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Working Paper Series

Working Paper # 03-03
April, 2003

U.S. Environmental Protection Agency
National Center for Environmental Economics
1200 Pennsylvania Avenue, NW (MC 1809)
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http://www.epa.gov/economics

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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 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.

Subject Area: Costs of Pollution Control, Air Pollution, and Environmental Policy
Key Words: 1) Environmental Performance; 2) Pollution Abatement Capital Stock;
3) Air Pollution Emissions; 4) Productive Efficiency

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 the 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'.

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 air pollution abatement expenditures, local regulatory stringency, and the plant's 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 early empirical research on the impact of environmental regulation concentrated on the relationship between productivity and reported pollution abatement costs. 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. Barbera and McConnell (1986,1990) first looked at time-series variation in a few selected industries and found some impacts of abatement cost on productivity, and then looked at indirect effects on productivity as regulation changed the use of other inputs (especially energy). Gray and Shadbegian (1995,2003) 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] Becker and Henderson (2001) and Greenstone (2001) use plant-level production data combined with air

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[1] Of the three industries (steel, oil, and paper) studied by Gray and Shadbegian (1995), the impact

pollution attainment status, finding that plants in non-attainment areas had significantly higher costs. Gollop and Roberts (1983) use information about regulatory stringency at individual electric utilities to show a significant impact of regulation on productivity. Becker (2001) also finds evidence that reported abatement costs may not reflect all of the information about differences in regulatory stringency contained in the county non-attainment status data.

There has also been some examination of the benefits of regulation, relating air quality to emissions from manufacturing facilities. Shadbegian, et. al. (2000) find that differences in abatement costs across paper mills are related to the benefits of pollution reductions at the mill. Kahn (1999) quantifies an improvement in air quality associated with plant closings in certain high-polluting industries. Henderson (1996) finds a significant impact of county attainment status on peak air quality measures in non-attainment areas.

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 productivity and investment in Gray and Shadbegian (1995,1998). 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,

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of pollution abatement costs on productivity was found to be the smallest for oil.

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 this emissions data does not contain much within-plant variation, we focus on a single year, 1985, and use the best available emissions numbers for each plant in that year. We also add characteristics of 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. A 10 percent increase in abatement capital stock appears to reduce emissions per unit of output by 6.9 percent – the results are quite similar when we study the pollutants separately: 6.3 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 about 75 cents in pollution reduction benefits.

Local regulatory stringency also appears to play an important role in determining a plant's emissions. Plants in non-attainment counties have an average of 43 percent lower emissions per unit of output than those in attainment counties, all else equal. However, this impact is entirely due to lower particulate emissions - not surprising since in our dataset nearly all of the cases of non-attainment status are caused by high particulate concentrations, not sulfur dioxide. More efficient plants also tend to have lower emissions, with a 10 percent higher productivity level being associated with 2.5 percent lower emissions per unit of output. Productivity affects both pollutants, with slightly more of an impact on sulfur dioxide than on particulates. Having older or less advanced equipment in a plant, proxied by the age or speed of its paper machines, has relatively little impact on overall emissions. In an alternative analysis we use a seemingly unrelated regression model to examine the relationship across the unexplained components of performance on both emissions and productivity. Plants with unexpectedly high emissions per unit of output on one pollutant tend to have higher emissions of the other pollutant. Plants with unexpectedly high productivity tend to have lower emissions of both of the pollutants, providing further evidence of the relationship between productive efficiency and environmental performance.

Our analysis of air pollution abatement operating costs yields somewhat puzzling results. We find unexpectedly positive (though always insignificant) coefficients on operating costs, especially when both capital and operating costs are included in the regression. On the other hand, the coefficient on abatement capital stock variable gets more negative when operating costs are included. This suggests that emissions reductions are more likely to be achieved by installing better control equipment, or perhaps 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. However, 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 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. In addition to county-level differences based on attainment status, there can be differences across states in their regulatory stringency, determined by such factors as the state’s budget constraint and political support for environmental issues within the state.

During the 1980s, regulatory attention for air pollution from paper mills was concentrated on sulfur dioxide and particulate emissions. Regulators also focused their attention on the emissions of volatile organic compounds (VOC), contributors to ozone pollution, but paper mills are not generally major sources of VOCs. Thus the relevant attainment status designations are for particulates and sulfur dioxide, and emissions of those pollutants are likely to face more regulatory pressures, and therefore be lower, in non-attainment counties.

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

As noted above, we measure the environmental performance of a paper mill by its emissions of air pollutants (particulates and sulfur dioxide) per unit of output. The determinants of emissions from a given paper mill (EMIT, calculated as pollution emissions divided by the plant’s output) can be separated into two groups:

(1) $\text{EMIT} = f(\text{EMIT}^*(), \text{ABATE}())$.

One set of factors influences the amount of 'uncontrolled' emissions, EMIT*(), generated by the production process in the absence of any special efforts by the plant to abate pollution. The second set of factors influences the fraction of pollution that is abated, ABATE(), before it reaches the environment. The first category includes the plant's size, capital intensity, production technology, and age. The second category includes the plant's air pollution control equipment, air pollution abatement operating expenses, regulatory pressures facing the plant, and the overall efficiency of the plant's management in achieving its abatement goals.

Consider the first set of factors, those affecting uncontrolled emissions (EMIT*), in more detail:

(2) $\text{EMIT}^* = \text{EMIT}^*(\text{SHIP}, \text{PRODCAP}, \text{PULP}, \text{AGE}, \text{TECH})$.

If the pollution generating process has constant returns, so that doubling a plant's output would be expected to double its pollution, then (because we are measuring emissions in intensity form) we should expect a zero coefficient on SHIP. There may be some economies of scale in air pollution abatement, which in our categorization of factors would cause the plant's output to appear also in the determinants of ABATE. In this case, the coefficient on SHIP would be negative.

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

The age of the plant is also likely to affect emissions, with newer plants having been designed to reduce emissions. Given current regulatory constraints, there was by the 1980s no way for a U.S. paper plant to buy ‘dirty’ paper-making equipment, or to design a dirty upgrade to a pulp facility. This variable also spans the two categories to some degree: we choose to consider age as a factor affecting uncontrolled emissions EMIT* before the plant does its abatement, but age could instead be treated as reflecting difficulties on the ABATE side of the equation, though the prediction remains the same - greater age should be associated with greater emissions.

Now consider the determinants of air pollution abatement:

(3) ABATE = ABATE(AIRCAP, AIRPAOC, NONATTAIN, VOTE, TFP, MULTIPLANT).

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 in intensity form, relative to real shipments). During the 1970s and 1980s, most of the abatement of air pollution was done with large capital equipment: scrubbers and precipitators connected to smokestacks, which represents so-called ‘end-of-line’ pollution abatement (AIRCAP-EOL). In more recent years there have been greater amounts of ‘change-in-process’ abatement capital, where the production process is redesigned to some degree to reduce pollution. We did try testing for differences between the impacts of end-of-line and change-in-process abatement capital, but did not find significant differences between them (in regressions not presented here, but available from the authors).

In addition to capital expenditures for air pollution abatement, operating costs may also 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 (measured relative to shipments), as well as AIRCAP, to be positively associated with abatement efficiency, and therefore lead to lower emissions.

Regulatory pressures are also likely to contribute to the extent of pollution abatement at a plant. It could be argued that regulatory pressure should be treated as a factor affecting the plant’s decision to devote resources towards pollution abatement. If so, regulatory pressures would operate through the plant’s choice of values for AIRCAP and AIRPAOC rather than independently entering the ABATE equation. Given our imperfect measures of the plant’s actual abatement efforts, as captured by AIRCAP and

AIRPAOC, some of the plant's pollution abatement activities are likely to remain unmeasured, and could be captured by measures of regulatory stringency. Alternatively, if there is some degree of ordinary inefficiency in the allocation of resources to pollution abatement, facing a high degree of regulatory scrutiny is likely to focus the plant's attention on abatement issues, reducing this inefficiency and increasing abatement. 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. Another variable, VOTE, measuring differences across states in their political support for environmental regulations is also included, to capture possible state-level factors.

Finally, we consider the possibility that plants may have different 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. We 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. However, the opposite relationship might hold if, for example, some managers concentrate on regulatory issues, while others concentrate on production, making the two types of efficiency substitutes rather than complements. Achieving higher productivity by speeding up and cutting corners in the production process could provide another reason for higher productivity to be associated with a greater probability of emissions, through more frequent accidental releases of emissions.[2]

The resulting equation for estimation includes both emission and abatement components:

(4) EMIT = f(SHIP, PRODCAP, PULP, AGE, TECH, AIRCAP, PAOC, NONATTAIN, VOTE, TFP, MULTIPLANT).

In addition to estimating equation (4), we can also look at the relationship between different pollutants, or between pollutants and productivity, with a multi-equation seemingly unrelated regression (SUR) model. In such a model, we would first estimate a regression for each of the equations we wanted to model, then examine the correlations between the residuals from those regressions. Equation (4), excluding TFP, is estimated along with the following equation for the determinants of productivity:

(5) TFP = f(PAOC, PULP, AGE, TECH, MULTIPLANT).

Here productive efficiency is explained by pollution abatement spending (using total pollution abatement operating costs for all media, not just air pollution), regulatory pressures (which may limit the plant's ability to adjust its production process), technology, age, and firm experience with paper mills. If more efficient producers are

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[2] However, such a temporary increase in emissions is unlikely to be captured in our emissions measures since most are based on engineering estimates as noted in the data description section below.

also more efficient at air pollution abatement, we would expect to see a negative correlation between the estimated residuals from equations (4) and (5) generated as part of the SUR analysis. Since we have emissions data for two different pollutants, particulates and sulfur dioxide, we can also estimate a three equation seemingly unrelated regression system (two pollutants plus productivity) and measure the correlation (expected to be positive) between the unexplained portion of each pollutant's emissions.

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.[3] 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 output

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[3] See Gray and Shadbegian (1995) 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).

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.[4] 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 PAOCRAT, 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

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[4] 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

analysis, as an explanatory variable possibly affecting the plant's productivity (PAOCRAT was found to be significantly related to TFP levels in Gray and Shadbegian, 1995).

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 average age and operating speed of each paper machine in operation at the mill.[5] To control for possible advantages to firms with more expertise in operating paper mills, we also include a MULTIPLANT dummy, indicating that the firm owns 10 or more paper mills, based on plant ownership data from the Lockwood Directory.

In addition to the plant-level data, we use two measures of the local 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

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provide an estimate of the plant's initial abatement capital stock in 1979.

[5] PMAGE is reported only in the 1979 Lockwood-Post Directory; PMSPEED is reported in each issue of the Lockwood Directory (although it does not necessarily 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

(Gray, 1997) and investment decisions (Gray and Shadbegian, 1998).

An alternative measure of regulatory stringency specific to air pollution regulation 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.[6] 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.

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.[7] This number is

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information is included in each of the regression models to correct for bias from the imputation.

[6] 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).

[7] 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

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 particulates and sulfur dioxide, since they are most commonly reported and were the major focus of air pollution regulation for this industry during the time period. We measure the emissions of each pollutant, PM and SO2, in tons per year and then aggregate them together into EMIT, 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). 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

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emissions.

case.[8]

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 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 - see Shadbegian, et. al. (2000).

Of the plants in our sample, about one-third are located in counties that are in non-attainment for either particulates or sulfur dioxide - as noted earlier, nearly all of the cases of non-attainment refer to particulate concentrations rather than to sulfur dioxide concentrations. Slightly over half of our sample are pulping mills, beginning the paper-making process with raw fiber from trees. Many of the plants are quite old, with an average plant's paper machines dating back to 1946 (39 years before the year 1985). More than half of the plants are located in firms with a large paper industry component as measured by MULTIPLANT (10 or more paper mills owned by the firm).

Turning first to the results for control variables 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-

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[8] The following variables are measured in logs in the regressions and are designated with an 'L': the three dependent variables PMEMIT, SO2EMIT, and TOTEMIT; and the following seven independent variables: AIRCAP; AIRPAOC; PAOC; SHIP; PRODCAP; PMSPEED; and VOTE.

intensive plants show somewhat greater emissions although the impact is only significant for sulfur dioxide. We find no evidence for economies of scale in pollution control. If anything, larger plants have more sulfur dioxide emissions per unit of output than do smaller 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 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 our focus to the main explanatory variables starting with the key abatement-related variable in Table 2, LAIRCAP (log of AIRCAP). We find that plants with larger stocks of air pollution abatement capital (all else equal) tend to have lower emissions. The results are somewhat larger and more significant for sulfur dioxide than for particulates. Plants with more abatement capital also show significantly lower emissions when particulates and sulfur dioxide are combined together in LTOTEMIT (log of TOTEMIT).

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 significantly less polluting, with more of an impact on sulfur dioxide and the combined emissions index than on particulates. Since the TFP productivity index is measured in percentage terms, a 10% higher productivity level at a plant is associated with 2.5% lower emissions (in Model 3F). This results adds credence to the idea that plants which use their inputs more efficiently also produce less waste, making it easier for them to achieve better environmental performance.

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 on sulfur dioxide emissions. This is not surprising, given that the non-attainment status for nearly all of the non-attainment counties in our data refers to particulate concentrations. The overall reduction in air emissions per unit of output is 35% relative to a plant located in an attainment county (model 4F).[9] The coefficients on LVOTE are not significant in any specifications, although they do tend to have the expected negative sign. These results indicate some impact of regulatory pressures, especially an effect of non-attainment on particulate emissions. It should be noted that these regressions already include controls for the air pollution abatement capital stock in place at a plant. Therefore the additional impacts of regulation here represent greater than expected reductions in emissions, after accounting for the increased pollution abatement capital that should result from being in a non-attainment area.[10]

Now, let us return to the key element in our model, the impact of abatement spending, in an effort to quantify the impacts on benefits and costs of pollution emission

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[9] Note that the marginal effect of a dummy variable is approximated as $e^{\beta}-1$ when the dependent variable is measured in logs (see Halvorsen and Palmquist (1980)).

[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

reductions. Consider the coefficient in Model 4F on air pollution abatement capital stock, 0.684. This indicates that a plant with a 10 percent larger air pollution abatement capital stock, all else equal, would have 6.84 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 6.84 percent reduction in annual aggregate air pollution emissions, about 306 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

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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. They report a benefit of $2172 per ton of reduced emissions, but this is in 1990 dollars for a ton of NOX. We translate these benefits into 1972 dollars (the benchmark year for our abatement cost deflator) for a ton of SO2. This yields benefits = ($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.

trillion of all categories of benefits from reductions in all air pollutants. We found an even larger benefit-cost ratio in Shadbegian, et. al. (2000), where the benefits from air pollution abatement were calculated at about 20 times the costs, but much of that difference is explained by our earlier paper concentrating on abatement operating costs rather than capital stocks (so both benefits and costs are in terms of annual dollars).

Table 5 adds air pollution abatement operating costs (AIRPAOC) to the analysis. Unlike the plant's pollution abatement capital stock, which was accumulated over earlier years, AIRPAOC is potentially endogenous as current emissions levels may influence the amount being currently spent on pollution abatement operating costs. We control for this using an instrumental variables estimation technique. Using lagged AIRPAOC as an instrument we predict air pollution abatement costs and use it 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. Although insignificant, we find unexpectedly positive 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 are more likely to be achieved by installing more or better control equipment, or perhaps that plants with higher pollution abatement operating costs are not using their resources efficiently. We tested a variety of models that included abatement operating costs, with

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[12] We also estimated each model in Table 5 using lagged AIRPAOC in place of its predicted

similar results to those presented in Table 5 – not significant, but often positive.

An alternative way of examining the determinants of environmental performance is shown in Table 6. Here we consider a seemingly unrelated regression model with three equations. This allows for correlations among the unexplained variation in each of the two emissions measures and plant-level productivity. We always find a negative correlation between the TFP residual and the two emissions residuals, reinforcing our earlier conclusion that more productive plants tend to have better environmental performance (see Table 6 panel B). We also find positive correlations between the residuals from the two pollutant 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 estimated 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, the productivity equation and one of the emissions equations; and using a predicted value for LPAOC (based on lagged values of LPAOC).

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value and found no qualitative difference in the results (these results are available upon request).

The results are similar in these alternative models. In particular 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. This reinforces the notion that plants which use their inputs more efficiently also produce less waste, making it easier for them to achieve better environmental performance.

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 their pollution abatement spending, local regulatory stringency, 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. A 10 percent increase in abatement capital stock appears to reduce annual emissions per unit of output by 6.8 percent. Translating these impacts into dollars suggests a sizable return on that investment: one dollar of abatement capital stock providing an annual return of about 75 cents in pollution reduction benefits to society. These large benefits come directly from the large estimated mortality impacts of particulates – more modest estimates of health effects would yield proportionately smaller social rates of return.

Local regulatory stringency also appears to play an important role in determining a plant's environmental performance. Plants in non-attainment counties have an average of 43 percent lower emissions per unit of output when compared to plants in attainment counties, even controlling for the plant's abatement capital stock. These emissions reductions occur primarily in particulate emissions. 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. Plants with older or less productive equipment stock, as proxied by the age or speed of their paper machines, also have higher emissions, although those results are not generally significant.

Our seemingly unrelated regression analysis also confirms the connections among emissions of different pollutants and productivity levels. We find that unexpectedly high productivity levels are associated with unexpectedly low levels of emissions per unit of output for both particulates and sulfur dioxide. In addition, plants with unexpectedly high levels of emissions per unit of output on one pollutant tend to have unexpectedly higher emissions on the other pollutant.

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. The results for the other variables in the model are not significantly affected by including abatement operating costs.

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 will control for unmeasured heterogeneity across plants, and may help shed light on our unusual operating cost results.

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Table 1
Summary Statistics
(68 observations)

Variable	Mean	Std.Dev.	Description
		Plant Air Pollution Emissions	
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)
		Pollution Abatement Spending ($000)	
POLCAP	7860.64	7816.86	Total pollution abatement capital
AIRCAP	4166.17	4599.40	Air pollution abatement capital
AIRPAOC	1022.78	1638.22	Air pollution operating costs
PAOCRAT	1.99	1.41	Total PAOC/peak capacity (*100)
		Local Regulatory Stringency	
NONATTAIN	.35	.48	County non-attainment for PM or SO2
VOTE	57.34	13.39	LCV pro-environment voting index
		Plant Characteristics	
PMSPEED	1640.21	560.40	Average paper-machine speed (fpm)
PMAGE	39.00	14.96	Average paper-machine age (in 1985)
PULP	.56	.50	Plant includes pulping process
PRODCAP	53796.56	46002.31	Productive capital stock ($000)
SHIP	46490.71	28233.23	Value of annual plant shipments
TFP	110.77	19.06	Total factor productivity index
MULTIPLANT	.53	.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	.93	Log(AIRCAP/SHIP)
LAIRPAOC	-5.99	3.87	Log(AIRPAOC/SHIP)
LSHIP	10.76	.60	Log(SHIP)
LPRODCAP	-.23	.50	Log(PRODCAP/SHIP)
LPMSPEED	7.33	.43	Log(PMSPEED)
LVOTE	4.02	.27	Log(VOTE)
LPAOC	.35	1.02	Log(PAOCRAT)

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

	(A)	(B)	(C)	(D)	(E)	(F)
Dep. Var.:	LPMEMIT	LPMEMIT	LSO2EMIT	LSO2EMIT	LTOTEMIT	LTOTEMIT
CONSTANT	-19.365	-17.788	-30.255	-27.554	-28.529	-26.337
	(-3.96)	(-3.27)	(-6.49)	(-5.69)	(-6.90)	(-6.01)
LAIRCAP	-0.408	-0.500	-0.444	-0.632	-0.419	-0.575
	(-1.33)	(-1.54)	(-1.52)	(-2.19)	(-1.62)	(-2.21)
LPRODCAP	0.477	0.454	0.738	0.975	0.572	0.708
	(0.88)	(0.79)	(1.43)	(1.90)	(1.25)	(1.53)
PMAGE		-0.464		1.445		0.661
		(-0.33)		(1.15)		(0.58)
LPMSPEED		-0.307		-0.616		-0.490
		(-0.68)		(-1.54)		(-1.35)
LSHIP	0.094	0.146	0.529	0.663	0.293	0.400
	(0.28)	(0.40)	(1.63)	(2.05)	(1.02)	(1.37)
PULP	1.716	1.819	0.668	1.029	1.090	1.366
	(3.12)	(3.14)	(1.28)	(1.99)	(2.35)	(2.93)
MULTIPLANT	0.014	-0.034	-0.521	-0.498	-0.397	-0.405
	(0.03)	(-0.08)	(-1.35)	(-1.33)	(-1.16)	(-1.20)
R-squared	0.433	0.448	0.594	0.655	0.672	0.709

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

Table 3
Determinants of Emissions
Plant Productivity

	(A)	(B)	(C)	(D)	(E)	(F)
Dep. Var.:	LPMEMIT	LPMEMIT	LSO2EMIT	LSO2EMIT	LTOTEMIT	LTOTEMIT
CONSTANT	-11.100	-11.507	-27.236	-25.539	-25.437	-24.460
	(-1.84)	(-1.82)	(-4.27)	(-4.13)	(-4.55)	(-4.53)
LAIRCAP		-0.614		-0.725		-0.684
		(-2.08)		(-2.51)		(-2.71)
LPRODCAP		0.139		0.764		0.420
		(0.26)		(1.45)		(0.91)
TFP		-0.020		-0.022		-0.025
		(-1.75)		(-1.98)		(-2.54)
PMAGE		-0.394		1.290		0.475
		(-0.31)		(1.03)		(0.43)
LPMSPEED		-0.238		-0.566		-0.460
		(-0.57)		(-1.39)		(-1.29)
NONATTAIN	-1.276	-1.376	-0.190	-0.121	-0.455	-0.433
	(-3.29)	(-3.37)	(-0.46)	(-0.30)	(-1.27)	(-1.24)
LVOTE	-0.442	-0.573	-0.157	-0.219	-0.016	-0.062
	(-0.62)	(-0.76)	(-0.21)	(-0.30)	(-0.02)	(-0.10)
LSHIP	-0.344	-0.037	0.462	0.843	0.164	0.568
	(-1.00)	(-0.10)	(1.27)	(2.27)	(0.52)	(1.75)
PULP	1.312	1.664	0.521	0.842	0.865	1.188
	(3.34)	(3.11)	(1.26)	(1.61)	(2.38)	(2.59)
MULTIPLANT	0.012	-0.052	-0.557	-0.488	-0.391	-0.382
	(0.03)	(-0.14)	(-1.43)	(-1.31)	(-1.15)	(-1.17)
R-squared	0.518	0.577	0.576	0.680	0.665	0.748

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

Table 4
Determinants of Emissions
Regulatory Pressures

	(A)	(B)	(C)	(D)	(E)	(F)
Dep. Var.:	LPMEMIT	LPMEMIT	LSO2EMIT	LSO2EMIT	LTOTEMIT	LTOTEMIT
CONSTANT	-11.100	-11.507	-27.236	-25.539	-25.437	-24.460
	(-1.84)	(-1.82)	(-4.27)	(-4.13)	(-4.55)	(-4.53)
LAIRCAP		-0.614		-0.725		-0.684
		(-2.08)		(-2.51)		(-2.71)
LPRODCAP		0.139		0.764		0.420
		(0.26)		(1.45)		(0.91)
TPF		-0.020		-0.022		-0.025
		(-1.75)		(-1.98)		(-2.54)
PMAGE		-0.394		1.290		0.475
		(-0.31)		(1.03)		(0.43)
PMSPEED		-0.238		-0.566		-0.460
		(-0.57)		(-1.39)		(-1.29)
NONATTAIN	-1.276	-1.376	-0.190	-0.121	-0.455	-0.433
	(-3.29)	(-3.37)	(-0.46)	(-0.30)	(-1.27)	(-1.24)
LVOTE	-0.442	-0.573	-0.157	-0.219	-0.016	-0.062
	(-0.62)	(-0.76)	(-0.21)	(-0.30)	(-0.02)	(-0.10)
LSHIP	-0.344	-0.037	0.462	0.843	0.164	0.568
	(-1.00)	(-0.10)	(1.27)	(2.27)	(0.52)	(1.75)
PULP	1.312	1.664	0.521	0.842	0.865	1.188
	(3.34)	(3.11)	(1.26)	(1.61)	(2.38)	(2.59)
MULTIPLANT	0.012	-0.052	-0.557	-0.488	-0.391	-0.382
	(0.03)	(-0.14)	(-1.43)	(-1.31)	(-1.15)	(-1.17)
R-squared	0.518	0.577	0.576	0.680	0.665	0.748

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

Table 5
Determinants of Emissions
Pollution Abatement Operating Costs

	(A)	(B)	(C)	(D)	(E)	(F)
Dep. Var.:	LPMEMIT	LPMEMIT	LSO2EMIT	LSO2EMIT	LTOTEMIT	LTOTEMIT
CONSTANT	-9.229	-11.195	-23.689	-24.917	-22.291	-23.999
	(-1.43)	(-1.75)	(-3.70)	(-4.02)	(-3.95)	(-4.42)
LAIRPAOC*	0.015	0.039	0.038	0.077	0.026	0.057
	(0.21)	(0.53)	(0.53)	(1.10)	(0.41)	(0.93)
LAIRCAP		-0.643		-0.784		-0.728
		(-2.13)		(-2.67)		(-2.83)
LPRODCAP		0.190		0.865		0.495
		(0.35)		(1.62)		(1.06)
TFP	-0.014	-0.020	-0.019	-0.022	-0.020	-0.024
	(-1.27)	(-1.71)	(-1.72)	(-1.94)	(-2.05)	(-2.49)
PMAGE	-0.034	-0.295	1.323	1.488	0.703	0.623
	(-0.03)	(-0.23)	(1.04)	(1.17)	(0.63)	(0.56)
LPMSPEED	-0.066	-0.209	-0.351	-0.509	-0.263	-0.418
	(-0.16)	(-0.50)	(-0.83)	(-1.24)	(-0.70)	(-1.16)
NONATTAIN	-1.335	-1.398	-0.150	-0.166	-0.422	-0.467
	(-3.17)	(-3.38)	(-0.36)	(-0.41)	(-1.14)	(-1.32)
LVOTE	-0.571	-0.562	-0.097	-0.198	-0.007	-0.047
	(-0.73)	(-0.74)	(-0.13)	(-0.27)	(-0.01)	(-0.07)
LSHIP	-0.169	-0.051	0.761	0.815	0.453	0.547
	(-0.44)	(-0.13)	(2.00)	(2.20)	(1.35)	(1.68)
PULP	1.094	1.591	0.359	0.697	0.637	1.080
	(2.21)	(2.86)	(0.73)	(1.29)	(1.47)	(2.28)
MULTIPLANT	0.063	-0.045	-0.446	-0.474	-0.295	-0.372
	(0.16)	(-0.12)	(-1.17)	(-1.27)	(-0.88)	(-1.14)
R-squared	0.540	0.580	0.642	0.688	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

	(A1)	(A2)	(A3)
Dep. Var.:	LPMEMIT	LSO2EMIT	TFP
CONSTANT	-14.194	-28.466	154.865
	(-2.54)	(-5.17)	(3.62)
LAIRCAP	-0.586	-0.693	
	(-2.28)	(-2.74)	
LPRODCAP	0.187	0.822	
	(0.40)	(1.80)	
LPAOC			-1.833
			(-0.89)
PMAGE	-0.004	0.013	-0.004
	(-0.31)	(1.18)	(-0.03)
LPMSPEED	-0.321	-0.656	4.720
	(-0.86)	(-1.78)	(1.03)
NONATTAIN	-1.374	-0.119	
	(-3.81)	(-0.34)	
LVOTE	-0.526	-0.166	
	(-0.79)	(-0.25)	
LSHIP	-0.079	0.791	
	(-0.25)	(2.54)	
PULP	1.884	1.084	-11.090
	(4.00)	(2.34)	(-2.27)
MULTIPLANT	-0.062	-0.499	0.640
	(-0.18)	(-1.48)	(0.16)
R-squared	0.549	0.653	0.312

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

Residual-TFP Correlations

	LPMEMIT*	LSO2EMIT*
LSO2EMIT*	0.4099	
TFP*	-0.1935	-0.2113

* = Residuals from the corresponding equation above
Breusch-Pagan test of independence: chi2(3) = 17.01, Pr = 0.0007