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Environmental Regulations and Technological Change: Pulp and Paper Mills and EPA's Cluster Rule

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Abstract: In this paper we propose a new model to calculate changes in pollution abatement costs (PAC) when data on bad outputs and information on the cost of inputs assigned to pollution abatement activities are not available. To calculate the PAC of reducing bad output, we introduce a measure of abatement intensity that captures variation in the technologies used to reduce water discharges. We then decompose the change in PAC into three components to identify their relative contribution to changes in PAC: (1) changes in the level of inputs, (2) technological change, and (3) changes in pollution abatement intensity. These three components are estimated using data from 1997 to 2007 on a sample of pulp mills required to comply with effluent limits of the U.S. EPA's Cluster Rule. We find technological change is consistently associated with declining PAC, while both changes in inputs and abatement intensity are associated with increasing PAC.

KEYWORDS: technological change, pulp and paper mills, Cluster Rule, pollution abatement costs, abatement intensity

JEL CODES: O33, Q52, Q53

I. Introduction[1]

Most regulations promulgated by the U.S. Environmental Protection Agency (U.S. EPA) focus on pollution releases into one environmental medium (e.g., land, air or water). However, often a production process releases pollutants into more than one medium. A good example is the pulp and paper-making process. Pulping involves separating lignin (glue) from wood pulp fibers and then mixing these fibers with water to create a slurry. The slurry is washed multiple times, dried and then whitened with bleach to make paper. Both processes result in conventional and toxic air and water pollutants.[2] Recognizing more cost-effective pollution reductions could be achieved by jointly setting air and water standards rather than instituting separate regulations for releases to each medium, EPA issued its first integrated, multi-media regulation– known as the "Cluster Rule" (CR) - in 1998 (U.S. EPA,1998).

One regulatory objective of the CR was limiting the formation of dioxin and furans from the pulp and paper-making process. The elemental chlorine used to bleach pulp reacts with organic compounds in the pulp (lignin) to form dioxins, furans, and chloroform in the wastewater stream.[3] The technology-based approaches considered by the EPA included 1) reducing the chlorine bleaching required via oxygen delignification (OD) and extended delignification (ED) and 2) substituting elemental chlorine-free bleaching (ECF) for chlorine

[1] We would like to thank Jim Davis at the Boston Research Data Center for his continued help; Wayne Gray at Clark University for his valuable input and help with the data; Jordan Marvakov, Sergey Kazakov, and Kaushik Ghosh for excellent research assistance; Lars Vilhuber at Cornell Virtual Research Data Center for help with compilation of R packages for use at the Research Data Center; and John Haltiwanger for providing us with capital stock data. We would also like to thank Will Wheeler for his helpful comments and suggestions.

[2] Conventional and toxic air and water pollutants include particulate matter, sulfur dioxide, and benzene, while conventional and toxic water pollutants include biochemical oxygen demand and dioxin.

[3] Dioxins and furans, which accumulate in human fatty tissue, are characterized by the EPA as highly toxic and can cause cancer, reproductive and development problems, damage to the immune system, and can interfere with hormones (see U.S. EPA 2018a).

bleaching. Both OD and ED decrease the amount of lignin in the pulp prior to the bleaching stage, which reduces the amount of bleaching chemicals needed to brighten the pulp, while ECF replaces elemental chlorine with chlorine dioxide (ClO_2) as the bleaching agent.[4] When EPA published the final CR regulations in 1998, the technology basis for the effluent limits of the CR required pulp and paper mills to switch from using elemental chlorine as the bleaching agent to ECF.

We are interested in how this change in bleaching technology affected the cost of producing pulp and paper. Two approaches have been developed in the extant literature to calculate the opportunity cost of producers being prohibited from freely disposing of their undesirable by-products. The first model - the joint production model - specifies the joint production of good and bad outputs with two technologies – one when the producer can freely dispose of its bad outputs (i.e., the unregulated technology) and one when the producer may not freely dispose of its bad outputs (i.e., the regulated technology) (see Färe et al., 2007). One advantage of this approach is it does not require information on the pollution abatement technology. Instead, using information on total inputs and the production of the good and bad output, the opportunity cost of pollution abatement is the foregone good output due to the bad output not being freely disposable.

In contrast, the second model - the assigned input model - requires information on the inputs assigned to good output production and pollution abatement, information on good

[4] Unlike chlorine, which combines with lignin to create dioxin and furans, chlorine dioxide breaks apart the lignin, resulting in organic, more water-soluble compounds. While ECF does not completely eliminate dioxin formation, its use greatly reduces the amount created.

output production, but no information about bad output production (see Aiken et al., 2009; Gray and Shadbegian, 2003). When inputs assigned to good output production are switched to pollution abatement, the subsequent decrease in good output production reflects the opportunity cost of pollution abatement.

In our case, we have neither data on bad output production (e.g., dioxin) nor the quantity of inputs assigned to pollution abatement, so instead of using a joint production or assigned input model, we use novel measures of pollution abatement intensity to calculate the opportunity cost of pollution abatement.[5] We construct pollution abatement intensity measures based on the regulated technology, which incorporates the non-chlorine bleaching technologies used by mills to reduce dioxin. We have a unique dataset that allows us to identify when OD and ED systems were installed and the extent of use of ECF or ClO_2 substitution at mills subject to the effluent limits of the Cluster Rule starting in 1997. Using these data, we introduce three measures of pollution abatement intensity that capture variation in the levels of ED, OD and ECF employed by pulp mills to comply with CR limits. These measures of abatement intensity serve as proxies for the reduction in dioxin releases by mills. That is, we assume that as more pulp production is subject to these technologies, abatement intensity increases which results in less dioxin being generated and released.

Gollop and Roberts (1983) developed a measure of abatement intensity to estimate the effect of restrictions on sulfur dioxide emissions on plant-level productivity of U.S. electric

[5] The EPA's Toxic Release Inventory (TRI) database contains facility-level annual data on the quantity and type of toxic releases for an extensive range of hazardous substances. EPA did not require monitoring of dioxins before the Cluster Rule and releases of dioxin and dioxin-related compounds were not collected by the TRI until 2000, by which time many facilities had already achieved the reductions required by the CR. For information on EPA's TRI database, please see https://www.epa.gov/toxics-release-inventory-tri-program.

utilities. They found that an increase in regulatory intensity increases abatement costs. We are also interested in how an increase in regulatory intensity affects pollution abatement costs. The increase in the level of abatement needed to comply with the CR limits increases abatement costs as more inputs are switched from producing the good output to reducing the bad output. However, technological change may moderate the increases in pollution abatement costs (PAC) associated with the regulation.[6]

To identify the relative importance of the factors that affect changes in PAC, we decompose PAC into the following components (1) changes in inputs, (2) changes in technology, and (3) changes in pollution abatement intensity.[7] The hypothesis of whether technological change can moderate pollution abatement costs can be evaluated by examining the magnitude of the technological change component of the decomposition. To our knowledge, because of our distinct dataset, we are the first to develop a measure of regulatory stringency to examine how changes in abatement technology affected the costs of complying with the effluent limits of the CR.

Several studies have explored how the CR affected technological change in the pulp and paper industry. Norberg-Bohm and Rossi (1999) argue the use of ECF by pulp and paper mills represents an incremental change in technology and the EPA, in designing the CR, did not push for more sweeping innovations such as totally-chorine free bleaching (TCF). [8] However, the

[6] Some have referred to this as the 'weak' version of the Porter Hypothesis – see Jaffe and Palmer (1997).
[7] Färe et al. (2016) decompose changes in PAC according to (1) changes in inputs, (2) technical change, (3) and changes in bad output production. Instead of changes in bad output production, changes in PAC are affected by changes in pollution abatement intensity in our decomposition.
[8] Mills could have used TCF, which uses hydrogen peroxide and ozone as bleaching agents to eliminate the formation of dioxin, to meet the CR water standards. However, EPA demonstrated that TCF was not technically feasible for all mill categories, i.e., ammonia-based sulfite mills, whereas ECF was both technically and economically feasible. Because TCF was feasible for some segments, EPA included voluntary alternative standards

incremental technological change to ECF had an upstream effect, namely changing the technology used to produce chlorine. Snyder et al. (2003) find the CR decreased the demand for chlorine, resulting in a significant increase in the number of closures among plants that did not adopt the cleaner, membrane technology to produce chlorine. The CR also had a downstream effect, changing the mix of bleached and unbleached products. Elrod and Malik (2017) find evidence that some mills, which faced the both air and water regulations of the CR, substituted away from bleached products instead of changing their production processes compared to mills that faced only the air regulations.

Using patent data on technologies designed to reduce dioxin from the pulp bleaching process in Canada, Finland, Japan, Sweden and the United States, Popp et al. (2011) find public pressure played a larger role than environmental regulation in the development and diffusion of ECF and TCF technologies. Because of growing health concerns about dioxin, public pressure led many mills to voluntarily adopt technologies that used less elemental chlorine (Maynard and Shortle, 2001). For example, some mills installed bleach-reducing technologies such as OD or ED systems in the early 1990's.

The remainder of our paper is organized as follows. Section II provides an overview of the pulp and paper industry and the Cluster Rule, while Section III specifies the regulated and unregulated production functions used to calculate PAC. Section IV presents the data, Section V discusses our estimation approach and the results, and Section VI summarizes our findings.

using TCF in order to encourage mills to use the bleaching technology whenever it is consistent with the type of pulping process they used. In the end, only the Samoa Mill in California used TCF.

II. Pulp and Paper Industry and EPA's "Cluster Rule"

While the pulp and paper industry confronts substantial levels of environmental regulation, the regulatory burden varies among mills depending on their age, location, production process used, whether or not the mill includes a pulping facility, and the regulatory intensity directed at a mill.[9] Prior studies, including Gray and Shadbegian (2003), found the main determinant of regulatory impact on a mill is whether or not it contains a pulping facility, since the pulping process is significantly more pollution intensive than the paper-making process.[10]

There are two methods employed to produce pulp from wood chips – mechanical and chemical wood pulping – and each process produces a different quality of paper and generates different types of pollutants. Mechanical pulping uses mechanical energy to separate the lignin from the wood fibers resulting in more air pollution from a power-generating boiler used to generate energy. But mechanical pulping generally produces lower quality pulp and consequently, is used to make lower quality printing paper such as newsprint. Kraft chemical pulping involves using "cooking" chemicals to separate the lignin from wood fibers. Bleaching the kraft pulp with elemental chlorine creates dioxins, furans and chloroform. Bleached kraft pulp is used to produce higher quality printing paper such as copy paper and magazine paper.

On December 5th, 1982 the Meramec River flooded Times Beach, Missouri contaminating virtually the entire town with dioxin that was in the oil the town contracted to

[9] Integrated mills make their own pulp, while non-integrated mills buy pulp or use recycled wastepaper.
[10] The most important environmental concerns during the paper-making phase are air pollution, if the mill produces electricity via a cogeneration system, and with the residual water pollution produced throughout the drying process.

have sprayed on its unpaved roads to alleviate dust in the early 1970's. As a result of this incident, two influential environmental groups, the Environmental Defense Fund (EDF) and the National Wildlife Federation (NWF), sued the EPA for not adequately protecting the U.S. public from the risks caused by dioxin. EPA, as part of a 1988 settlement with the EDF and NWF, agreed to examine the health risks of dioxin and to promulgate regulations to decrease dioxin emissions (Environmental Defense Fund and National Wildlife Federation vs. Thomas, D.D.C. No. 85-0973). In 1997, as part of the CR, the EPA implemented regulations that included dioxin reductions.

EPA promulgated the CR on April 15, 1998, and while most air provisions became effective on April 16, 2001, best available technology (BAT) standards for water effluents became effective the next time an existing mill's National Pollutant Discharge Elimination System (NPDES) permit was renewed.[11] Because NPDES permits are generally renewed every five years, the effective BAT compliance dates for the water provisions were spread over the 1998 to 2003 period. The CR rule affected pulp and paper mill in three subcategories: (1) bleached papergrade kraft and soda (BPK) mills; (2) papergrade sulfite (PS) mills, and (3) semi-chemical mills. The rule set limits on releases of toxic, conventional, and nonconventional pollutants (e.g., chlorine, nitrogen, and phosphorus) to both air and water from the pulp and paper mills in these subcategories.

[11] The rule and implementation information for the air portion of the Cluster Rule can be found at U.S. EPA (2018b), while information about the Effluent Guidelines for the Cluster Rule can be found at U.S. EPA (2018c). Rule information can also be found in the Federal Register: https://www.govinfo.gov/content/pkg/FR-1998-04-15/pdf/98-9613.pdf.

For air pollutants, EPA established maximum achievable control technology (MACT) standards requiring existing mills to capture and treat toxic air pollutant emissions produced during the cooking, washing, and bleaching stages of the pulp manufacturing process. Specifically, the CR called for hazardous air pollutants to be reduced by almost 60%. Additional provisions of the CR included reducing releases of sulfur, volatile organic compounds, and particulate matter by 47%, 49%, and 37%, respectively. For water pollutants, EPA set effluent limits - Best Available Treatment (BAT) and Pretreatment Standards for Existing Sources (PSES) requirements- based on mills substituting ECF for elemental chlorine in the bleaching process. The CR's technology-based water regulations required a 96% reduction in dioxin and furan, and a 99% reduction in chloroform (see Morgan et al., 2014, for a detailed discussion of the Cluster Rule).

Initially, the EPA expected approximately 490 pulp and paper mills would be subject to the CR air regulations. EPA expected 155 of the 490 pulp and paper mills would need to comply with the more stringent MACT emission standards, and of those 155 mills, the 96 using chemical pulping techniques would also be required to comply with a new set of BAT effluent standards. In the economic analysis conducted in support of the rule, the EPA estimated the cost for these 96 mills to comply with the BAT standard, expressed in 1995 dollars, was $1.039 billion in capital and $0.158 billion in annual operation and maintenance (O&M) expenses (U.S. EPA, 1997).

In anticipation of the CR, as well as some state requirements and public pressure to reduce dioxin releases, some mills installed OD and ED systems in the early 1990's. Of the 37 mills that installed OD systems from the early 1990's through 2008, 24 mills installed this

system by 1995. Similarly, 23 of the 33 mills that installed ED systems between 1987 and 2008 did so by 1995 (Beca AMEC, 2013b). Although some mills installed ED/OD systems, other mills delayed adopting cleaner pulping technologies during the prolonged development of the CR regulations (the first CR regulations were proposed in 1993). Maynard and Shortle (2001) found mills delayed investing due to the uncertainty associated with making large irreversible investments prior to the EPA issuing its final CR regulations.

Converting pulp lines from elemental chlorine bleaching to ECF takes time. Because chlorine dioxide gas is flammable and may not be transported within the US, chlorine dioxide is made onsite at the mill. Because it takes from 12 to 24 months to install a new chlorine dioxide generator and adsorption tower (which optimizes the generation process) or expand the capacity of the existing generator, full implementation of 100% chlorine dioxide substitution (i.e., switching to ECF) depends on a mill's initial on-site chlorine dioxide generation (U.S Congress, 1989, Chapter 4). In 1998, the year the CR was promulgated, only 28% of active mills had completely switched to ECF (50% of active mills had switched at least 50% of their total pulp production to ECF). In 2001, 71% of mills had adopted 100% ECF (85% of active mills had switched at least 50% of their total pulp production to ECF), and in 2002, 90% of active mills had completely switched (Beca AMEC, 2013a). Thus, the level of dioxin discharged into surface waters was below the effluent limitations and standards required by the CR for most mills by 2001.[12]

[12] The CR limits for NPDES dischargers would have been written into permits upon next issuance, which is generally every five years. Using the renewal dates from EPA's Permit Compliance System (PCS) to determine when the CR limits were written into the permits, 60% of the 96 mills permits were renewed between April 15, 1998 and 2001. By 2003, 80% of the permits had been renewed and by 2007, 100% of the permits had been renewed.

III. Model

In this paper we use a data envelopment analysis (DEA) framework, combined with our measures of pollution abatement intensity, to calculate the opportunity cost of changing the bleaching process to comply with the CR. Specifically, we model two production technologies – one when the bad output is unregulated (or least regulated) and another when the bad output is regulated - where the regulated technology captures the effect of variation in use of chlorine dioxide substitution, as well as use of extended and oxygen delignification, among mills. In other words, the bad output is freely disposable with the unregulated technology, but not freely disposable with the regulated technology. In this model, the difference in maximum good output production between the unregulated and regulated technologies constitute the PAC of reducing dioxin, furans and chloroform loadings to water.

We will now formally specify the unregulated and regulated technologies. As an example, we present the unregulated and regulated production functions for period t. If we have k=1,…,K mills with information on x_n inputs (n=1,…, N), and one good output y_k for t=1,…,T periods, the unregulated production function for mill k' (FUR) in period t is (see Aiken et al., 2009):

$$\mathrm{FUR}(x^t, t) = \max \sum_{k=1}^{K} z_k^t \, y_k^t \qquad (1)$$

$$\text{s.t.} \quad \sum_{k=1}^{K} z_k^t \, x_{kn}^t \leq x_{k'n}^t \qquad n = 1, \ldots, N$$

$$\sum_{k=1}^{K} z_k^t \leq 1$$

$$z_k^t > 0 \qquad\qquad k = 1, \ldots\ldots, K$$

The unregulated production technology for mill k' is constructed from all observations (K) that are available in period t. The linear programming (LP) problem calculates the maximum good output of mill k' subject to its input constraints and a constraint that imposes non-increasing returns to scale (i.e., the summation of the weights assigned to each mill when constructing the production frontier, z, is less than or equal to unity).[13] Hence, linear combinations of all observations subject to the LP constraints are used to calculate the maximum good output of mill k' in period t. Guaranteeing the maximum good output of the unregulated technology equals or exceeds the maximum good output of the regulated technology requires employing sequential frontiers, which construct the frontier for period t with observations from period 1 up to and including period t. In other words, using all observations to construct the unregulated frontiers eliminates the possibility of the model identifying negative pollution abatement costs.

To capture variation in chlorine dioxide substitution and the use of OD and/or ED among pulp lines at a mill, we define the regulated technology by the share of total pulp production in period t subject to ECF (m=1), OD (m=2), and ED (m=3).[14] Specifically, for each line i=1,…,I, within a mill, we multiply the percent of abatement technology used on line i, a_{im}, by the pulp production on line i, p_i, which yields the amount of pulp production on line i subject to abatement technology m. For each mill, we sum this value over all its lines of production and

[13] The occasional occurrence of infeasible LP problems in the decomposition with variable returns to scale led us to specify non-increasing returns to scale.

[14] The pollution abatement intensity measures are patterned after the measure of regulatory intensity developed by Gollop and Roberts (1983).

divide by its total pulp production, which yields the weighted average of total mill production subject to abatement technology m. Hence, for mill k', the abatement intensity (i.e., the share of pulp production subject to ECF, OD, or ED) in period t is written as:

$$\frac{\sum_{i=1}^{I}(a_{im}^{t}\times p_{i}^{t})}{\sum_{i=1}^{I} p_{i}^{t}} \qquad m=1,2,3 \qquad (2)$$

Using equation (2) to define the share of pulp production subject to each abatement technology, the regulated production function (FR) for mill k' in period t is specified as:

$$FR(x^{t},a^{t},t)=\max \sum_{k=1}^{K} z_{k}^{t}\, y_{k}^{t} \qquad (3)$$

s.t. $\sum_{k=1}^{K} z_{k}^{t}\, x_{kn}^{t} \le x_{k'n}^{t}, \qquad n=1,\ldots..,N$

$$\frac{\sum_{k=1}^{K}\sum_{i=1}^{I} z_{k}^{t}(a_{kim}^{t} \times p_{ki}^{t})}{\sum_{k=1}^{K}\sum_{i=1}^{I} z_{k}^{t}\, p_{ki}^{t}} \ge a_{k'm}^{t} \qquad m = 1,2,3$$

$$\sum_{k=1}^{K} z_{k}^{t} \le 1$$

$$z_{k}^{t} > 0 \qquad k = 1, \ldots\ldots, K$$

or rewriting

$$FR(x^{t}, a^{t}, t) = \max \sum_{k=1}^{K} z_{k}^{t}\, y_{k}^{t} \qquad (3')$$

s. t. $\sum_{k=1}^{K} z_{k}^{t}\, x_{kn}^{t} \le x_{k'n}^{t}, \qquad n = 1, \ldots.., N$

$$\sum_{k=1}^{K}\sum_{i=1}^{I} z_{k}^{t}(a_{kim}^{t} \times p_{ki}^{t}) \ge a_{k'm}^{t}\left(\sum_{k=1}^{K}\sum_{i=1}^{I} z_{k}^{t}\, p_{ki}^{t}\right) \qquad m = 1,2,3$$

$$\sum_{k=1}^{K} z_k^t \leq 1$$

$$z_k^t > 0 \qquad\qquad k = 1, \ldots\ldots, K$$

Like the unregulated technology, the regulated production technology for mill k' is also constructed from all observations (K) that are available in period t via sequential frontiers. However, in addition to the input constraint(s) and non-increasing returns to scale constraint, the regulated production function is also subject to constraint(s) on abatement intensity where the abatement intensity for mill k' is equal or less than that of the best-practice plant (i.e., the left-hand side of the second constraint).[15] These abatement intensity constraints reflect degrees of abatement intensity for the three abatement technologies used by the regulated mills.

Having defined the unregulated and regulated production functions, PAC is the ratio of the maximum good output production of the unregulated (FUR) and regulated (FR) technologies for plant k' in periods t and t+1.[16] That is, in period t pollution abatement costs (PAC^t) is defined as follows:

$$PAC^t = FUR(x^t, t)/ FR(x^t, a^t, t) \qquad (4)$$

and

[15] In equation (3), the numerator of $\frac{\sum_{k=1}^{K}\sum_{i=1}^{I} z_k^t(a_{kim}^t \times p_{ki}^t)}{\sum_{k=1}^{K}\sum_{i=1}^{I} z_k^t p_{ki}^t}$ calculates the amount of pulp production of the best-practice frontier for mill k' that is subject to abatement process m, while the denominator calculates the total pulp produced by the best-practice frontier for mill k'.

[16] Because we define PAC as the ratio of a mill's good output production when the bad output is unregulated (i.e., the mill is producing on its unregulated frontier) to its good output production when the bad output is regulated (i.e., the mill is producing on its regulated frontier), the foregone good output production associated with technical inefficiency is excluded.

$$PAC^{t+1} = FUR(x^{t+1}, t+1)/FR(x^{t+1}, a^{t+1}, t+1) \quad (4')$$

is PAC^{t+1} in period t+1.

In Figure 1, $FR(x^t, a^t, t)$, the regulated frontier, represents the maximum good output produced using input vector x^t, abatement intensity vector a^t, and technology in period t, while $FR(x^{t+1}, a^{t+1}, t+1)$ represents the maximum good output produced using input vector x^{t+1}, abatement intensity vector a^{t+1}, and regulated technology in period t+1. The unregulated $FUR(x^t, t)$ and $FUR(x^{t+1}, t+1)$ frontiers represent the maximum good output produced by the vector of inputs and unregulated technology in periods t and t+1, respectively. Using Figure 1, the PAC for period t (equation 4) is (aB/aA) and (bD/bC) for period t +1 (equation 4').

To examine how pollution abatement cost changes over time, we calculate the ratio of good output production between the regulated and unregulated frontiers in period t and t+1. We define the change in pollution abatement costs between period t and t+1 as:

$$\Delta PAC_t^{t+1} = \left[\frac{FUR(x^{t+1}, t+1)/FR(x^{t+1}, a^{t+1}, t+1)}{FUR(x^t, t)/FR(x^t, a^t, t)}\right] \quad (5)$$

Using Figure 1, $\Delta PAC_t^{t+1} = \frac{(bD/bC)}{(aB/aA)}$. The ΔPAC_t^{t+1} is unity if there is no change in PAC, greater than unity when there is an increase in PAC, and less than unity when there is a decrease in PAC.

Using shifts in both the regulated and unregulated frontiers, we decompose changes in PAC into three components - technological change (TC), changes in inputs (IC), and changes in pollution abatement intensity (AI). Since using period t or period t+1 as the reference technologies typically yield different values for the relative importance of the factors associated

with changes in PAC, we use the arithmetic means of period t and t+1 as reference technologies when specifying the mixed-period LP problems: [17]

$$\Delta PAC_t^{t+1} = \left\{\left[\left(\frac{[FUR(x^{t+1},t+1)/FUR(x^{t+1},t)]}{[FR(x^{t+1},a^{t+1},t+1)/FR(x^{t+1},a^{t+1},t)]}\right)+\left(\frac{[FUR(x^{t},t+1)/FUR(x^{t},t]}{[FR(x^{t},a^{t},t+1)/FR(x^{t},a^{t},t)]}\right)\right]\times 0.5\right\}$$
$$\times \left\{\left[\left(\frac{[FUR(x^{t+1},t)/FUR(x^{t},t)]}{[FR(x^{t+1},a^{t+1},t)/FR(x^{t},a^{t+1},t)]}\right)+\left(\frac{[FUR(x^{t+1},t+1)/FUR(x^{t},t+1]}{[FR(x^{t+1},a^{t},t+1)/FR(x^{t},a^{t},t+1)]}\right)\right]\times 0.5\right\}$$
$$\times \left\{\left[\left(\frac{[FUR(x^{t},t)/FUR(x^{t},t)]}{[FR(x^{t},a^{t+1},t)/FR(x^{t},a^{t},t)]}\right)+\left(\frac{[FUR(x^{t+1},t+1)/FUR(x^{t+1},t+1]}{[FR(x^{t+1},a^{t+1},t+1)/FR(x^{t+1},a^{t},t+1)]}\right)\right]\times 0.5\right\}$$
$$= (TC_{UR}/TC_R)\times(IC_{UR}/IC_R)\times(AI_{UR}/AI_R) \quad (6)$$

where (TC_{UR}/TC_R) represents the change in PAC associated with TC, (IC_{UR}/IC_R) is the change in PAC associated with IC and (AI_{UR}/AI_R) is the change in PAC associated with AI.

More precisely, (TC_{UR}/TC_R), measures the change in good output production associated with technological change of the unregulated technology relative to the change in good output production associated with technological change of the regulated technology. (IC_{UR}/IC_R), measures the change in good output production of the unregulated frontier relative to the regulated frontiers associated with changes in the level of inputs. Finally, because AI does not affect the unregulated frontier, FUR(•) cancel out in the numerator. The AI component then, reflects movements along the regulated frontier associated with changes in the share of inputs assigned to good output production and pollution abatement. To illustrate, as shown in Figure 1, equation (6) can be written as

$$\Delta PAC_t^{t+1} = \left\{\left[\frac{(bD/bB')}{(bC/bG)}+\frac{((aD'/aB)}{(aH/aA)}\right]\times 0.5\right\}$$
$$\times \left\{\left[\frac{(bB'/aB)}{(bG/aF)}+\frac{(bD/aD')}{(bI/aH)}\right]\times 0.5\right\}$$

[17] The expressions for the mean of the ratios for TC, IC, and AI when using period t and period t+1 as reference technologies are not calculated using FR(▪) and FUR(▪) values for individual mills (i.e., observations) and then aggregating those ratios. Instead, the FR(▪) and FUR(▪) values used in our calculations are summations of values for all observations from periods t and t+1 in the dataset.

$$\times \left\{\left[\frac{(aB/aB)}{(aF/aA)} + \frac{(bD/bD)}{(bC/bI)}\right] \times 0.5\right\} \qquad (6')$$

For TC, IC, and AI, a value exceeding unity indicates the component is associated with increasing PAC between period t and period t+1. A value less than unity signifies the component is associated with declining PAC. Finally, a value of unity indicates the component is associated with no change in PAC.

IV. Data

The EPA released a list identifying the 96 pulp and paper mills that were expected to meet the MACT air and BAT water standards of the CR rule.[18] In order to model a homogeneous production technology, we focus on the kraft (i.e., sulfate) and sulfite pulp and paper mills on that list. In this section, we describe the production and abatement intensity data for these mills.

IV.1 Production Data

Information on mill-level inputs and outputs comes from restricted-use establishment-level data accessible at Federal Statistical Research Data Centers (RDCs).[19] Specifically, we use production information collected by the quinquennial *Census of Manufactures* (CM) for 1967–2007 (U.S. Census Bureau, various years), the *Annual Survey of Manufactures* (ASM) in non-census years for 1973–2014 (U.S. Census Bureau, various years), which are linked together

[18] The EPA also released a list identifying the 155 pulp and paper mills with sufficiently large air toxic releases to qualify for the MACT standards of the CR rule. The 96 mills subject to the BAT requirements were a subset of the 155 mills subject to the MACT requirements. Because the process changes required by the BAT requirements were substantial, we do not include the 59 mills subject only to the MACT standards in our core analysis of the regulatory cost. See Appendix A, U.S. EPA (1998b) for list.

[19] See U.S. Census Bureau (2018).

using the Longitudinal Business Database (LBD), as described in Jarmin and Miranda (2002). We also use data from the *Manufacturing Energy Consumption Survey* (MECS) that is available triennially for 1985–1994 and quadrennially for 1998–2010 (U.S. Department of Energy, various years). [20]

We measure the good output (y) using the total value of shipments (TVS) in dollars from CM/ASM, adjusted for inventories and work in progress. This output measure excludes the value of on-site co-generated electricity sold, which is computed as the product of the quantity of electricity sold and the implied electricity price for each mill/year observation (i.e., expenditures on purchased electricity divided by the quantity of purchased electricity). By excluding revenue generated by the sale of electricity from the revenue measure of output, the good output of the mill consists solely of the revenue generated from the sale of pulp and paper.

We use the following five inputs: labor, materials, capital, electricity and fuels. Labor (L) is measured by the total production worker hours from the CM/ASM. Materials (M) is represented by the dollar expenditures on materials, resale, and contract work from CM/ASM. Capital (K) is represented by mill-specific estimates of real capital stock (equipment and structures, expressed in dollar terms). We rely on an LBD-linked database that uses the perpetual inventory method to calculate establishment-specific real capital stock from annual

[20] In addition, the 59 MACT mills may not be analyzed separately because the number of mills with complete LBD data does not meet Census disclosure requirements.

data on new capital expenditures from the CM/ASM, the nominal capital gross book value from CM, and other data (Foster et al., 2014).[21,22]

Electricity (E) is measured as the quantity of purchased electricity in British thermal units (BTU) from the CM/ASM. Fuel (F) is measured as consumption of fuels produced off-site in BTU, which is estimated using data from MECS. While fuel transfers are not a significant share of fuel for our plants, our analysis includes measures of fuel with and without transfers.[23] Because MECS data are not available annually, we interpolate fuel consumption for the non-MECS years using annual fuel expenditures from CM/ASM.[24] This approach closely follows the value-based interpolation used by the U.S. Department of Energy (1992). Finally, our measures of labor, materials, capital, and energy consumption may include resources used for electric power co-generated by the mill, which may introduce measurement errors into the input data.

IV.2 Pollution Abatement Intensity Data

Information on mill name, location, annual bleaching sequence, total annual pulp production, and annual data on the percent of chlorine dioxide substitution by pulp line for every pulp mill subject to the ELGs of the CR from 1997 to 2007 comes from Beca AMEC (2013a). Because most mills phased in chlorine dioxide (ClO_2) over a period of months (see U.S. EPA, 2000), chlorine dioxide substitution for a pulp line may range from zero to 100% in any

[21] We thank John Haltiwanger for providing access to this database.
[22] All variables expressed in dollar terms (i.e., output, materials, and capital stock) are converted into real terms—2009 dollars—by dividing those variables with an appropriate industry-specific price index (Bartelsman and Gray, 1996).
[23] MECS defines transfers as quantities 1) delivered from any other establishment in your company, 2) transferred from other establishments of your company for which payment was not made, 3) purchased centrally within your company, separate from this establishment, or 4) for which payment was made in-kind.
[24] Because some of our mills were not present in the 2010 MECS, we estimated these values by extrapolating their 2007 fuel consumption (in BTUs).

given year. The Beca AMEC data (2013b) is also used to identify the year a mill started using OD and/or ED technologies on its pulp lines.[25] However, because the standards for the CR are based on ECF, many lines at the 96 mills subject to the BAT provisions do not use OD or ED.[26]

Unlike the measure of ClO_2 abatement intensity for a pulp line, $a_{im}(m=1)$, that can assume a value between zero and one, abatement intensity for OD and/or ED assumes a value of either zero or one. That is, the abatement intensity of a pulp line, a_{im} (m=2,3), is equal to one when a pulp line employs OD and/or ED, respectively, on the line, otherwise its intensity is set to zero. As shown in equation 2, the measures of abatement intensity for ECF, OD and ED at the mill level are calculated by summing pulp production across lines subject to each abatement technology, respectively, and dividing that value by total pulp production at each mill.[27]

IV.3 Linking Data Sources

Using mill name and location, we match the regulatory intensity measures from the Beca AMEC data to the list of 96 mills EPA expected to comply with the water technology standards of the CR. We then use a probabilistic matching method based on Felligi and Sunter (1969) to link this data to the LBD, which allows us to link all relevant production data from the CM, the ASM, the MECS, and Haltiwanger capital stock estimates (Foster et al., 2014).[28] While a link to the LBD was established for approximately 70 CR pulp and paper mills, only 50 mills had

[25] Pulp lines may use only ECF or a combination of ECF and/or ED/OD.
[26] For a more detailed description of the Beca AMEC data, see Morgan et al. (2014).
[27] Since abatement intensity is based on pulping operations, our results may be biased because of heterogeneity among plants in terms of the share of production associated with pulping operations.
[28] We use a probabilistic matching method to account for differences in mill names and addresses between our different data sources.

complete CM/ASM production data that were consistently available between 1997 and 2007.[29] These 50 mills constitute our balanced panel dataset.

IV.4 Treatment of Non-Pulping Mills

Among our 50 CR mills, several switched from pulping to non-pulping operations during 1997-2007. Because disclosure rules established by the U.S. Census Bureau prohibit removing the non-pulping mills from the sample, we treat them as unregulated mills (i.e., we set a_{kim}=0) for year(s) that mill k has no pulping operations. Even though these mills are regulated by the CR, since they are no longer pulping, they are in essence, unregulated. By setting a_{kim}=0, we maintain a balanced panel for both the regulated and unregulated technology.[30]

V. Linear Programming Problems and Results

We construct four models using different combinations of input and abatement intensity vectors.[31] The first model (M1) is defined using an input vector x^t, in which energy use in BTU is represented by the sum of purchased electricity and fuels produced off-site without fuel transfers, and an abatement intensity vector a^t, where all three abatement intensity measures are represented. Model 2 (M2) differs from M1 in that we use the sum of purchased electricity and fuels produced off-site which includes fuel transfers. Since CR limits are based on

[29] We focused on this period for two reasons. First, compliance intensity data for the regulated mills are available starting from 1997. Second, there were considerably fewer mills with production data continuously available for 1997-2008 and 1997-2009, compared to 1997-2007.

[30] Because we are not allowed to drop the mills that stopped pulping from our sample, including them may affect the results for the pulping mills. The unregulated production frontier, which is constructed from all available observations, may include a non-pulping mill. In addition, if all a_{kim} for pulping mill i are less than unity, then its regulated production frontier might include an observation with a_{kim} = 0, which can either be an unregulated pulping mill or a non-pulping mill. For more details on this issue, please contact the corresponding author for Appendix.

[31] The estimation process was implemented within the R language and environment (R Development Core Team, 2016) using the open-source linear programming package Rsymphony (Harter et al., 2016).

chlorine dioxide substitution, we examine two additional models (M3 and M4) where the abatement intensity vector, a^t, contains only the share of pulp production subject to chlorine dioxide bleaching. The model M3 uses the same input vector as M1, while M4 uses the input vector of M2.

For each model, we solve for the maximum good output for the unregulated frontier in year t and year t+1, i.e., $FUR(x^t, t)$ and $FUR(x^{t+1}, t+1)$, as specified by LP problem (1). We also solve for the maximum good output for the regulated frontier in year t and year t+1, i.e., $FR(x^t, a^t, t)$ and $FR(x^{t+1}, a^{t+1}, t+1)$, as specified by LP problem (3) for each model. The decomposition strategy (6) requires two additional unregulated frontiers and four additional regulated frontiers. Both the unregulated and regulated frontiers for each period are constructed using sequential frontiers, which are comprised of observations from 1997 up to year t or year t+1.[32] As a result, there are ten two-year pairs from 1997-1998 to 2006-2007 associated with each mill based on equations (4) and (5).

Due to data confidentially concerns, mill-level results are not released by the Census Bureau; however, summary statistics of the data, and aggregate results allow us to calculate indexes of change for pollution abatement costs and the factors associated with changes in PAC - technological change, input change, and abatement intensity - for each two-year pair from 1997-1998 to 2006-2007 for the fifty mills can be released. While we are unable to present the results for ΔPAC and its components for individual mills, the decomposition procedure allows to explore the relative importance of factors associated with changes in pollution abatement costs for the 50 mills.

[32] Sequential frontiers do not allow the possibility of technical regress (i.e., inward shifting production frontiers).

Table 1 presents summary statistics of the data for 1997, 2002, and 2007. For the 50 mills in our sample, output increased. This increase in output is associated with fewer workers and reduced capital stock. These decreases reflect trends observed in the pulp and paper industry over the same period. Using annual industry-level data from the NBER-CES Manufacturing Industry database (see http://data.nber.org/nberces/), the number of workers decreased by 27% while capital stock decreased by 33% from 1997 to 2007. However, substantial differences are observed between pulp mills (SIC 2611) and paper mills (SIC 2621). For pulp mills, employment fell by less than 10%, but capital stock declined by 32% between 1997 and 2007, whereas paper mills experienced a decline in employment of 42% while capital stock decreased by 12% over the same period.

Table 2 presents summary statistics of each measure of regulatory intensity. Regulatory intensity for chlorine dioxide increases each year until it reaches a peak in 2004, an increase of 44% from 1997, before slightly decreasing, and then remaining constant through 2007. This increase in intensity reflects the trend in ClO_2 substitution adopted by mills over the period. As Morgan et al (2014) point out, only 28% of mills were using 100% ClO_2 substitution in 1998, 67% switched by 2000, and at least 95% switched to 100% ClO_2 substitution by 2005. While there are some year-to-year fluctuations, regulatory intensity for both ED and OD slightly increased over the sample period. The small increase in pulp production subject to ED and OD, roughly 5% and 16%, respectively, over the 1997-2007 is not surprising given only nine mills installed OD during 1998-2008 while four mills installed ED over the same period (Morgan et al, 2014).

The ΔPAC and its components for each model are presented in Tables 3, 4, and 5.[33] Table 3 presents the results for model M1. The ΔPAC ranges from a minimum of 0.9725 for 2000-2001 to a maximum of 1.0527 for 2002-2003, with an average increase of 0.26% over the 1997-2007 period. Across all two-year periods in our sample, the increase in ΔPAC in 2002-2003 is associated with the largest increases in PAC due to TC and IC, 3.55% and 1.96%, respectively, and the largest decrease in PAC is associated with AI of 0.28%.

For models M3 and M4, whose results are presented in Tables 4 and 5, overall changes in PAC, TC, IC, and AI generally follow similar patterns and magnitudes over the entire period. The maximum ΔPAC for both models occur during the 1999-2000 period, while the minimum ΔPAC for both models occur in the next period, 2000-2001. Unlike model M1, where average ΔPAC increased over the 1997-2007 period, average ΔPAC decreased by 0.33% and 0.47% over the entire period for models M3 and M4, respectively.

For all models, TC is the only component that is associated with reducing average PAC over the entire 1997-2007 period. More specifically, for model M1, where the abatement intensity vector includes all three abatement measures, TC is associated with a 1.59% decrease in PAC. For models M3 and M4, where the abatement intensity vector only includes ECF, TC is associated with a 0.93% and 1.06% decrease in PAC for models M3 and M4, respectively. In general, for models M3 and M4, the fluctuations over time with PAC are associated with similar fluctuations in TC. That is, in years when PAC increased, TC is associated with increased PAC.

[33] Unfortunately, we did not catch a mistake in our code and disclosed negative outputs for model M2, preventing us from evaluating PAC and its component. Census Bureau policy prevents us from accessing our data at this time to correct the code and re-run the model.

The relationship between PAC and TC reflects relative shifts in the unregulated and regulated frontiers. The decline in PAC associated with TC may reflect the reallocation of R&D resources from the unregulated technology to regulated technology (e.g., ECF bleaching process to reduce production of dioxin). Because the CR required mills to substitute ECF for chlorine bleaching, mills were able to adopt the new technology while simultaneously expanding production of pulp and paper. The reallocation of R&D resources yields slower TC for the unregulated technology and faster TC for the regulated technology. This results in the regulated frontier shifting outward more rapidly than the unregulated frontier which reduces the foregone output associated with reducing dioxin in period t+1 relative to period t, leading to values of ΔPAC less than one.

Unlike TC, both IC and AI are associated with increases in PAC for all models. The increase in PAC is the highest for M1 where IC and AI are associated with an average annual increase in PAC of 1.01% and 0.90%, respectively. Except for 2004-2005, when AI is less than unity for M3 and M4, and thus associated with decreases in PAC, AI is associated with increases in PAC. While the year-to-year fluctuations in IC are similar between M3 and M4, the relationship between PAC and IC is not as clear. In both models, IC and ΔPAC move in opposite directions between 2000-2001 and 2003-2004. That is, an increase in IC is associated with a decrease in PAC and vice versa. Overall, for models M3 and M4, IC is associated with an average annual increase in PAC of 0.14% and 0.10%, respectively, while AI is associated with an average annual increase in PAC of 0.47% and 0.50%, respectively.

Given that employment and capital stock were decreasing in the pulp and paper industry over our sample period, we were surprised to find inputs are associated with increases

in PAC. This result made us examine more closely, industry trends in our other two inputs – material and energy. For the industry, the cost of materials remained stable for paper mills from 1997 to 2002, only increasing roughly 2% over the period. However, material costs increased nearly 40% for pulp mills. On the other hand, both pulp and paper mills experienced large increases in energy costs over the time period, roughly 50% and 29%, respectively.[34] The large increase in energy costs for pulp mills may reflect increases in ClO_2 substitution. Because the production of ClO_2 is unstable and explosive, it is generally made on site and the electricity requirements to make ClO_2 are sizeable.[35]

We are interested in the behavior of PAC over time. Recall, PAC is the ratio of the maximum good output production of the unregulated and regulated technologies in period t as given by equation 4.[36] Table 6 presents PAC in period t for each model. For model M1, PAC starts at 9.68% in 1997, decreases until 1999, increases in 2000 before decreasing to 5.44% in 2002. After 2002, PAC increases again. On average, PAC for model M1 was roughly 9.4%, which seems high relative to historical abatement costs in the pulp and paper industry. The results are strikingly different for models M3 and M4. PAC starts much lower for M3 and M4, at 3.49% and 4.97%, respectively. And, except for 2004, when PAC increases slightly, pollution abatement costs decrease over the time period in both models. On average from 1997 to 2006, PAC is 1.69% and 1.96% for models M3 and M4, respectively which is more in line with historical abatement costs in the pulp and paper industry.

[34] See http://data.nber.org/nberces/
[35] See http://www.paperenvironment.org/PDF/chcompounds/energy/CC_E_Electricity.pdf.
[36] Except for 1997, the values for PAC(t+1) given by equation 4' are the same values as PAC(t), just shifted one year.

Intuitively, smaller estimates of PAC for M3 and M4 are expected. Recall, unlike model M1 which has three abatement intensity constraints for each abatement technology, models M3 and M4 only have one abatement intensity constraint for ClO_2 substitution. Additional constraints limit the good output a mill produces using the regulated technology, and because the output produced by the unregulated technology remains the same, lower output for the regulated technology when subject to additional constraints means overall, PAC will be higher, as exhibited by PAC for M1.

To put our pollution abatement costs in perspective with other estimates of the cost of implementing the Cluster Rule, we examined some other estimates of pollution abatement costs. Table 7 shows industry estimates of pollution abatement capital expenditures from 1997-2002 from the National Council for Air and Stream Improvement's (NCASI) survey of pulp and paper firms.[37,38] According to results published by NCASI, the percentage of total capital expenditures for environmental protection spent on water pollution abatement ranges from 32% to 56% over the 1998 -2002 period, which amounts to approximately $1.5 billion dollars. NCASI also reports the percentage of total capital expenditures spent on environmental protection each year (see Table 7). Multiplying that percentage by the percent spent on water pollution yields an average of roughly 6% of total capital expenditures are spent on water pollution abatement.

[37] NCASI is the main trade association of the forest products industry and has been conducting a pollution abatement capital cost survey since 1970. NCASI receives survey responses from a subset of companies and extrapolates to the entire U.S. pulp and paper industry assuming the companies that did not report expenditure data, spend at a similar rate. NCASI stopped conducting this survey in 2002.

[38] See Morgan, Pasurka, and Shadbegian (2014) for more information on the CR and NCASI Survey.

Looking at historical pollution abatement operating costs (PAOC) and capital expenditures (PACI) for water from the Pollution Abatement Costs and Expenditures Survey (PACE) conducted by the U.S. Census Bureau, the percent of PAOC for water compared to total value of shipments and PACI for water compared to all new capital expenditures is small.[39] As shown in Table 8, for various years from 1992 to 2005, the percent of water PAOC to value of shipments ranges from 0.19% to 0.62% while the percent of water PACI to new capital expenditures ranges from 2.7% to 4.7%. While water pollution abatement costs are a small percentage of other costs for pulp and paper mills, those costs are a larger percent of total pollution abatement costs. The percent of water PACI compared to total PACI ranges from 21% to almost 40%.

The fluctuations over time and the magnitude of pollution abatement costs from other sources are not unlike what we find, especially for models M3 and M4. The PAC captured by our models are the opportunity costs of pollution abatement activities, which is a more inclusive measure of the cost of pollution abatement than the accounting costs captured by the NCASI and PACE surveys. More specifically, opportunity costs measure the forgone opportunity of using inputs for pollution abatement as opposed to producing the good output, thus we may also capture some additional costs of pollution abatement activities (e.g. changes in production processes) that are not captured by these surveys. Moreover, as is often the case with DEA models, the cost estimates from our models may exceed those found from industry and government surveys because of outliers in our data.

[39] The PACE survey was conducted annually from 1973-1994 (except 1987), and then in 1999 and 2005.

VI. Conclusions

Two approaches have been developed in the literature to calculate pollution abatement costs (PAC): the joint production model, which requires data on bad outputs and the assigned input model, which requires information on the inputs assigned to pollution abatement. The main contribution of this paper is we are the first to demonstrate how to use information on pollution abatement intensity to measure PAC when there are no data on bad output production, or quantities of inputs assigned to pollution abatement. Using the U.S. EPA's Cluster Rule as a case study, we employ a unique dataset that identifies the year and extent of adoption of different pollution abatement technologies by mills to calculate the opportunity cost of pollution abatement. This data allows us to include the degrees of pollution abatement intensity, captured by variation in the levels of adoption of extended delignification (ED), oxygen delignification (OD) and elemental chlorine free (ECF) or chlorine dioxide substitution, into our specification of the regulated technology. Specifically, we include three intensity constraints when modeling the regulated mills: 1) the share of pulp production subject to ECF or chlorine dioxide substitution, 2) the share of pulp production subject to OD, and 3) the share of pulp production subject to ED. These shares range from zero to one and change over our time period as mills increase the share of pulp production subject to these abatement technologies.

Using these constraints, we calculate the maximum good output production when the bad output is regulated and when it is unregulated, where the unregulated technology excludes the constraints on abatement intensity. The difference in good output production between the regulated and unregulated technologies is the PAC of reducing dioxins, furans, and chloroform

loadings to water. We then investigate the relative importance of changes in the quantities of inputs used, technological change, and changes in pollution abatement intensity in explaining changes in PAC.

While there were fluctuations in pollution abatement cost over the 1997-2007 period for our 50 pulp and paper mills, on average pollution abatement costs appear to decrease, especially for our two models that focus on the abatement intensity changes in pulp production subject to ECF. Most importantly, our findings suggest that technological change moderated the increase in pollution abatement costs associated with reducing releases of effluents to comply with the CR. On the other hand, input change and abatement intensity are associated with increases in PAC. These results are similar across all models.

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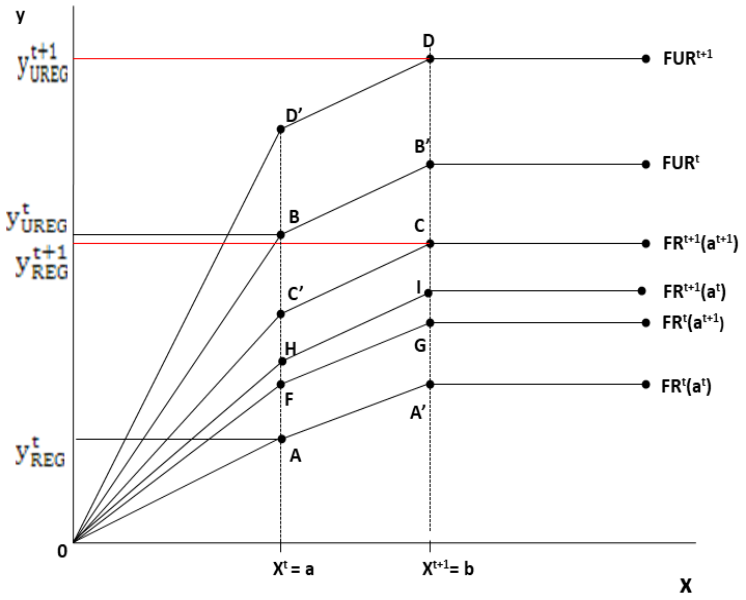

Figure 1. Unregulated and Regulated Frontiers in Periods t and t+1

Table 1. Summary Statistics for Output and Inputs

	Units	Mean	Std. Deviation
50 Pulp and Paper Mills, 1997			
Output	in millions, 2009$	435,100	196,700
Labor	Workers	1553	750
Capital	in millions, 2009$	517,300	283,900
Materials	in millions, 2009$	185,600	79,180
Qty of Energy	Btu (in billions)	6,778,000	4,070,000
Qty of Energy plus Fuel Transfers	Btu (in billions)	7,704,000	4,192,000
50 Pulp and Paper Mills, 2002			
Output	in millions, 2009$	450,400	214,500
Labor	Workers	1287	558
Capital	in millions, 2009$	421,500	219,500
Materials	in millions, 2009$	171,400	77,350
Qty of Energy	Btu (in billions)	7,547,000	5,351,000
Qty of Energy plus Fuel Transfers	Btu (in billions)	7,713,000	5,526,000
50 Pulp and Paper Mills, 2007			
Output	in millions, 2009$	426,500	231,900
Labor	Workers	1160	544
Capital	in millions, 2009$	344,700	189,200
Materials	in millions, 2009$	167,400	78,020
Qty of Energy	Btu (in billions)	6,978,000	4,557,000
Qty of Energy plus Fuel Transfers	Btu (in billions)	7,050,000	4,530,000

Table 2. Annual Means for Regulatory Intensity (standard deviation)

Year	ClO_2	ED	OD
1997	0.5161 (0.378)	0.2600 (0.443)	0.3139 (0.443)
1998	0.5835 (0.390)	0.2600 (0.443)	0.3179 (0.445)
1999	0.7005 (0.377)	0.2600 (0.443)	0.3301 (0.444)
2000	0.7631 (0.367)	0.2593 (0.442)	0.3380 (0.452)
2001	0.8081 (0.342)	0.2593 (0.442)	0.3380 (0.452)
2002	0.9050 (0.280)	0.2593 (0.442)	0.3398 (0.453)
2003	0.9050 (0.280)	0.2737 (0.445)	0.3377 (0.452)
2004	0.9176 (0.274)	0.2738 (0.445)	0.3683 (0.467)
2005	0.8800 (0.328)	0.2741 (0.446)	0.3665 (0.464)
2006	0.8800 (0.328)	0.2745 (0.446)	0.3658 (0.464)
2007	0.8800 (0.328)	0.2745 (0.446)	0.3754 (0.463)

Table 3. Decomposition of ΔPAC for two-year pairs for M1
(**BOLD = maximum** value and ***ITALICS = minimum*** value)

Two-year pairs	ΔPAC	TC	IC	AI
1997-1998	1.0000	0.9762	1.0116	1.0127
1998-1999	0.9895	***0.9492***	1.0009	**1.0428**
1999-2000	1.0200	0.9848	1.0153	1.0204
2000-2001	***0.9725***	0.9525	1.0176	1.0036
2001-2002	0.9794	0.9654	1.0075	1.0070
2002-2003	**1.0527**	**1.0355**	**1.0196**	***0.9972***
2003-2004	1.0091	0.9876	1.0163	1.0054
2004-2005	0.9851	0.9835	***1.0023***	0.9994
2005-2006	0.9867	0.9842	1.0026	0.9999
2006-2007	1.0310	1.0219	1.0075	1.0014
Arithmetic Mean	1.0026	0.9841	1.0101	1.0090

Note: subtracting unity from values in this table and multiplying by 100 yield percentage changes.

Note: For Tables 3, 4, and 5, the arithmetic means are calculated by taking unweighted means of the 10 2-year pairs for ΔPAC and its three components. However, using unweighted means to calculate ΔPAC, TC, IC, and AI for each 2-year pair results in a slight discrepancy when compared to calculating ΔPAC and its three components using the sum of maximum good output values for all mills for the 10 2-year pairs. For model M1, the largest discrepancy is for the AI component, where the mean value of AI found using values for all mills across the 10 2-year pairs is 1.0084.

Table 4. Decomposition of ΔPAC for two-year pairs for M3
(**BOLD = maximum** value and ***ITALICS = minimum*** value)

Two-year pairs	ΔPAC	TC	IC	AI
1997-1998	0.9966	0.9803	**1.0059**	1.0107
1998-1999	0.9891	0.9694	***0.9980***	**1.0226**
1999-2000	**1.0081**	0.9961	1.0034	1.0085
2000-2001	***0.9855***	***0.9792***	1.0038	1.0026
2001-2002	0.9991	0.9979	0.9986	1.0026
2002-2003	0.9970	0.9922	1.0048	1.0000
2003-2004	1.0008	**1.0000**	1.0005	1.0003
2004-2005	0.9960	0.9979	0.9984	***0.9997***
2005-2006	0.9960	0.9963	0.9996	1.0000
2006-2007	0.9985	0.9981	1.0004	1.0000
Arithmetic Mean	0.9967	0.9907	1.0014	1.0047

Note: subtracting unity from values in this table and multiplying by 100 yield percentage changes.

Table 5. Decomposition of ΔPAC for two-year pairs for M4
(**BOLD = maximum** value and ***ITALICS = minimum*** value)

Two-year pairs	ΔPAC	TC	IC	AI
1997-1998	0.9835	***0.9705***	1.0006	1.0129
1998-1999	0.9936	0.9741	***0.9979***	**1.0223**
1999-2000	**1.0068**	0.9911	**1.0052**	1.0105
2000-2001	***0.9825***	0.9763	1.0035	1.0029
2001-2002	0.9987	0.9970	0.9998	1.0020
2002-2003	0.9963	0.9919	1.0045	1.0000
2003-2004	1.0005	**0.9999**	1.0005	1.0001
2004-2005	0.9967	0.9988	0.9981	***0.9998***
2005-2006	0.9954	0.9961	0.9993	1.0000
2006-2007	0.9987	0.9981	1.0006	1.0000
Arithmetic Mean	0.9953	0.9894	1.0010	1.0050

Note: subtracting unity from values in this table and multiplying by 100 yield percentage changes.

Table 6. Pollution Abatement Costs in period t for each model
(**BOLD = maximum** value and ***ITALICS = minimum*** value)

	Model M1	Model M3	Model M4
Year	PAC^t	PAC^t	PAC^t
1997	1.0968	**1.0349**	**1.0497**
1998	1.0969	1.0314	1.0324
1999	1.0853	1.0202	1.0257
2000	1.1070	1.0284	1.0326
2001	***1.0766***	1.0135	1.0146
2002	1.0544	1.0125	1.0133
2003	1.1100	1.0095	1.0095
2004	**1.1201**	1.0103	1.0100
2005	1.1034	1.0063	1.0067
2006	1.0888	***1.0023***	***1.0021***
Arithmetic Mean	1.0939	1.0170	1.0197

Note: subtracting unity from values in this table and multiplying by 100 yield percentage changes.

Table 7. Environmental Protection Expenditures for Pulp and Paper Industry (NCASI)

Year	Total Capital Expenditures for Environmental Protection (EP) (millions of dollars)	% of Capital Expenditures Assigned to Water Protection	Total Capital Expenditures for Water EP (millions of dollars)	% of Total Capital Expenditures Assigned to EP (% water protection)
1997	560	56	314	
1998	630	50	315	13 (6.5)
1999	790	42	332	17 (7.1)
2000	1220	34	415	23 (7.8)
2001	612	32	196	12 (3.8)
2002	363	56	203	9 (5.0)

Source: National Council for Air and Stream Improvement, Inc. (various years)

Table 8. Pollution Abatement Costs and Expenditure Survey - Water

Year	Water PAOC/Value of Shipments (in percent)	Water PACI/New Capital Expenditures (in percent)	Water PACI/ Total PACI (in percent)
1992	0.62	4.7	37.2
1994	0.58	2.7	30.8
1999	0.19	3.9	39.4
2005	0.35	2.7	21.1

PAOC: Pollution Abatement Operating Costs

PACI: Pollution Abatement Capital Expenditures

Sources: U.S. Bureau of the Census, *Pollution Abatement Costs and Expenditures Survey* (various years), *Annual Survey of Manufactures* (various years)