Topics in Economic Analysis & Policy

Volume 3, *Issue* 1 2003 *Article* 15

What Determines Environmental Performance at Paper Mills? The Roles of Abatement Spending, Regulation, and Efficiency

Ronald J. Shadbegian[*] Wayne B. Gray[†]

[*]University of Massachusetts, Dartmouth, rshadbegian@umassd.edu

[†]Clark University, wgray@clarku.edu

What Determines Environmental Performance at Paper Mills? The Roles of Abatement Spending, Regulation, and Efficiency*

Ronald J. Shadbegian and Wayne B. Gray

Abstract

This paper examines the determinants of environmental performance at paper mills, measured by air pollution emissions per unit of output. We consider differences across plants in air pollution abatement expenditures, local regulatory stringency, and productive efficiency. Emissions are significantly lower in plants with a larger air pollution abatement capital stock: a 10 percent increase in abatement capital stock appears to reduce emissions by 6.9 percent. This translates into a sizable social return: one dollar of abatement capital stock is estimated to provide an annual social return of about 75 cents in pollution reduction benefits. Local regulatory stringency and productive efficiency also matter: plants in non-attainment counties have 43 percent lower emissions and plants with 10 percent higher productivity have 2.5 percent lower emissions. For pollution abatement operating costs we find (puzzlingly) positive, but always insignificant, coefficients.

KEYWORDS: air pollution, pollution abatement costs, emissions, productivity

---

[*] Financial support for the research from the National Science Foundation (grant # SBR-9809204) and the Environmental Protection Agency (grant #R-826155-01-0) is gratefully acknowledged, as is access to Census data at the Boston Research Data Center. We are grateful to the many people in the paper industry who were willing to share their knowledge of the industry with us. We would also like to thank Yukako Ono and Amanda Lee as well as seminar participants at the Chicago Federal Reserve Bank, the Western Economic Association meetings, and American Economic Association meetings for their useful comments. Excellent research assistance was provided by Bansari Saha, Aleksandra Simic, Nadezhda Baryshnikova and Melanie Lajoie. The opinions and conclusions expressed are those of the authors and not the Census Bureau, EPA, or NSF. All papers using Census data are screened to ensure that they do not disclose confidential information. Any remaining errors or omissions are the authors'. Ronald J. Shadbegian: University of Massachusetts at Dartmouth, 285 Old Westport Road, North Dartmouth, MA 02747, rshadbegian@umassd.edu, and National Center for Environmental Economics, U.S. Environmental Protection Agency. Wayne B. Gray: Economics Department, Clark University, 950 Main Street, Worcester, MA 01610, wgray@clarku.edu, and National Bureau of Economic Research.

1. INTRODUCTION

The past 30 years have seen significant improvements in US environmental quality, driven in large part by reductions in industrial emissions. This paper examines the determinants of environmental performance by plants in the pulp and paper industry, where performance is measured as air pollution emissions – particulates and sulfur dioxide – per unit of output. We relate differences in air pollution emissions across plants to differences in the plant's air pollution abatement expenditures, local regulatory stringency, and productive efficiency. The results indicate some role for each of these factors in determining a plant's air pollution emissions, although their relative importance differs across different pollutants.

Much of the empirical research on the impact of environmental regulation has concentrated on the impact of reported pollution abatement costs on productivity. Denison (1979) used growth accounting to calculate the expected impact of regulation on productivity. Gray (1986,1987) compared all manufacturing industries and found that high-abatement-cost industries had a bigger productivity slowdown in the 1970s. Gray and Shadbegian (2002,2003b) found that plants with higher abatement costs had lower productivity levels, though Berman and Bui (2001) found little impact of abatement costs on productivity for oil refineries.[1] Looking at the determinants of abatement costs, Shadbegian, et. al. (2000) find that paper mills with greater benefits per unit of pollution spend more on pollution abatement.

Past studies of environmental performance have tended to focus on the effectiveness of EPA enforcement in terms of increasing compliance or reducing emissions. Three studies find that plants receiving more air pollution inspections and enforcement actions perform better: Gray and Deily (1996) find increases in compliance at steel mills; Nadeau (1997) finds reductions in the length of spells of non-compliance, and Gray and Shadbegian (2003a) find increases in compliance at pulp and paper mills. Looking at the impact of water pollution enforcement activity, Magat and Viscusi (1990) find reductions in both BOD discharges and the probability of noncompliance at US pulp and paper mills, while Laplante and Rilstone (1996) find that both actual inspections and the threat of an inspection reduce BOD and TSS discharges at Canadian pulp and paper mills. Looking at an alternative indicator of the stringency of air pollution regulations, Henderson (1996) finds a significant impact of county non-attainment status on peak ambient concentrations of air pollutants.

We use confidential annual plant-level Census data from the Longitudinal Research Database (LRD) to develop a database for 68 U.S. paper mills. We have used this sample of plants in earlier papers, studying the impact of environmental regulation on plant-level investment in Gray and Shadbegian (1998). Here, we find effects of productivity and abatement capital on emissions. Using the LRD, we can identify each plant's production, investment, productivity, age, and production technology in 1985. We have plant-level air pollution abatement capital investments from the Pollution Abatement Costs and Expenditures (PACE) survey, which allows us to create an air pollution abatement capital stock for each plant. To the Census data we add plant-level air pollution emissions information from various EPA datasets in the 1980s for both particulate and sulfur dioxide emissions. Because our emissions data do not contain much within-plant variation, we focus on 1985 emissions. We also add characteristics of

---

[1] Of the three industries (steel, oil, and paper) studied by Gray and Shadbegian (2002), the impact of pollution abatement costs on productivity was found to be the smallest for oil.

the plant's production technology, taken from the Lockwood Directory, and measures of local regulatory stringency faced by the plant.

Our basic analysis finds that aggregate emissions per unit of output (a weighted average of particulates and sulfur dioxide) are significantly lower in plants with a larger air pollution abatement capital stock. The PACE survey has been criticized for asking difficult or confusing questions, but our results suggest that PACE data does reflect abatement-related activity: a plant with 10 percent more pollution abatement capital has 6.9 percent lower emissions per unit of output. The results are quite similar when we study the pollutants separately: 6.1 percent for particulates and 7.3 percent for sulfur dioxide. Translating the impact on total emissions into dollars suggests a sizable *social* return: one dollar of abatement capital stock is estimated to provide an annual return of 75 cents in pollution reduction benefits, though the size of these benefits depends heavily on existing estimates of the mortality effects of air pollution.

Emissions also tend to be lower at more efficient plants, with a 10 percent higher productivity level being associated with 2.5 percent lower emissions per unit of output. This indicates that productive efficiency and pollution abatement efficiency are complements, with better managers being better at both production and abatement (rather than substitutes, with managers concentrating on productive efficiency at the expense of their abatement performance). A plant's productivity affects its emissions of both pollutants, with slightly more of an impact on sulfur dioxide than on particulates. Similar results are observed using a seemingly unrelated regression model to test for a relationship between emissions and productivity: plants with unexpectedly high productivity tend to have lower emissions of both of the pollutants. In addition, we find that plants with unexpectedly high emissions per unit of output on one pollutant tend to have higher emissions of the other pollutant.

We find some influence for regulatory pressures on performance. Plants facing the more stringent regulation required in non-attainment counties have lower emissions of both pollutants, but this is only significant for particulates. This is what the regulations are supposed to accomplish, but our results could have gone the other way if counties were driven into non-attainment status by lax local regulators that permitted greater emissions. Having newer or more advanced equipment in a plant, proxied by the age or speed of its paper machines, or being owned by a multi-plant firm, tends to reduce overall emissions as expected, but not significantly. Air pollution abatement operating costs show unexpectedly positive (though always insignificant) coefficients, especially when both capital and operating costs are included in the regression. On the other hand, the abatement capital stock coefficient gets more negative when operating costs are included. This suggests that emissions reductions in the mid-1980s were usually achieved by installing more abatement capital, or that plants with higher pollution abatement operating costs are not using their resources efficiently.

Section 2 provides some information about the generation and regulation of air pollution in the paper industry. Section 3 presents a brief model of the determinants of pollution emissions, in conjunction with a plant's productivity and technology. Section 4 describes the data used in the analysis. Section 5 provides the results, and section 6 concludes the paper.

2. AIR POLLUTION IN THE PAPER INDUSTRY

Pulp and paper mills are major sources of both air and water pollution. The key distinction for production technology among paper mills is whether or not the plant begins the paper-making process with a pulping stage or not. Pulping plants begin the process with trees, separating out the wood fibers by a variety of chemical and mechanical methods. Non-pulping mills can begin with purchased pulp, or with recycled paper to provide the fibers for the paper. During the paper-making stage, a combination of fiber and water is set on a wire mesh and passed through several sets of steam-heated dryers to dry into paper.

Air pollution is generated primarily during the pulping process. Most pulping mills incorporate large boilers, either power boilers to generate energy for the pulping process and steam for the paper-making dryers, or recovery boilers to recycle chemicals in some pulping techniques. Pulping mills have a convenient supply of fuel, the remaining parts of the trees after the wood fiber is extracted, and co-generation plants are common, with boilers generating high-pressure steam to run electric power turbines. The resulting low-pressure steam is used in the paper-making dryers. Non-pulping mills are more likely to purchase their energy inputs or use small boilers to provide needed energy and steam. The paper-making process can produce some air pollution, as some paper is chemically treated to produce smoother surfaces, but this is definitely less serious than the air pollution created by pulping.

This study covers air pollution emissions in 1985. At this time, air pollution in the U.S. was regulated by the 1977 amendments to the 1970 Clean Air Act. Each year, U.S. counties are designated as ‘attainment’ (meeting ambient air quality standards) or ‘non-attainment’ (violating ambient air quality standards) for each of several criteria pollutants. Plants located in non-attainment counties are supposed to face substantially more stringent regulation than those in attainment counties, with limitations on new plant openings and modifications of existing plants. These regulatory pressures can come from both state environmental agencies and the federal EPA, which oversees activity in non-attainment areas more closely. On the other hand, it’s possible that non-attainment status in some counties could be due to regulators being more lax in enforcing regulations there, in which case emissions could be higher in those non-attainment counties. States can also differ in regulatory stringency: having greater political support for environmental issues within the state should result in stricter regulation and lower emissions.

An important feature of the regulatory process is the grandfathering of existing plants. For the most part, existing manufacturing plants were not subject to regulations as stringent as those applied to new facilities. This is at least partly justified by the extreme difficulty in retrofitting existing facilities, designed before pollution control was a major priority. For example, reducing air pollution emissions can involve capturing vapors from the production process and burning them in a recovery boiler; in one older mill this required installing hundreds of yards of extra piping because the recovery boiler was located in a distant building. Thus older production facilities are likely to have higher emissions for two reasons: they face less regulatory pressure and pollution abatement is more difficult for them. As facilities are updated and rebuilt with newer equipment, some of these drawbacks of being older may be reduced, as the new equipment is likely to incorporate some pollution-reducing characteristics. Updating an existing facility can also bring the plant under closer scrutiny by regulators, as some facility renovations lead the facility to be treated as if it were a ‘new’ source.

3. DETERMINANTS OF ENVIRONMENTAL PERFORMANCE

We measure the environmental performance of a paper mill by its emissions of particulate matter (PMEMIT) and sulfur dioxide (SO2EMIT), measured per unit of output. To describe how different factors affect emissions we separate the factors into two groups: one set of factors influencing the amount of ‘uncontrolled’ emissions from the plant, EMITX(), and a second set of factors influencing the fraction of pollution that the plant abates before it reaches the environment, ABATE(). These factors need not be mutually exclusive (though we treat them as such when we describe the model), and we actually estimate a single regression equation containing all the variables expressed in log form:

$$\text{(1) EMIT} = \text{EMITX(SHIP, PRODCAP, PULP, PMAGE, PMSPEED)} * \\ [1 - \text{ABATE(AIRCAP, AIRPAOC, NONATTAIN, VOTE, TFP, MULTIPLANT)}].$$

Consider the first set of factors, those affecting uncontrolled emissions (EMITX), in more detail. If the pollution generating process has constant returns, so that doubling a plant's output (SHIP) doubles its pollution, then (because we are measuring emissions relative to output) we should expect a zero coefficient on SHIP. Economies of scale in air pollution abatement could be reflected by having SHIP also enter the ABATE() portion of the equation. In this case, the coefficient on SHIP in our regression would be negative.

Plants with more production capital (PRODCAP, also measured relative to plant output) are likely to generate more air pollution. This occurs because most air pollution arises from burning fossil fuels for energy. Capital-intensive plants require more energy to operate than labor-intensive ones, with larger power boilers and more air pollution. A key element of paper mill technology is whether or not the plant incorporates a pulping process (PULP), with pulping mills having substantially higher energy requirements and hence greater air pollution emissions.

The characteristics of a plant's productive capital are also likely to affect emissions, with newer equipment more likely to incorporate features designed to reduce emissions. We don't have direct measures for all of a plant's capital, but do have two measures for the paper machines in use at the plant: their average age (PMAGE) and their average speed (PMSPEED). Plants using older and slower paper machines are likely to have less advanced production equipment overall, and hence have greater emissions (or less abatement).

Now consider the second set of factors, the determinants of air pollution abatement. A key element affecting the ability of the firm to reduce air pollution is the plant's level of air pollution abatement capital (AIRCAP, also measured relative to plant output). During the 1970s and 1980s, most of the abatement of air pollution was done with large capital equipment: scrubbers and precipitators connected to smokestacks, called 'end-of-line' pollution abatement, which are likely to be relatively well-measured by the PACE survey.[2]

In addition to capital expenditures, air pollution abatement operating costs (AIRPAOC, measured relative to shipments) may play an important role. Without proper maintenance and operation, pollution control equipment may fail to operate as designed. There may also be areas where labor (e.g. more workers to check for and fix process failures) may be substitutable for capital in air pollution abatement. Thus we would expect AIRPAOC, like AIRCAP, to be associated with greater abatement efficiency and lower emissions.

We expect regulatory pressures to influence the extent of pollution abatement at a plant. As noted earlier, the main indicator of the air pollution regulatory stringency faced by a plant is the attainment status of the county in which the plant is located, NONATTAIN. State-level

---

[2] In recent years plants have increased their use of 'change-in-process' abatement capital, where the production process is redesigned to reduce pollution, which makes abatement costs more difficult to measure. We tested for differences between the impacts of end-of-line and change-in-process abatement capital, but did not find significant differences between them (results available from the authors).

support for regulation is proxied by the pro-environment voting of the state's Congressional delegation (VOTE). We expect both NONATTAIN and VOTE to have negative coefficients in our regressions, as stricter regulations lead to greater abatement and less emissions.

Stringent regulation could simply lead plants to spend more on AIRCAP and AIRPAOC, with no additional impacts of NONATTAIN and VOTE on emissions. We do anticipate additional impacts, both because we expect AIRCAP and AIRPAOC to be imperfect measures of the plant's actual abatement efforts (leaving part of the plant's abatement efforts to be captured by the stringency variables), and because greater regulatory pressures should reduce the extent of inefficiency in the plant's allocation of resources to pollution abatement, increasing the actual degree of abatement achieved per dollar of abatement spending.

Finally, we consider the possibility that plants differ in their overall pollution abatement efficiency levels, due either to greater firm-level expertise in dealing with environmental regulation or to greater plant-level productive efficiency. To measure firm-level expertise we include MULTIPLANT, measuring whether the plant is owned by a firm with ten or more paper mills. To measure plant-level efficiency we use the plant's total factor productivity level, TFP. One might expect higher TFP to be associated with increased abatement efficiency, since higher TFP indicates that the plant uses less inputs per unit of output and therefore should be producing less waste. This need not always be true, however: if some managers concentrate on regulatory issues, while others concentrate on production issues, the two types of efficiency should be substitutes rather than complements. In such a case, achieving higher productivity by cutting corners and speeding up the production process would increase emissions, through more frequent accidental releases.[3]

We also consider an alternative approach, using a seemingly unrelated regression (SUR) model to look for correlations between emissions of both air pollutants and the plant's productivity. This model involves estimating three equations simultaneously, two emissions equations and a productivity equation:

(2a) PMEMIT = PMEMITX() * (1 – PMABATE()).
(2b) SO2EMIT = SO2EMITX() * (1 – SO2ABATE()).
(2c) TFP = f(PAOC, PULP, PMAGE, PMSPEED, MULTIPLANT).

Here a plant's productive efficiency (TFP) depends on its total pollution abatement operating costs for all media (PAOC, measured relative to shipments). TFP also depends on characteristics of the plant's production technology (PULP, PMAGE, PMSPEED) and firm-level expertise in dealing with paper mills (MULTIPLANT). We are especially interested in the correlations across the residuals for the three equations. We expect plants that achieve low emissions of one pollutant to achieve lower emissions of the other, resulting in a positive correlation between the residuals of the two emissions equations (though differences in pollutant-specific regulatory pressures could lead plants to substitute abatement activity across pollutants, resulting in a negative correlation instead). One might expect more efficient producers to be better at pollution abatement, resulting in a negative correlation between the residuals from the emissions (2a,2b) and productivity (2c) equations, though if production-conscious managers ignore environmental concerns we would instead see a positive correlation.

---

[3] Such a temporary increase in emissions might not be captured in our emissions measures, most of which are based on engineering estimates, as noted in the data description section below.

4. DATA DESCRIPTION

Our research was carried out at the Census Bureau's Boston Research Data Center, where we can access confidential Census databases developed by the Census's Center for Economic Studies. The principal source for our sample of plants is the Longitudinal Research Database (LRD). The LRD contains annual information on a large sample of individual manufacturing plants from the Census of Manufactures and Annual Survey of Manufacturers over time (for a more detailed description of the LRD data, see McGuckin and Pascoe (1988)). The LRD includes data on each plant's real inventory-adjusted shipments (SHIP), labor, materials, and investment spending. From the LRD data we can calculate a productivity index, TFP, for each plant.[4] Using LRD data we also calculate a measure of the plant's total capital stock, TOTCAP, based on a standard perpetual inventory calculation. Finally, detailed information on plant outputs and inputs from the LRD allows us to construct a PULP dummy (indicating that the plant begins its papermaking with raw wood).

We combine the LRD data with another plant-level Census data source: the Pollution Abatement Costs and Expenditures (PACE) survey, conducted annually by the Census Bureau. The PACE questionnaire is sent to a subset of firms in the Annual Survey of Manufactures, oversampling high-pollution plants such as paper mills. In prior research we have used both a sample of 116 plants with some PACE data during the 1979-1990 period, and a subsample with 68 plants with complete pollution abatement investment data from 1979-1990. Here we focus on the 68 plant dataset, since we wish to include data on the accumulated stock of pollution abatement capital.

Using the PACE data, we calculate the stock of total pollution abatement capital (POLCAP) and air pollution abatement capital (AIRCAP) in place at each plant over time.[5] The 'productive' capital stock of the plant, PRODCAP, is calculated as the difference between TOTCAP and POLCAP. The PACE survey also distinguishes between end-of-line investment and change-in-process investment spending. Finally, the PACE survey contains information on air pollution abatement operating costs (AIRPAOC), which is also tested to see whether it is related to the plant's air pollution emissions. We also use PAOCFRAC, the plant's total pollution abatement operating costs as a fraction of its peak capacity (an average of the highest two years of shipments) in the analysis, as an explanatory variable possibly affecting the plant's productivity (PAOCFRAC was found to be significantly negatively related to TFP levels in Gray and Shadbegian, 2002, 2003b).

We combine the LRD and PACE data with two other plant-level information sources: the Lockwood Directory and various EPA air pollution datasets. The Lockwood Directory is an annual listing of pulp and paper mills, from which we extracted several pieces of information about the plants' production technology. The Lockwood Directory includes information on the production technology being used at each mill: PMAGE and PMSPEED are the mean age and

---

[4] See Gray and Shadbegian (2002) for details of this calculation. The productivity index is in logarithmic form, expressed as percentage changes, so our TFP variable can be thought of as 100*log(productivity level).

[5] Since significant amounts of abatement investment were done during the 1970s, when the plant-level abatement investment is not available, we combine the plant-specific total investment data from the LRD with the published ratio between abatement investment and total investment from the PACE survey to impute abatement investment during the 1970s, which is then aggregated up over time to provide an estimate of the plant's initial abatement capital stock in 1979.

operating speed of each paper machine in operation at the mill.[6] To control for possible advantages to firms with more expertise in this industry, we include a MULTIPLANT dummy, indicating that the firm owns 10 or more pulp and paper mills, based on plant ownership data from the Lockwood Directory.

In addition to the plant-level data, we use two measures of the regulatory stringency faced by the plant. The stringency of each state's pollution abatement effort is proxied by VOTE, the League of Conservation Voters' pro-environment voting score for the state's Congressional delegation during each congressional session. In prior research, VOTE was found to be significantly related to manufacturing plant location decisions (Gray, 1997) and investment decisions (Gray and Shadbegian, 1998).

A measure of local regulatory stringency specific to air pollution is NONATTAIN, a dummy variable indicating whether the plant is located in a county that failed to attain the ambient air quality standards for particulates or sulfur dioxide in 1985. The attainment status of each county is published annually in the Federal Register.[7] For the paper mills in our sample, non-attainment status is nearly always due to excessive particulates; sulfur dioxide non-attainment is much less common.[8]

The key dependent variable for our analyses, the plant's air pollution emissions, comes from various EPA regulatory datasets which span the 1980s. For most of the plants in our dataset we are able to use emissions information from the 1985 National Emissions Data System (NEDS). For plants without 1985 NEDS data, we look for the closest available year of data from the Compliance Data System (CDS), the 1980 NEDS data, and the Aerometric Information Retrieval System (AIRS). We should note that relatively few emissions reports are based on an actual measurement of emissions; most emission reports are based on calculated emissions or engineering estimates, based on the capacity of the production process times the expected emissions per unit of capacity times the design efficiency of the installed pollution control equipment.[9] This number is less likely to provide changes over time than would a continuously-measured stream of data on actual emissions for each pollutant. This is the main reason why we perform our analysis with cross-sectional rather than panel data.

The emissions data is provided separately for the major criteria air pollutants. Our analysis focuses on particulate matter (PM) and sulfur dioxide (SO2), since they are most commonly reported and were the major focus of air pollution regulation for this industry during

---

[6] PMAGE is reported only in the 1979 Lockwood-Post Directory. PMSPEED is reported in each issue of the Lockwood Directory (although the reported values do not change very often). Each variable is weighted by the width of the paper machine as a rough proxy for its importance in overall plant output when we calculate the plant-average value for 1985. In cases where no PMSPEED or PMAGE data is available for a particular plant (roughly 40% of plants for PMSPEED and 60% for PMAGE), the missing values are filled in (with average industry value for PMSPEED and with a regression based on the age of the entire paper mill, respectively). A dummy variable for imputed information is included in each of the regression models to correct for bias from the imputation.

[7] We would like to thank Randy Becker, who created this dataset and graciously made it available to us for this project. The data is described in more detail in Becker (2001).

[8] We did test PM and SO2 non-attainment status separately (SO2 non-attainment was never significant), but we have too few cases of sulfur dioxide non-attainment to report the coefficients.

[9] Census Bureau disclosure concerns limit our ability to present the exact numbers for our analysis sample, but for the full set of all paper industry facilities with 1985 NEDS data we observe actual measurements for only 6% of sulfur dioxide emissions and 19% of particulate emissions.

the time period. We measure the emissions of each pollutant, PMEMIT and SO2EMIT, in tons per year and then aggregate them together into TOTEMIT, weighting them using a measure of the relative health damages for the two pollutants (based on Shadbegian, et. al (2000), one ton of PM emissions = 2.45 tons of SO2 emissions), since we are interested in comparing the aggregate benefits and costs of pollution abatement capital. In the actual analyses, we express the emissions numbers in intensity terms, as tons of emissions per thousand dollars of output.

5. RESULTS

Table 1 presents summary statistics and variable descriptions for all the variables included in the analysis. Examining the dependent variables, we see that the greater weight placed on emissions of particulates (2.45:1) is more than offset by the greater mean emissions of sulfur dioxide (520:3200), so SO2 emissions account for about 70% of the total value of EMIT. Each of the emission variables shows substantial variability across observations, with the mean being exceeded by the standard deviation in each case.

The air pollution abatement capital stock at a typical plant is substantial, approximately 8% of the productive capital stock at the plant: $4.17 million out of $53.8 million. The average value of the total pollution abatement capital stock is $7.9 million, so air pollution abatement requires over half of the plant's abatement capital. Pollution abatement operating costs represent about 2% of total costs, with the majority of those costs going to abating water pollution: about twice as large as air pollution costs.

Of the plants in our sample, about one-third are located in counties that are in non-attainment for either particulates or sulfur dioxide. Slightly over half of our sample are pulping mills. Many of the plants are quite old, with an average plant's paper machines dating back to 1946 (39 years before 1985). More than half of the plants are owned by firms with a large paper industry component as measured by MULTIPLANT (10 or more pulp and paper mills owned by the firm).

Turning first to the results in Table 2, we see that plants which incorporate a pulping process generate significantly more air pollution per unit of output, with a stronger impact on particulates than on sulfur dioxide. More capital-intensive plants show somewhat greater emissions although the impact is only significant (marginally) for sulfur dioxide. We find no evidence for economies of scale in pollution control: if anything, we find more emissions per unit of output (for sulfur dioxide) at larger plants. The characteristics of a plant's production technology (age or speed of paper machines) are not significant, although they have slightly more impact on sulfur dioxide emissions and the signs are generally consistent with our expectations: plants with newer and faster paper machines emit less pollution. Being part of a firm that owns many paper mills also has an insignificant negative effect, though again having a bit more impact on sulfur dioxide emissions.

We now turn to our key abatement-related variable in Table 2, LAIRCAP (log of AIRCAP). Plants with larger stocks of air pollution abatement capital (all else equal) have lower emissions. We find that a 10% increase in AIRCAP reduces particulate emissions by 5.0% (model 2B), sulfur dioxide emissions by 6.4% (model 2D), and total emissions by 5.8% (model 2F), although the particulate coefficient is insignificant.

Table 1
Summary Statistics
(68 observations)

Variable	Mean	Std.Dev.	Description
PM	520.59	939.69	Particulate emissions (tons/yr)
SO2	3200.30	3650.60	Sulfur Dioxide emissions (tons/yr)
TOTEMIT	4483.97	5158.42	Weighted sum (PM*2.455 + SO2)
POLCAP	7860.64	7816.86	Total pollution abatement capital ($000)
AIRCAP	4166.17	4599.40	Air pollution abatement capital ($000)
PAOC	1245.34	1277.01	Total pollution operating costs ($000)
AIRPAOC	355.62	569.62	Air pollution operating costs ($000)
PAOCFRAC	1.99	1.41	Total PAOC/peak capacity (*100)
NONATTAIN	0.35	0.48	County non-attainment for PM or SO2
VOTE	57.34	13.39	LCV pro-environment voting index
PMSPEED	1640.21	560.40	Average paper-machine speed (feet per minute)
PMAGE	39.00	14.96	Average paper-machine age (in 1985)
PULP	0.56	0.50	Plant includes pulping process
PRODCAP	53796.56	46002.31	Productive capital stock ($000)
SHIP	46490.71	28233.23	Value of annual plant shipments ($000)
TFP	110.77	19.06	Total factor productivity index
MULTIPLANT	0.53	0.50	Firm owns 10+ paper mills
Variables in Logs, for Regressions			
LPMEMIT	-5.90	1.81	Log(PM/SHIP)
LSO2EMIT	-3.92	2.04	Log(SO2/SHIP)
LTOTEMIT	-3.48	2.01	Log(TOTEMIT/SHIP)
LAIRCAP	-3.09	0.93	Log(AIRCAP/SHIP)
LAIRPAOC	-5.99	3.87	Log(AIRPAOC/SHIP)
LSHIP	10.76	0.60	Log(SHIP)
LPRODCAP	-0.23	0.50	Log(PRODCAP/SHIP)
LPMSPEED	7.33	0.43	Log(PMSPEED)
LPMAGE	3.58	0.43	Log(PMAGE)
LVOTE	4.02	0.27	Log(VOTE)
LPAOC	0.35	1.02	Log(PAOCFRAC)

All values are expressed in 1972 dollars, using the paper industry (SIC 2621) price deflator from Bartelsman and Gray (1996).

Table 2
Determinants of Emissions
Abatement Capital and Plant Technology

Dep. Var.:	LPMEMIT		LSO2EMIT		LTOTEMIT	
	(A)	(B)	(C)	(D)	(E)	(F)
CONSTANT	-19.365	-17.356	-30.255	-28.797	-28.529	-26.961
	(-3.96)	(-3.10)	(-6.49)	(-5.78)	(-6.90)	(-5.98)
LAIRCAP	-0.408	-0.499	-0.444	-0.635	-0.419	-0.576
	(-1.33)	(-1.54)	(-1.52)	(-2.20)	(-1.62)	(-2.21)
LPRODCAP	0.477	0.458	0.738	0.954	0.572	0.703
	(0.88)	(0.80)	(1.43)	(1.87)	(1.25)	(1.52)
LPMAGE		-0.168		0.485		0.243
		(-0.34)		(1.09)		(0.61)
LPMSPEED		-0.308		-0.615		-0.488
		(-0.68)		(-1.53)		(-1.35)
LSHIP	0.094	0.147	0.529	0.661	0.293	0.398
	(0.28)	(0.41)	(1.63)	(2.04)	(1.02)	(1.36)
PULP	1.716	1.816	0.668	1.035	1.090	1.371
	(3.12)	(3.13)	(1.28)	(2.00)	(2.35)	(2.93)
MULTIPLANT	0.014	-0.029	-0.521	-0.519	-0.397	-0.412
	(0.03)	(-0.07)	(-1.35)	(-1.39)	(-1.16)	(-1.23)
R-squared	0.433	0.448	0.594	0.654	0.672	0.710

(T-Statistics)
Regressions include dummies for missing values as needed, including PMAGE.

Table 3 adds a measure of plant-level productivity (TFP) to the regressions, to see whether more productive plants are more or less polluting. The other variables have similar impacts to those noted in Table 2. Overall, it appears that high productivity plants are less polluting, particularly for sulfur dioxide and total emissions. This suggests that the two types of efficiency (productive and pollution abatement) are complements rather than substitutes. Since the TFP productivity index is measured in percentage terms, a 10% higher productivity level at a plant is associated with 2.5% lower total emissions (in Model 3F).

Table 4 adds measures of the regulatory pressures faced by plants. Plants in non-attainment areas show significantly lower emissions of particulates per unit of output, with little or no impact of non-attainment on sulfur dioxide emissions (recall that most cases of non-attainment in our data refer to particulates). The coefficients on LVOTE are never significant, although they have the expected negative sign. It should be noted that these regressions already include controls for the plant's air pollution abatement capital stock, so the impact of these stringency measures represents an additional reduction in emissions, after accounting for any increased pollution abatement capital required by plants in non-attainment areas.[10]

Now, let us return to our results for pollution abatement capital stocks, in an effort to compare the benefits and costs of pollution abatement. Consider the coefficient in Model 4F on air pollution abatement capital stock, -0.685. This indicates that a plant with a 10 percent larger air pollution abatement capital stock, all else equal, would have 6.85 percent lower emissions. Does this make pollution abatement capital a worthwhile investment (from society's point of view)? At the mean level of AIRCAP in our data, a 10 percent increase in pollution abatement capital would cost about $417,000. This would achieve a 6.85 percent reduction in annual aggregate air pollution emissions, about 307 tons. We can compare these benefits and costs, using information from Shadbegian, et. al. (2000) which includes a calculation of the health benefits per ton of reduced emissions which translates into $1013 benefits per ton in these terms.[11] Thus a $417,000 investment yields annual benefits of $310,000, about a 75 percent annual rate of return on the investment.

This may seem like an excessively high rate of return, but it is based on estimated health effects used by EPA in their calculations. Exposure to airborne particulates is linked to mortality, and this turns out to be by far the largest source of dollar benefits from pollution abatement. For example, a recent EPA study (US EPA 1997) finds that particulate-based reductions in mortality contributed more than $20 trillion of benefits (aggregating benefits over many years). This was nearly all of the estimated $22.2 trillion of all categories of benefits from

---

[10] Becker (2001) also finds that differences in reported abatement costs between attainment and non-attainment areas may not capture all the differences in regulatory stringency faced by plants in those areas.

[11] Shadbegian et. al. (2000) calculate the health benefits from reduced air pollution emissions (PM, SO2 and NOX), based on the predicted reduction in mortality associated with the decline in ambient particulate concentrations. Using a $4.8M (1990 dollars) value of a statistical life (US EPA, 1997) in conjunction with the estimated decline in pre-mature mortality from reductions in primary and secondary particulate matter based on the work of Pope et al. (1995), Rowe et al. (1995), and Levy et al. (1999) they estimate a benefit of $2172 per ton of reduced emissions. However, their estimate is for a ton of NOX in 1990 dollars, so we must translate these benefits into 1972 dollars (the benchmark year for our abatement cost deflator) for a ton of SO2. This yields benefits per ton = ($2172*1.45)/3.11 = $1013, where 1.45 accounts for the greater impact of SO2 on ambient particulates, and 3.11 puts the dollar value of benefits into 1972 dollars.

Table 3
Determinants of Emissions
Plant Productivity

Dep. Var.:	LPMEMIT		LSO2EMIT		LTOTEMIT	
	(A)	(B)	(C)	(D)	(E)	(F)
CONSTANT	-16.256	-16.593	-26.861	-27.949	-24.950	-26.004
	(-3.52)	(-2.99)	(-6.16)	(-5.73)	(-6.54)	(-6.03)
TFP	-0.016	-0.020	-0.023	-0.022	-0.023	-0.025
	(-1.45)	(-1.57)	(-2.14)	(-1.99)	(-2.49)	(-2.54)
LAIRCAP		-0.578		-0.723		-0.675
		(-1.79)		(-2.54)		(-2.69)
LPRODCAP		0.266		0.741		0.464
		(0.46)		(1.46)		(1.03)
LPMAGE		-0.249		0.395		0.142
		(-0.50)		(0.91)		(0.37)
LPMSPEED		-0.286		-0.591		-0.460
		(-0.64)		(-1.51)		(-1.33)
LSHIP	0.251	0.367	0.767	0.905	0.524	0.673
	(0.71)	(0.95)	(2.31)	(2.68)	(1.80)	(2.25)
PULP	1.221	1.663	0.172	0.865	0.520	1.180
	(2.69)	(2.86)	(0.40)	(1.69)	(1.39)	(2.61)
MULTIPLANT	0.094	-0.006	-0.453	-0.493	-0.303	-0.383
	(0.24)	(-0.01)	(-1.22)	(-1.36)	(-0.93)	(-1.19)
R-squared	0.435	0.472	0.604	0.678	0.687	0.741

(T-Statistics)
Regressions include dummies for missing values as needed, including PMAGE.

Table 4
Determinants of Emissions
Regulatory Pressures

Dep. Var.:	LPMEMIT		LSO2EMIT		LTOTEMIT	
	(A)	(B)	(C)	(D)	(E)	(F)
CONSTANT	-11.100	-11.146	-27.236	-26.711	-25.437	-24.923
	(-1.84)	(-1.76)	(-4.27)	(-4.29)	(-4.55)	(-4.59)
NONATTAIN	-1.276	-1.373	-0.190	-0.130	-0.455	-0.437
	(-3.29)	(-3.36)	(-0.46)	(-0.32)	(-1.27)	(-1.25)
LVOTE	-0.442	-0.579	-0.157	-0.196	-0.016	-0.057
	(-0.62)	(-0.77)	(-0.21)	(-0.26)	(-0.02)	(-0.09)
LAIRCAP		-0.613		-0.728		-0.685
		(-2.08)		(-2.52)		(-2.71)
LPRODCAP		0.146		0.740		0.416
		(0.27)		(1.41)		(0.91)
TFP		-0.020		-0.022		-0.025
		(-1.75)		(-1.97)		(-2.52)
LPMAGE		-0.129		0.416		0.171
		(-0.28)		(0.93)		(0.44)
LPMSPEED		-0.237		-0.569		-0.460
		(-0.57)		(-1.40)		(-1.29)
LSHIP	-0.344	-0.037	0.462	0.843	0.164	0.566
	(-1.00)	(-0.10)	(1.27)	(2.27)	(0.52)	(1.74)
PULP	1.312	1.662	0.521	0.850	0.865	1.193
	(3.34)	(3.09)	(1.26)	(1.61)	(2.38)	(2.60)
MULTIPLANT	0.012	-0.046	-0.557	-0.506	-0.391	-0.387
	(0.03)	(-0.12)	(-1.43)	(-1.36)	(-1.15)	(-1.19)
R-squared	0.518	0.577	0.576	0.679	0.665	0.748

(T-Statistics)
Regressions include dummies for missing values as needed, including PMAGE.

reductions in all air pollutants. Shadbegian, et. al. (2000) examine abatement operating costs and find the benefits from air pollution abatement greatly exceeding its costs while water pollution abatement benefits and costs are similar in magnitude.

Table 5 adds air pollution abatement operating costs (AIRPAOC) to the analysis. Unlike the plant's pollution abatement capital stock, the value of which is accumulated over many years, operating costs are completely determined in the current year, so are potentially endogenous if current emissions levels influence current abatement spending. We control for this potential endogeneity by using lagged AIRPAOC as an instrument to predict AIRPAOC and using this predicted value in place of the actual value in the second stage.[12]

Unlike the results we found earlier for pollution abatement capital, pollution abatement operating costs do not seem to be associated with reduced emissions. We find unexpectedly positive, though insignificant, signs on operating costs, especially when both operating and capital costs are included in the regression. On the other hand, the coefficient on the abatement capital stock variable gets more negative when operating costs are included. This suggests that emissions reductions in 1985 were primarily achieved by installing better abatement control equipment, or perhaps that plants with higher pollution abatement operating costs were not using their resources efficiently. We tested a variety of models that included abatement operating costs, with similar results to those presented in Table 5 – not significant, but often positive.

A final approach to examining the determinants of environmental performance is shown in Table 6. Here we estimate the seemingly unrelated regression model from Equation 2. This allows for correlations among the unexplained variation in the two emissions measures and plant-level productivity. We find a negative correlation between the TFP residual and the two emissions residuals, reinforcing our earlier conclusion that productive and abatement efficiency are complements rather than substitutes (see Table 6 panel B). We also find positive correlations between the residuals from the emission equations, indicating that plants which perform well on one pollutant also perform well on the other. These correlations across equations are statistically significant. The individual coefficients estimated in the SUR equations are similar to those found earlier. Plants with more abatement capital have lower emissions of both pollutants, while pulping mills emit more of both pollutants. Mills in non-attainment areas emit less particulates, while smaller, less capital-intensive mills emit less sulfur dioxide.

We tested alternative specifications of the seemingly unrelated regression model not presented here (but available on request), including: using more of the explanatory variables from the emissions equation in the productivity equation; doing the SUR estimation with only two equations, TFP and TOTEMIT; and using a predicted value for LPAOC (based on lagged values of LPAOC). The results are similar to those found here. We always find a negative correlation between the residuals from the emissions and productivity regressions, indicating that plants which are more efficient in production are also more efficient in pollution abatement. These results are consistent with the idea that plants which use their inputs more efficiently also produce less waste, making it easier for them to achieve better environmental performance.

---

[12] We also estimated each model in Table 5 using lagged AIRPAOC in place of its predicted value and found no qualitative difference in the results (these results are available upon request).

Table 5
Determinants of Emissions
Pollution Abatement Operating Costs

Dep. Var.:	LPMEMIT		LSO2EMIT		LTOTEMIT	
	(A)	(B)	(C)	(D)	(E)	(F)
CONSTANT	-9.194	-10.934	-24.865	-26.290	-22.950	-24.608
	(-1.41)	(-1.71)	(-3.84)	(-4.23)	(-4.03)	(-4.52)
LAIRPAOC*	0.015	0.039	0.039	0.077	0.026	0.058
	(0.21)	(0.53)	(0.53)	(1.10)	(0.42)	(0.94)
LAIRCAP		-0.643		-0.787		-0.729
		(-2.13)		(-2.68)		(-2.83)
LPRODCAP		0.196		0.841		0.491
		(0.36)		(1.58)		(1.06)
TFP	-0.014	-0.020	-0.019	-0.021	-0.020	-0.024
	(-1.27)	(-1.71)	(-1.69)	(-1.92)	(-2.03)	(-2.48)
LPMAGE	-0.014	-0.091	0.438	0.492	0.250	0.228
	(-0.03)	(-0.20)	(0.96)	(1.09)	(0.62)	(0.58)
LPMSPEED	-0.066	-0.208	-0.352	-0.511	-0.263	-0.417
	(-0.16)	(-0.49)	(-0.83)	(-1.25)	(-0.70)	(-1.16)
NONATTAIN	-1.335	-1.396	-0.157	-0.177	-0.427	-0.472
	(-3.16)	(-3.37)	(-0.37)	(-0.44)	(-1.15)	(-1.34)
LVOTE	-0.572	-0.568	-0.079	-0.174	-0.000	-0.040
	(-0.74)	(-0.75)	(-0.10)	(-0.23)	(-0.00)	(-0.06)
LSHIP	-0.169	-0.051	0.756	0.814	0.449	0.544
	(-0.44)	(-0.13)	(1.98)	(2.19)	(1.34)	(1.67)
PULP	1.094	1.590	0.355	0.706	0.638	1.086
	(2.20)	(2.85)	(0.72)	(1.30)	(1.47)	(2.29)
MULTIPLANT	0.063	-0.040	-0.461	-0.495	-0.302	-0.378
	(0.17)	(-0.11)	(-1.21)	(-1.33)	(-0.90)	(-1.16)
R-squared	0.540	0.580	0.641	0.686	0.714	0.753

(T-Statistics)

Regressions include dummies for missing values as needed, including PMAGE.

LAIRPAOC* is predicted value of log(air pollution abatement operating costs)

Table 6
Determinants of Emissions
Seemingly Unrelated Regressions Model

PANEL A

Dep. Var.:	LPMEMIT (A1)	LSO2EMIT (A2)	TFP (A3)
CONSTANT	-13.917	-29.711	158.374
	(-2.48)	(-5.37)	(3.45)
LAIRCAP	-0.585	-0.695	
	(-2.27)	(-2.74)	
LPRODCAP	0.195	0.799	
	(0.42)	(1.76)	
LPAOC			-1.877
			(-0.90)
LPMAGE	-0.100	0.449	-1.093
	(-0.25)	(1.12)	(-0.21)
LPMSPEED	-0.319	-0.658	4.671
	(-0.85)	(-1.79)	(1.02)
NONATTAIN	-1.371	-0.128	
	(-3.80)	(-0.36)	
LVOTE	-0.532	-0.143	
	(-0.80)	(-0.22)	
LSHIP	-0.079	0.790	
	(-0.25)	(2.53)	
PULP	1.885	1.094	-11.292
	(4.00)	(2.35)	(-2.31)
MULTIPLANT	-0.056	-0.517	0.586
	(-0.16)	(-1.54)	(0.14)
R-squared	0.549	0.652	0.312

(T-Statistics)
Regressions include dummies for missing values as needed, including PMAGE.

PANEL B

Residual Correlations

	LPMEMIT*	LSO2EMIT*
LSO2EMIT*	0.4082	
TFP*	-0.1929	-0.2085

* = Residual from equation in Panel A
Breusch-Pagan test of independence:
chi2(3) = 17.01, Pr = 0.0007

6. CONCLUSIONS

We have examined the determinants of environmental performance at U.S. pulp and paper mills, as measured by their air pollution emissions per unit of output in 1985. Significant determinants include the plant's pollution abatement capital stock and productive efficiency. In our basic regression analysis, we find that aggregate emissions (a weighted average of particulates and sulfur dioxide) are significantly lower in plants with a larger air pollution abatement capital stock: 10 percent more abatement capital stock is associated with 6.9 percent less emissions. Translating these impacts into dollars suggests a sizable *social* return on abatement investments: one dollar of abatement capital stock provides an annual return of about 75 cents in pollution reduction benefits. These large benefits are directly connected to the large estimated mortality impacts of particulates – more modest estimates of health effects would yield a smaller social rate of return.

More productive plants also have lower emissions per unit of output, with a 10 percent higher productivity level being associated with 2.5 percent lower emissions. This indicates that productive efficiency and pollution abatement efficiency are complements, with better managers being better at both production and abatement (rather than substitutes, with managers concentrating on productive efficiency at the expense of their abatement performance). The residual correlations in our seemingly unrelated regression analysis confirm these results: plants with surprisingly high productivity have surprisingly low emissions for both particulates and sulfur dioxide. In addition, plants with surprisingly high levels of emissions for one pollutant tend to have high emissions for the other.

Plants facing more stringent local regulations, as indicated by being in a non-attainment county, have lower particulate emissions, though a state-level measure of stringency is not significant. One puzzle among our results is the insignificant, but positive coefficient on air pollution abatement operating costs. Including operating costs in the model increases the emissions reductions attributed to abatement capital, but the positive sign on operating costs is still surprising.

We plan future research in this area, broadening the scope of pollution data included in the models. Expanding the data into the 1990s will enable us to include more recent air pollution emissions data, which provides more within-plant variation in emissions levels. This will also enable us to add data on water pollution discharges (which are directly measured on a monthly basis), and compare a plant's performance across different pollution media. Using panel data analyses could control for unmeasured heterogeneity across plants, and may help shed light on our unusual operating cost results.

REFERENCES

Bartelsman, Eric J. and Wayne B. Gray, "The NBER Manufacturing Productivity Database." *NBER Technical Working Paper 205*, October 1996.

Becker, Randy, "Air Pollution Abatement Costs Under the Clean Air Act: Evidence from the PACE Survey," Center for Economic Studies Working Paper 01-12, 2001.

Berman, Eli and Linda Bui, "Environmental Regulation and Productivity: Evidence from Oil Refineries," *Review of Economics and Statistics*, 83, 2001, 498-510.

Denison, Edward P., *Accounting for Slower Economic Growth: The U.S. in the 1970s*, Washington: The Brookings Institution, 1979.

Gray, Wayne B., "Manufacturing Plant Location: Does State Pollution Regulation Matter?," *NBER Working Paper no. 5880*, January 1997.

_____, "The cost of regulation: OSHA, EPA and the Productivity Slowdown," *American Economic Review*, 77, 1987, 998-1006.

_____, *Productivity Versus OSHA and EPA Regulations*,UMI Research Press, Ann Arbor, MI, 1986.

Gray, Wayne B. and Mary E. Deily, "Compliance and Enforcement: Air Pollution Regulation in the U.S. Steel Industry," *Journal of Environmental Economics and Management*, 31, 1996, 96-111.

Gray, Wayne B. and Ronald J. Shadbegian, "When and Why do Plants Comply? Paper Mills in the 1980s," Clark University mimeo (2003a).

_____, "Plant Vintage, Technology, and Environmental Regulation," *Journal of Environmental Economics and Management,* 46, (2003b), 384-402.

_____, "Pollution Abatement Costs, Regulation, and Plant-Level Productivity," *in Economic Costs and Consequences of Environmental Regulation*, Wayne B. Gray, ed., Ashgate Publishing, 2002.

_____, "Environmental Regulation, Investment Timing, and Technology Choice." *Journal of Industrial Economics*, 46, 1998, 235-256.

Halvorsen, Robert, and Raymond Palmquist, "The Interpretation of Dummy Variables in Semilogarithmic Equations." *American Economic Review*, 70, 1980, 474-75.

Henderson, J. Vernon, "Effects of Air Quality Regulation," *American Economic Review*, 86, 1996, 789-813.

Laplante, Benoit and Paul Rilstone, "Environmental Inspections and Emissions of the Pulp and Paper Industry in Quebec," *Journal of Environmental Economics and Management*, 31, 1996, 19-36.

Lockwood-Post Pulp and Paper Directory, Miller-Freeman Publishing Company, various issues.

Magat, Wesley A. and W. Kip Viscusi, "Effectiveness of the EPA's Regulatory Enforcement: The Case of Industrial Effluent Standards," *Journal of Law and Economics*, 33, 1990, 331-360.

McGuckin, Robert H. and George A. Pascoe, "The Longitudinal Research Database: Status and Research Possibilities." *Survey of Current Business*, November 1988.

Nadeau, Louis W., "EPA Effectiveness at Reducing the Duration of Plant-Level Noncompliance," *Journal of Environmental Economics and Management*, 34, 1997, 54-78.

Shadbegian, Ronald J., Wayne B. Gray, and Jonathan Levy, "Spatial Efficiency of Pollution Expenditures", Presented at the Western Economic Association Annual Meetings (June 1999), Harvard University's Kennedy School of Government (March 2000), and the National Bureau of Economic Research (April 2000).

U.S. Bureau of the Census, "Pollution Abatement Costs and Expenditures," U.S. Govt. Printing Office, Washington, DC, various issues.

U.S. Environmental Protection Agency, "The Benefits and Costs of the Clean Air Act, 1970 to 1990," October 1997.