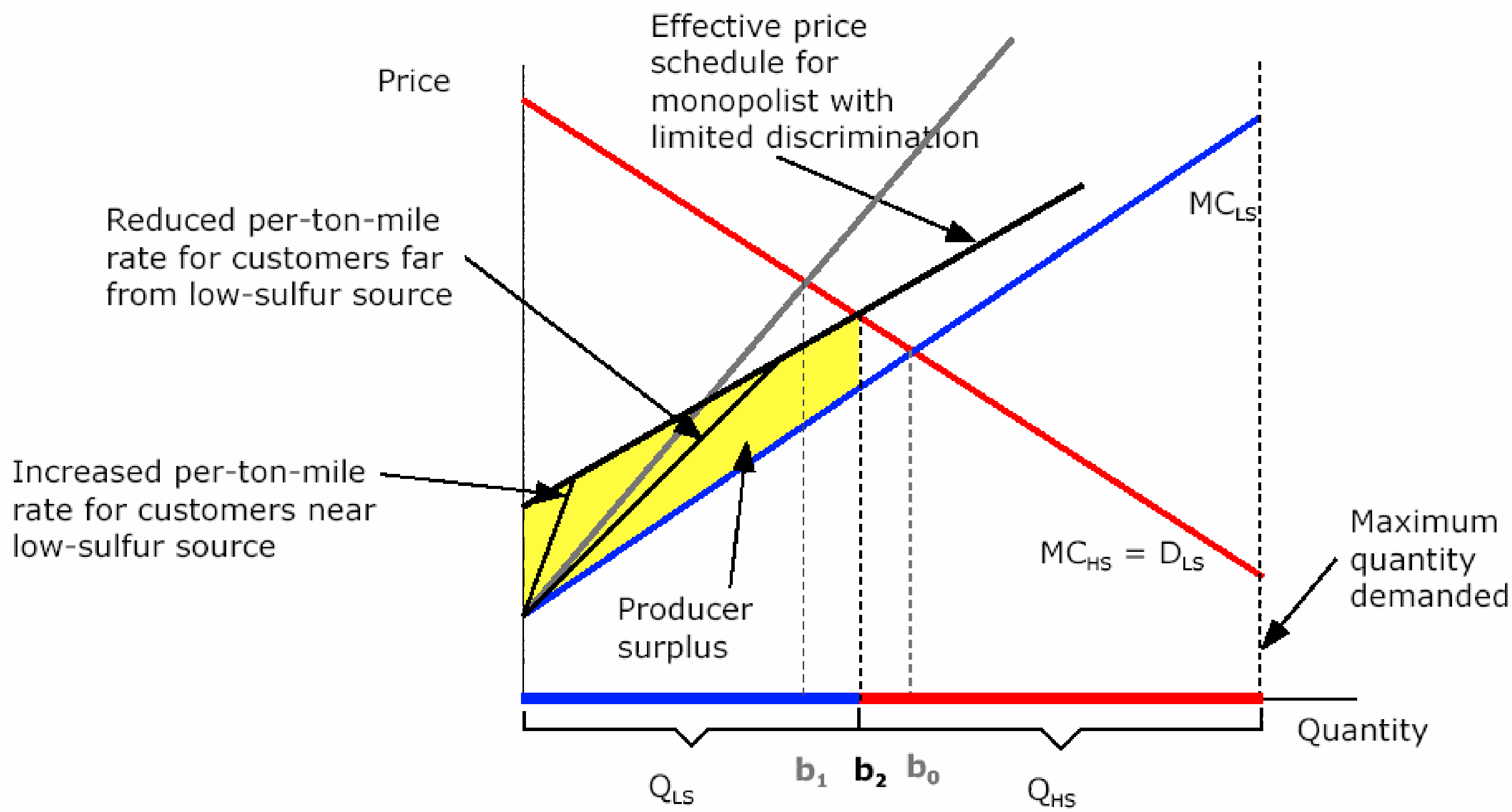


Figure 5 – Estimated marginal abatement cost curve for Title IV plants (1997).

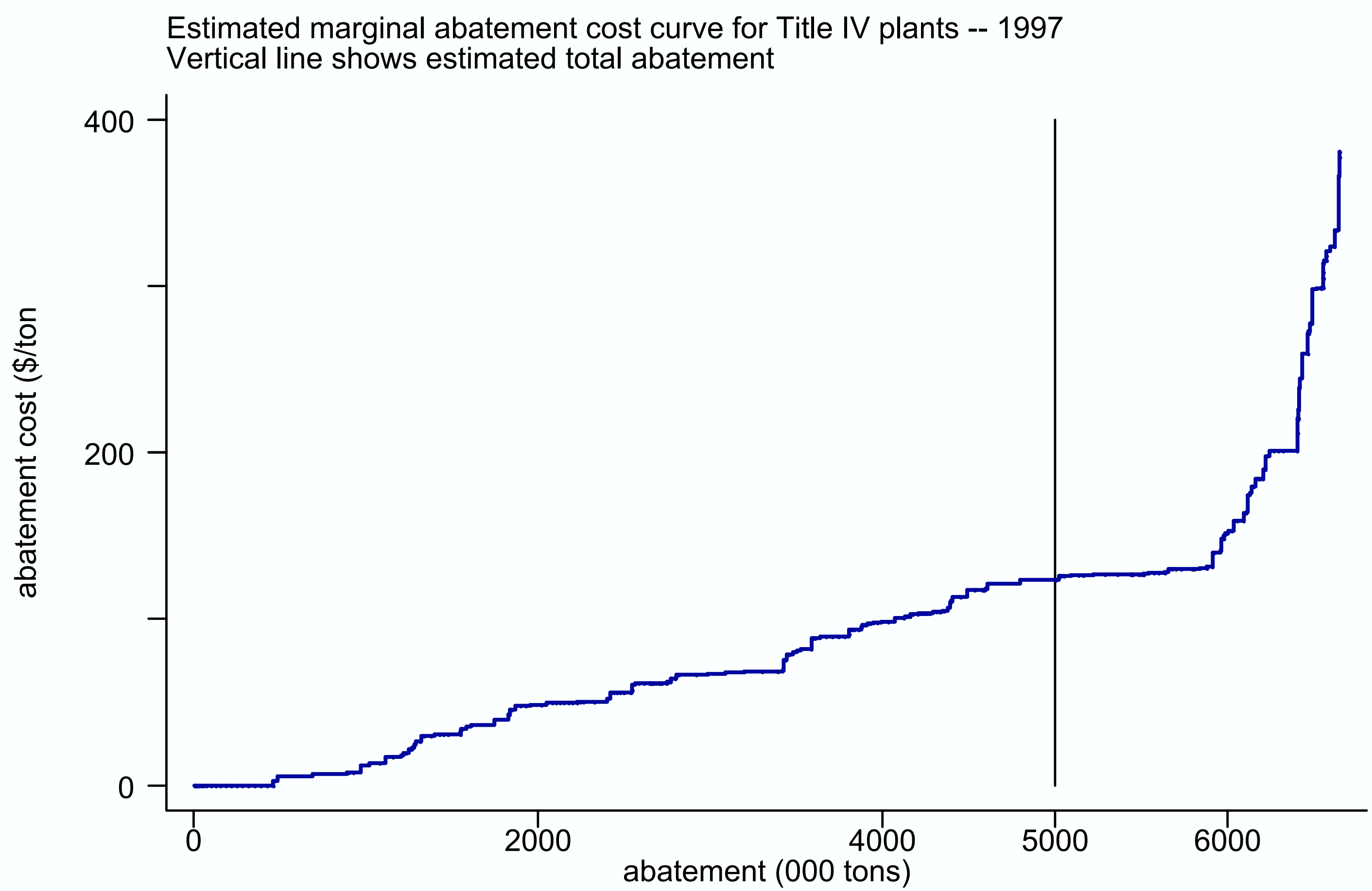


Figure 6 – Minemouth prices of PRB coal, 1990-1999.

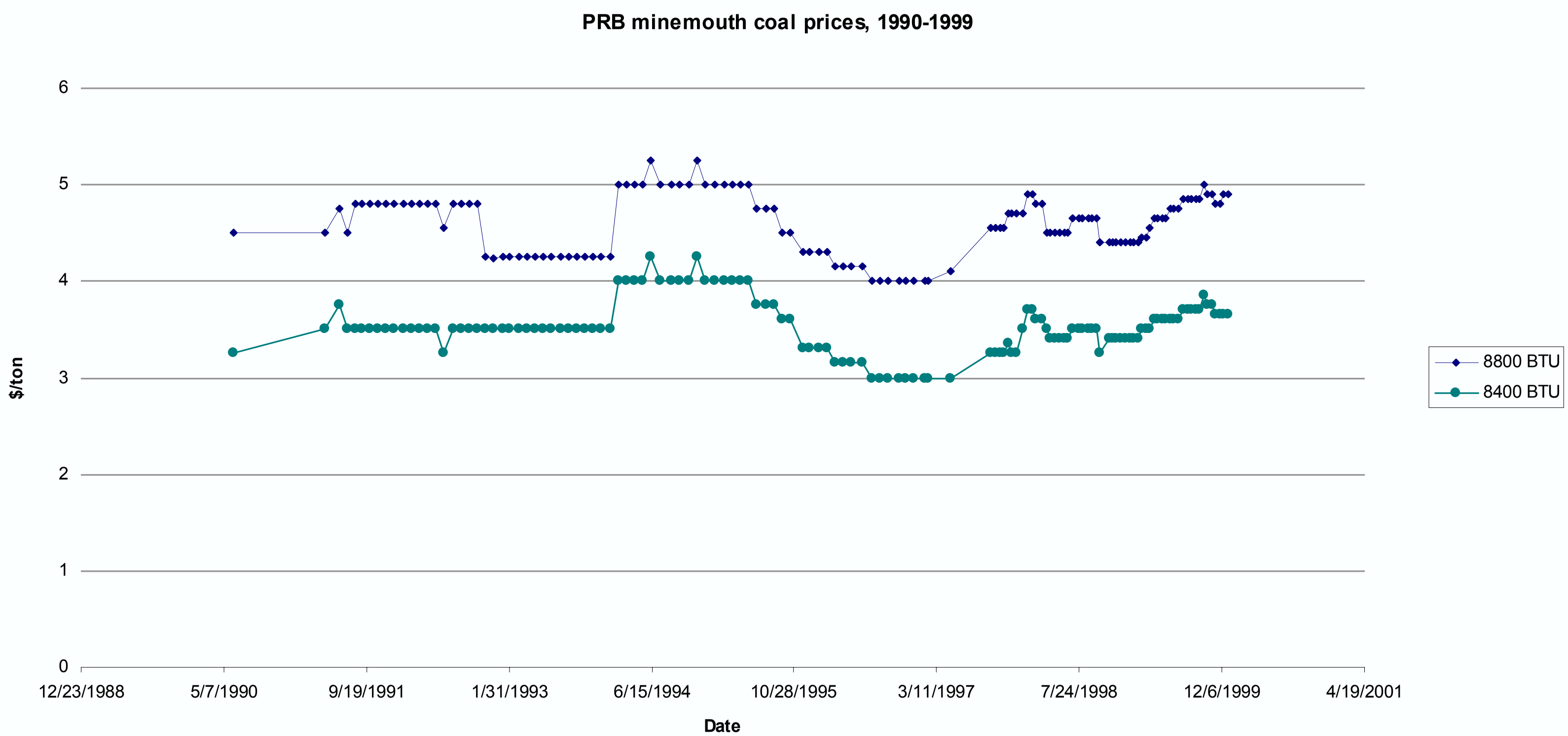


Figure 7 – Spot-market prices of delivered coal from the Powder River Basin, 1983-1999.

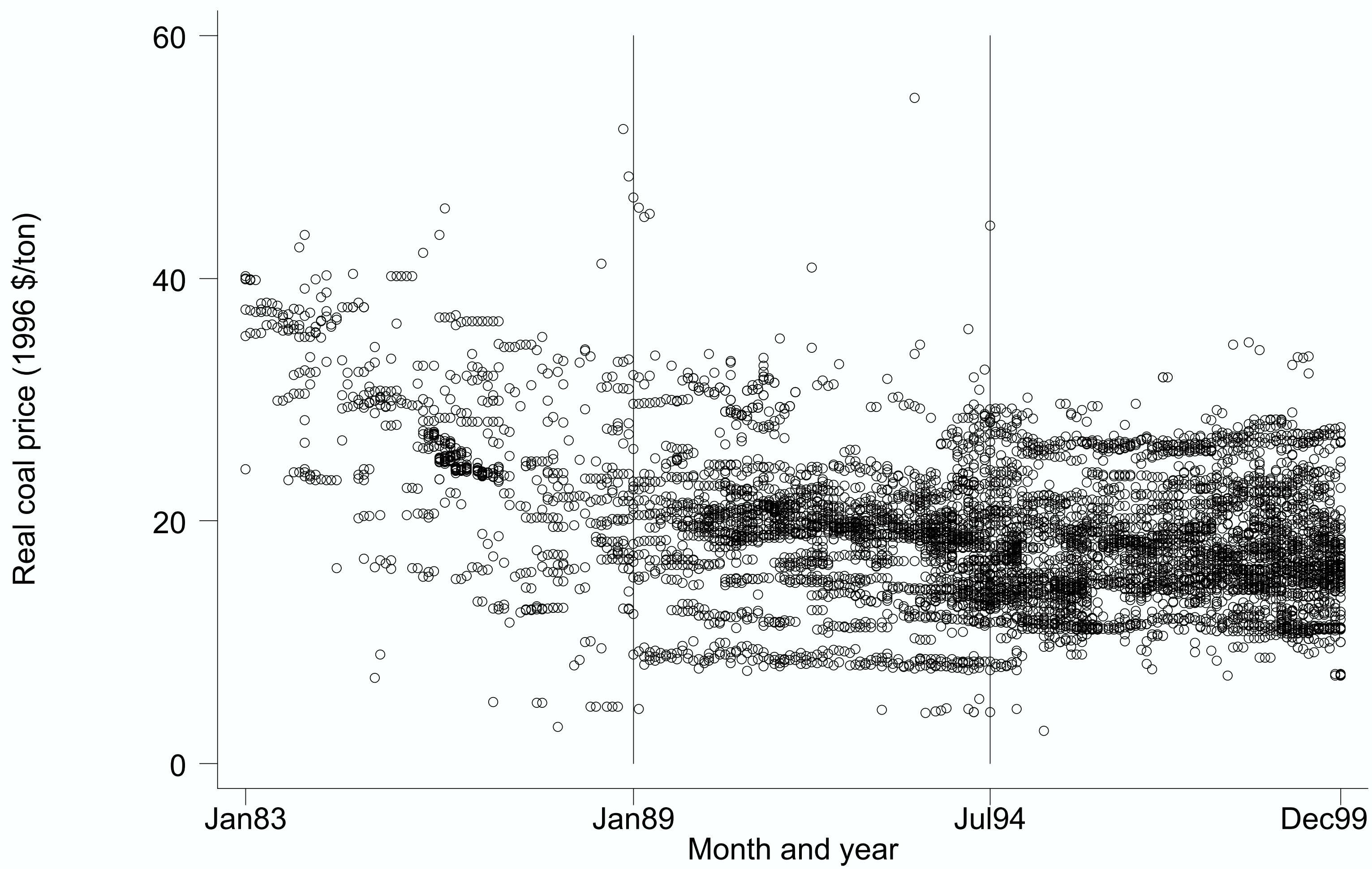


Figure 8 – Coal map of the United States.

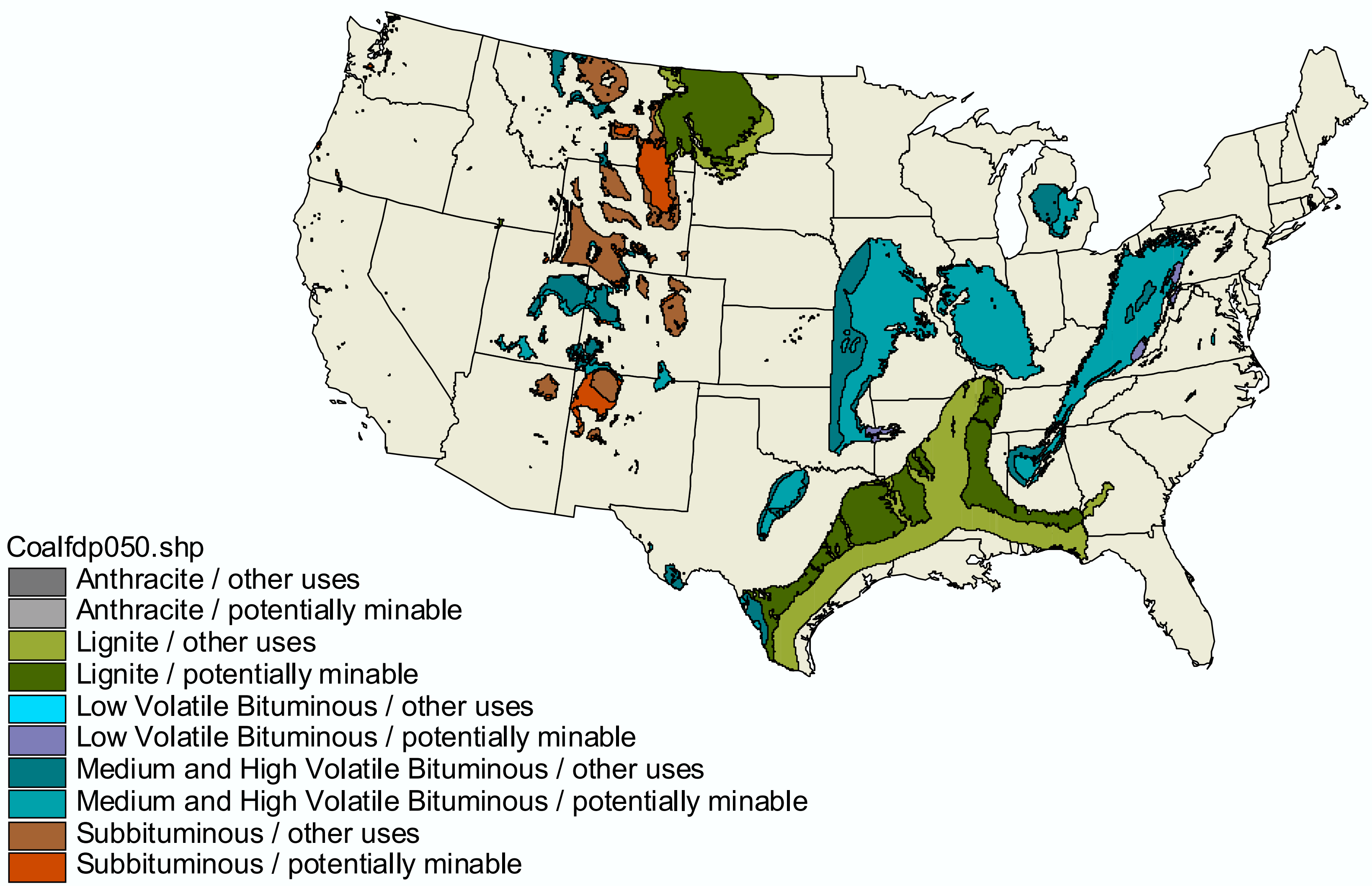
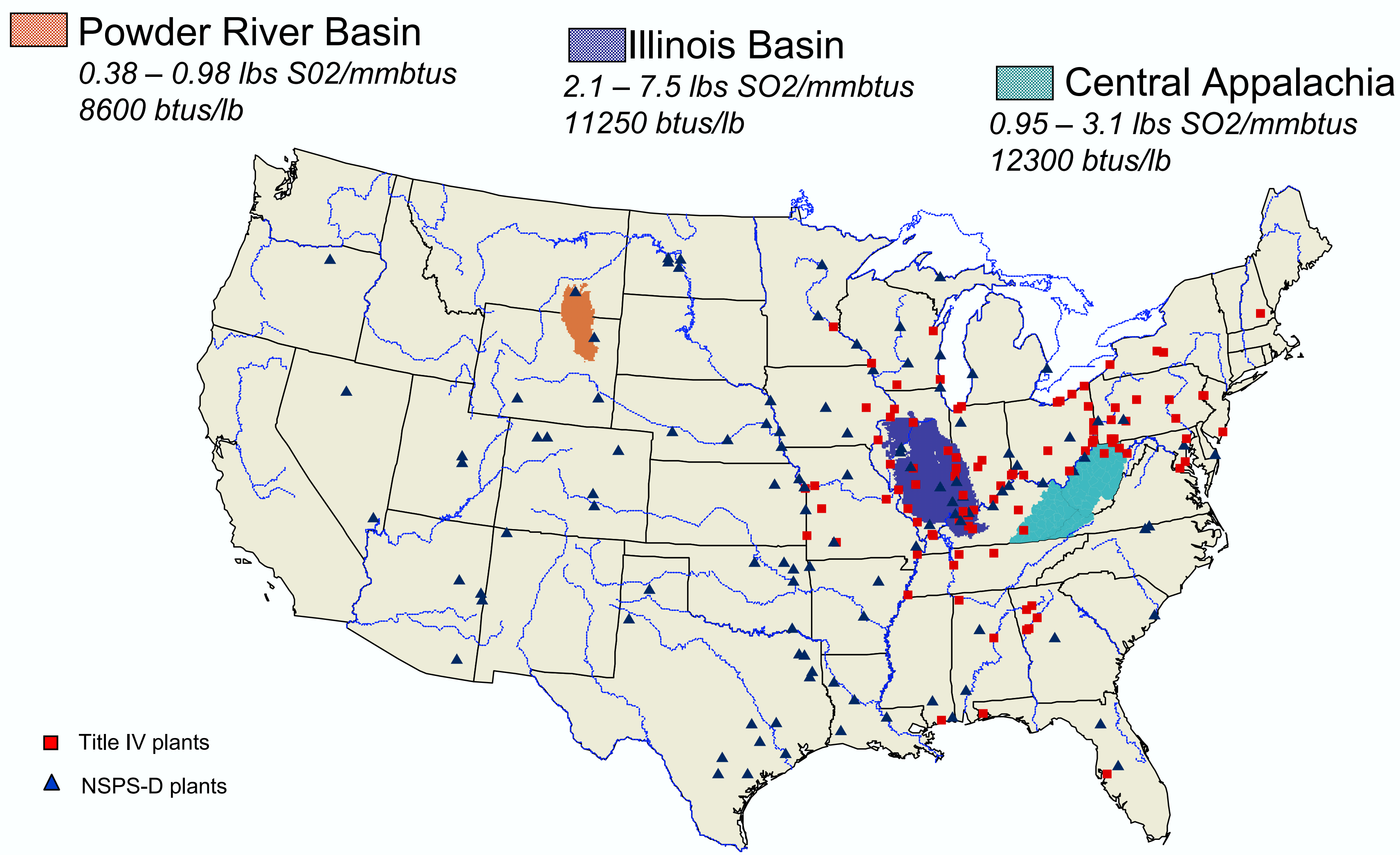
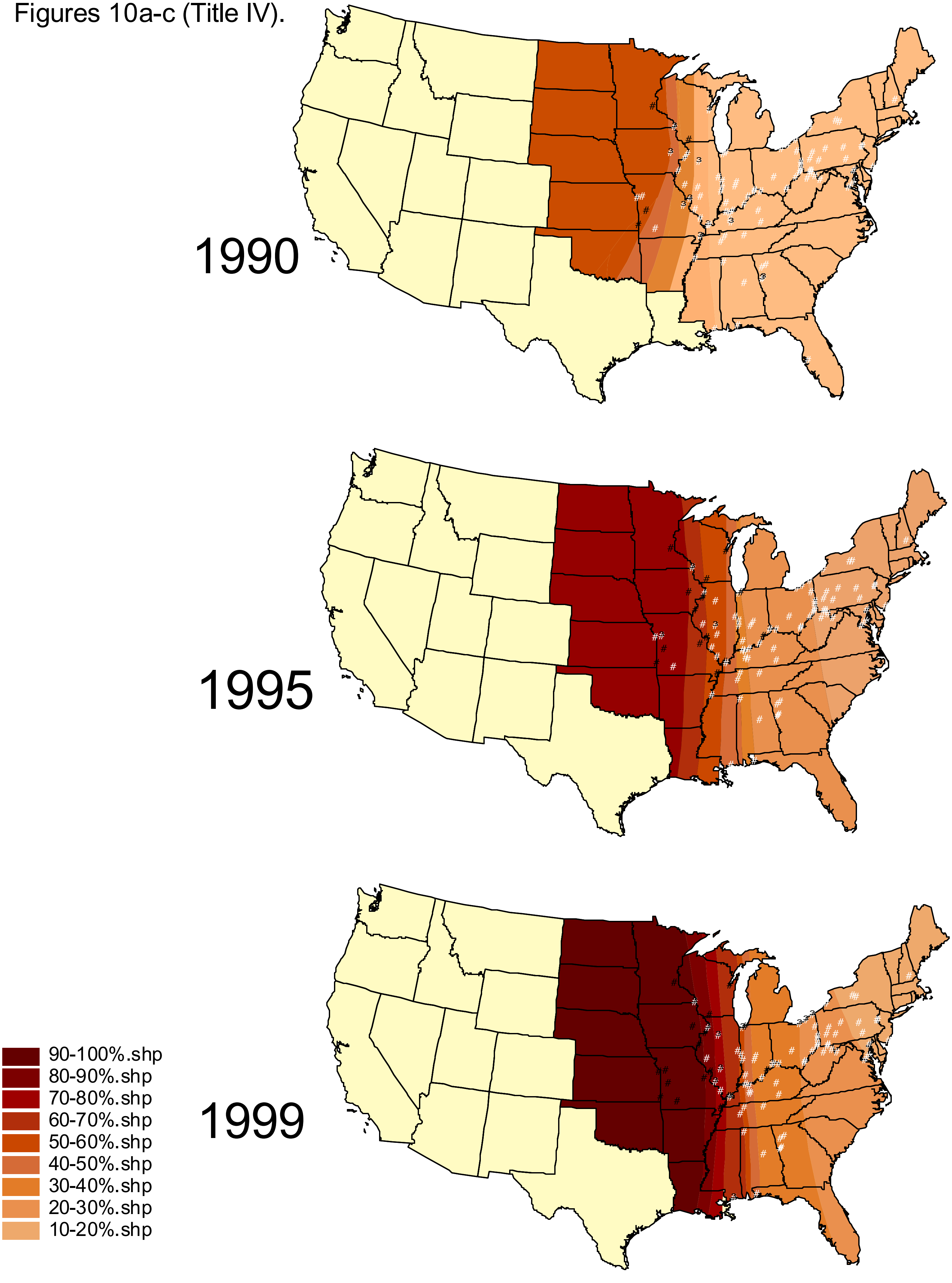


Figure 9 – Geographic distribution of regulated power plants and major coal deposits of the United States.



Figures 10a-c (Title IV).



Figures 11a-c (NSPS-D).

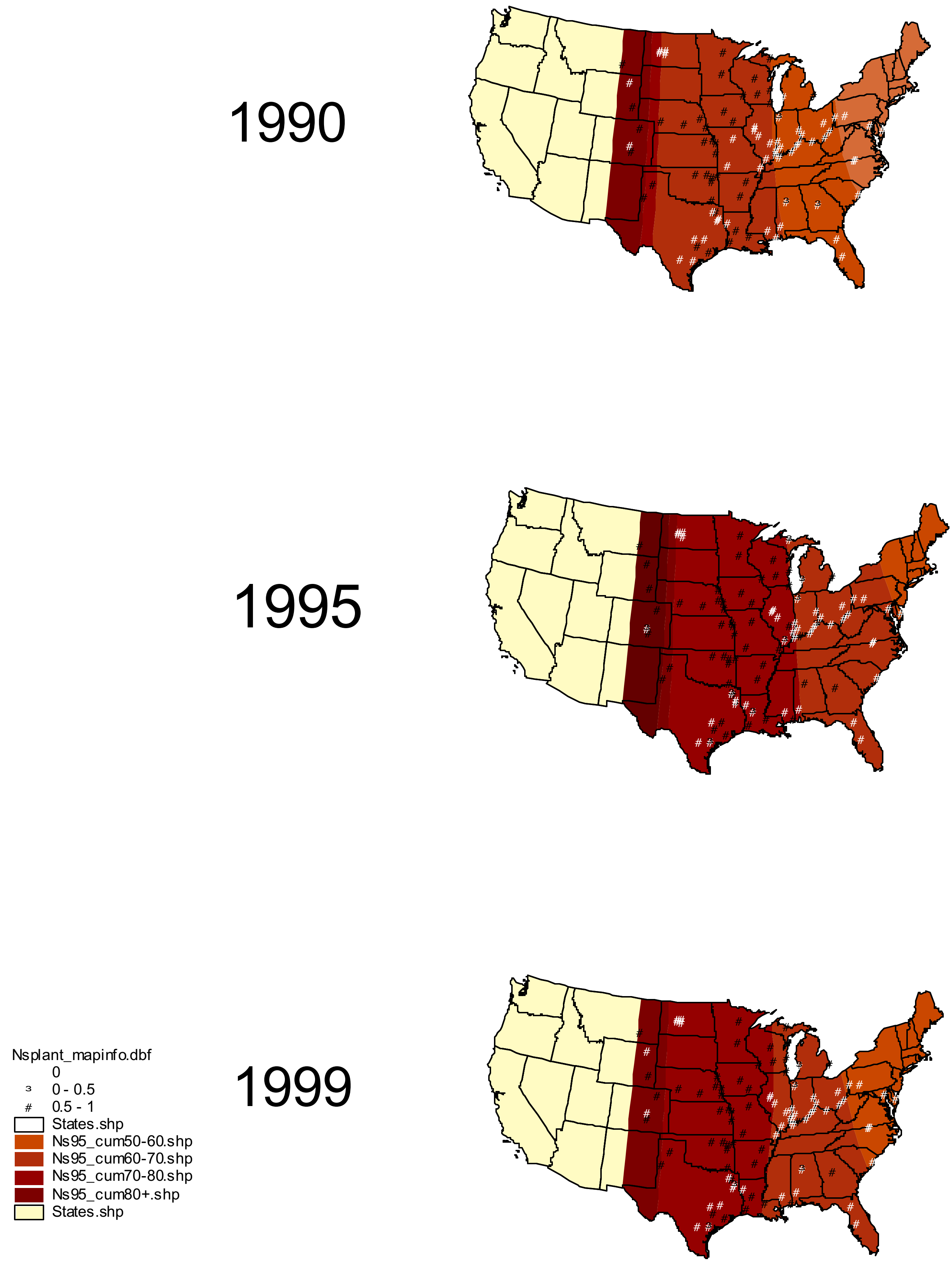
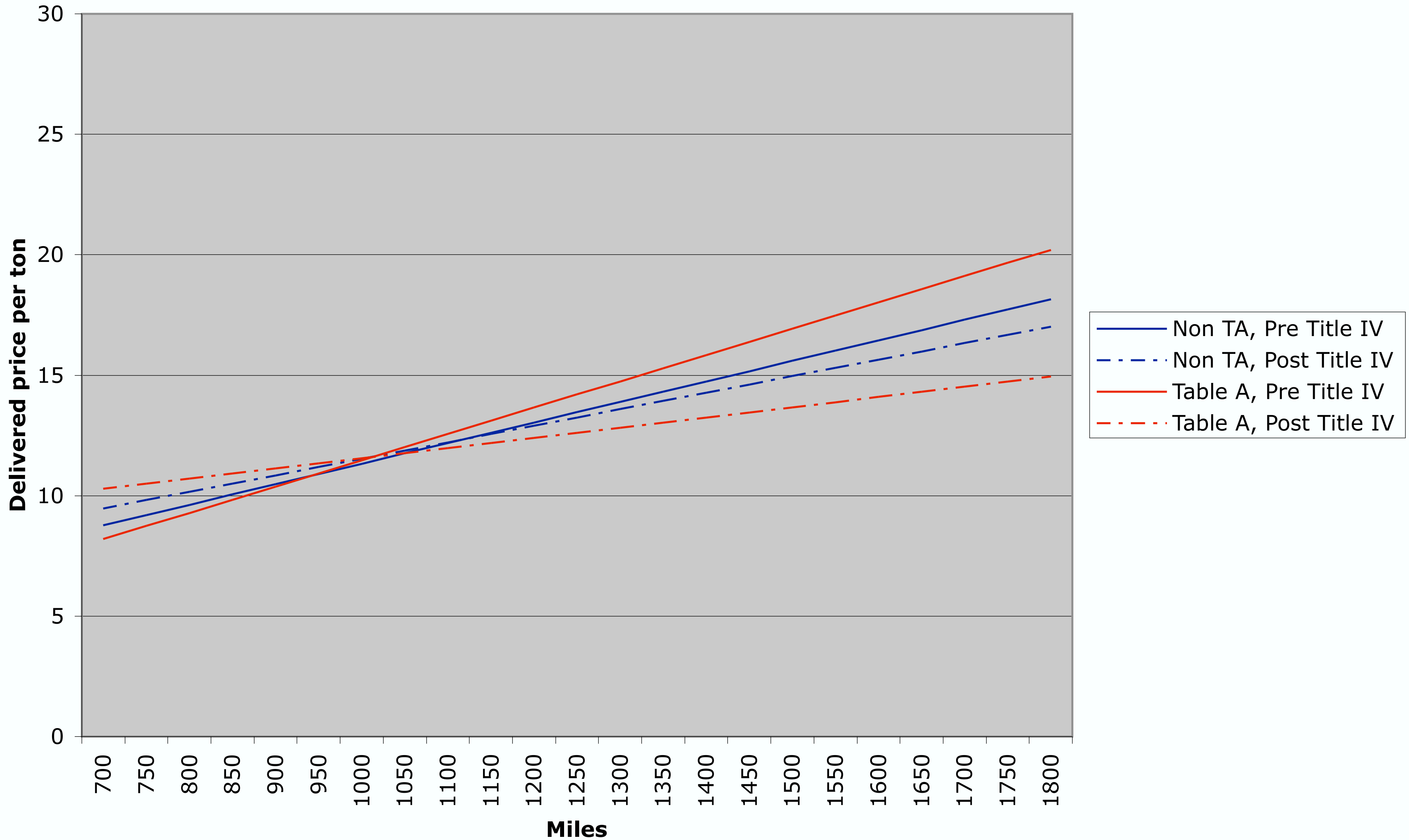
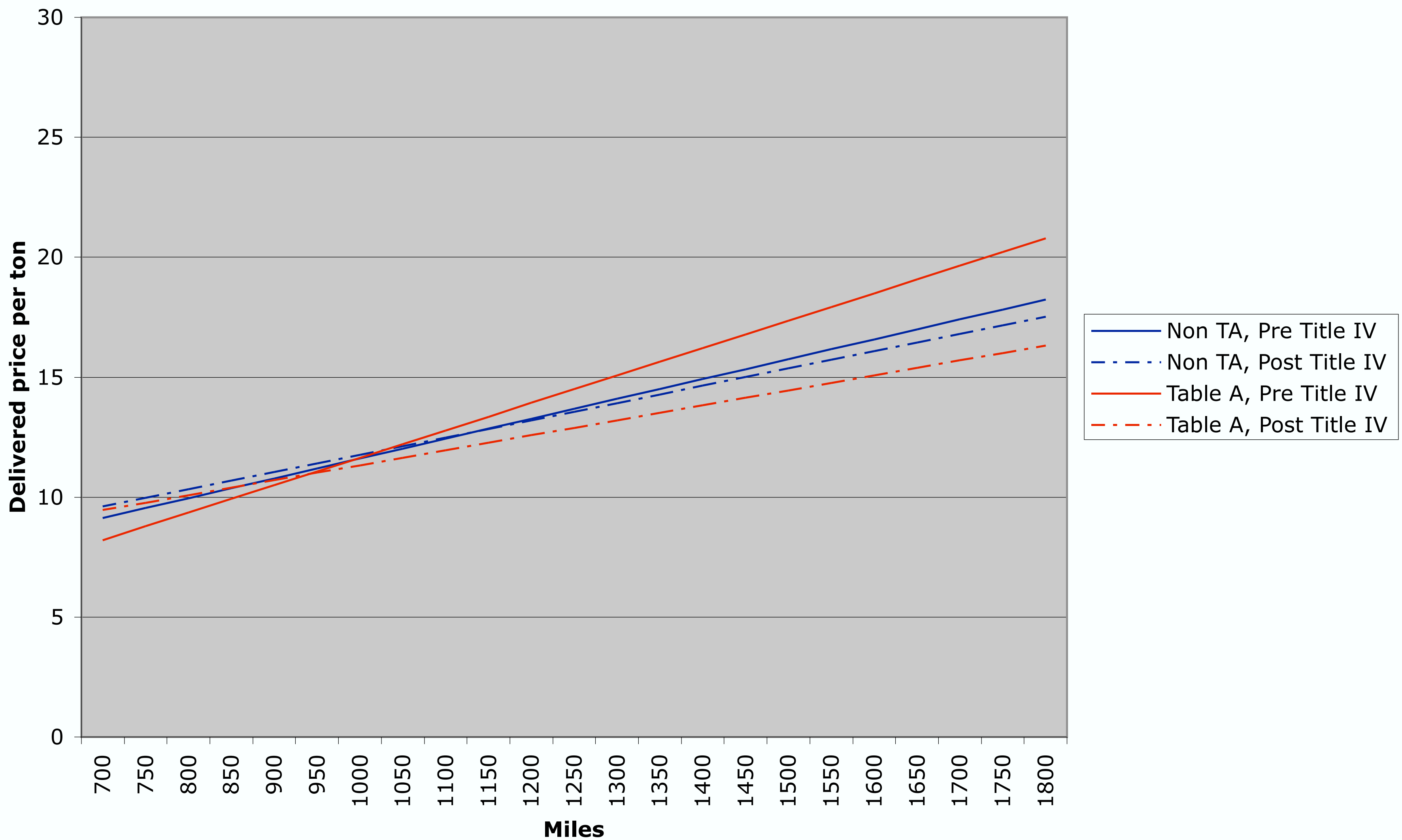


Figure 12



Delivered price per ton
30
25
20
15
10
5
0
700
750
800
850
900
950
1000
1050
1100
1150
1200
1250
1300
1350
1400
1450
1500
1550
1600
1650
1700
1750
1800
Miles
Non TA, Pre Title IV
Non TA, Post Title IV
Table A, Pre Title IV
Table A, Post Title IV

Figure 13



Delivered price per ton
30
25
20
15
10
5
0
700
750
800
850
900
950
1000
1050
1100
1150
1200
1250
1300
1350
1400
1450
1500
1550
1600
1650
1700
1750
1800
Miles
Non TA, Pre Title IV
Non TA, Post Title IV
Table A, Pre Title IV
Table A, Post Title IV