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# Environmental investment and firm performance: A network approach

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**Abstract**

This study examines the role of investment in environmental production practices for both environmental performance and energy efficiency over time. We employ a network DEA approach that links successive production technologies through intertemporal investment decisions with a period by period estimation. This allows us to estimate energy efficiency and environmental performance separately, as well as productivity change and its associated decompositions into efficiency change and technology change. Incorporating a network model also allows us to account for both short-term environmental management practices and long-term environmental investments in each of our productivity measures. We apply this framework to a panel of detailed plant-level production data for Swedish manufacturing firms covering the years 2002 - 2008.

Keywords: Energy Efficiency, Environmental Performance, Network DEA, Malmquist Index, Investment

# 1 Introduction

Investment in new technology serves as one important way for firms to reduce their energy use and pollution emissions in response to more stringent climate policies. This form of investment, which we refer to as *environmental investment*, has the potential to drive technological change, both directly through design improvements, and indirectly through spillover effects (Clarke et al., 2006: Fischer and Newell, 2008). When this potential exists, it is likely optimal for climate policies to couple emissions taxes with environmental investment incentives (Acemoglu et al., 2012). In addition to lowering the costs of emissions reductions over time, environmental investment-driven technological change can also lead to overall increases to firm productivity and profits, commonly known as the Porter hypothesis (Porter and van der Linde, 1995)[1]. The corporate social responsibility literature finds a similar potential for increased competitiveness resulting from environmental investments (Kitzmueller and Shimshack, 2012).

In light of this, it is important to incorporate investment and environmental management decisions into technology models that measure firm performance, both in terms of conventional productivity and its components, as well as in terms of environmental performance and energy efficiency. Environmental decisions also extend over different time scales. While short term management practices largely depend on existing technologies, investment decisions are made over longer time horizons and likely contribute to technological change. To account for the intertemporal nature of investment decisions, we apply a network approach linking previous investments to current production, in order to gauge firm performance along each of the three dimensions.

We introduce firm-level investments, both environmental and production

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[1] For a review on theory and empirics related to the Porter hypothesis see Bränlund and Lundgren, 2009.

oriented, into a network data envelopment analysis (DEA) (Charnes et al., 1978) representation of the production technology to better understand how investment enters into firm productivity, energy efficiency and environmental performance. There is now considerable literature on the use of DEA to model environmental and energy technologies (Zhou et al., 2008a), much of which focuses on methods to model undesirable outputs such as pollution emissions as part of an economic production process. However, only a handful of studies adopt network or multistage modeling frameworks to characterize the production process for emissions and estimate environmental performance. Murty et al. (2012) develop a bi-production framework that decomposes the overall technology into a standard intended production technology and a residual-generation technology for inputs that directly contribute to pollution, such as the use of fossil fuels or abatement activities. Färe et al. (2013) break the technology into two stages. In the first, firms use inputs to jointly produce good and bad output, and then in the second stage, they use inputs for abatement. In their framework, some of the good and bad outputs from the first stage serve as intermediate inputs in the abatement stage, so that the problem becomes to solve for the optimal allocation of intermediate inputs, along with other exogenous inputs, between stages of production. Hampf (2014) incorporates a materials balance condition into a similar two-stage network and proposes a measure of environmental efficiency as the product of production efficiency and abatement efficiency.

This study contributes to the nascent use of network approaches to model environmental production processes by connecting the technologies for good and bad outputs through intertemporal investment decisions. We consider both energy efficiency and environmental performance, as well as overall productivity change, for a panel of Swedish firms in the pulp and paper manufacturing sector for the years 2002 - 2008. Working with detailed production data at the firm level allows us to examine environmental investments separately from production-oriented investments, and to distinguish longer term environmental investments from annual environmental management expenditures. Following Jaraite et al. (2014), we categorize investments and expenditures for Swedish manufacturing. Environmental investments include both pollution treatment, or 'end-or-pipe' techniques (e.g., air filters and scrubbers), and pollution prevention processes (e.g., fuel switching/saving equipment and re-circulation of process gases); Environmental expenditures include operating costs of existing environmental equipment, internal monitoring, personnel training, and remediation costs. Our data also include information on energy use and emissions of $CO_2$, $SO_2$, and $NO_x$.

Modeling these factors separately provides additional insight that could be of practical use, from both a policy and a managerial perspective. For instance, policy incentives for emissions reductions, such as emissions taxes or permit systems, may pose additional costs if ensuing environmental investments crowd out productive investments (Gray and Shadbegian, 1998; Kneller and Manderson, 2012). On the other hand, emissions policies may also promote energy efficiency objectives if they induce firms to invest in fuel-saving production processes or substitute other inputs for energy use (Orlov et al., 2013). Likewise, incentives to increase energy efficiency, such as fuel taxes or subsidies for R&D, can also lead to investments in emissions reductions (Löfgren et al., 2008; Hammar and Löfgren, 2010; Triguero et al., 2014).

We take an index approach to measure each aspect of performance, jointly accounting for environmental and production-oriented investments, environmental expenditures, emissions and energy use. This approach draws on the use of Malmquist quantity indexes to measure environmental performance as presented in Färe et al. (2004) and the more recent extension to panel data presented in Färe et al. (2006; 2010). This paper also adds to the growing use of productivity theory-driven methods to measure energy efficiency and environmental performance (Zhou et al., 2010; Juraite and Di Maria, 2012; Wu et al., 2012; Zhang et al., 2013). To the best of our knowledge, this study represents the first extension of this framework to include intertemporal environmental investment decisions.

We introduce our environmental investment network technology in the next section, and then explain how we use this framework to construct index measures for energy efficiency, environmental performance and productivity change in Section 3. We present our application to Swedish manufacturing firms in Section 4.

## 2 Modeling Framework

In each time period, production output and its associated pollution emissions depend on the resources that firms use and their previous investments. The production technology, $T$, characterizes this relationship, which we define for a given time period, $t$, as

$$T^t = \left\{ (x^t,\, i^{t-1},\, y^t,\, u^t) : x^t \, \text{and} \, i^{t-1} \, \text{can produce} \, y^t \, \text{and} \, u^t \right\}, \tag{1}$$

where $x^t = (x_1^t, \, ..., \, x_N^t)$ denotes the vector of current period resource inputs, $i^{t-1}$ total investment from the previous period, $y^t = (y_1^t, \, ..., \, y_M^t)$ the vector of current period production output, and $u^t = (u_1^t, \, ..., \, u_J^t)$ the vector of pollution emissions. We further decompose investment into production investment, $pi$, and environmental investment, $ei$, where $pi^t + ei^t = i^t$. Given our interest in energy efficiency, we also decompose inputs into energy inputs, $ex$, and all other inputs, $ox$, so that $x^t = ex^t + ox^t$. This is consistent with previous environmental technology formulations that also focus on energy inputs (Zhou and Ang, 2008; Zhou et al., 2010; Mandal,, 2010; Wu et al., 2012).

The network diagram in Figure 1 illustrates the technology linkage through investment for three time periods, $t-1$, $t$, and $t+1$. In each period, inputs, $ex^t$ and $ox^t$, along with investment from the previous period, $pi^{t-1}$ and $ei^{t-1}$, enter into the technology to produce current period output and emissions, $y^t$ and $u^t$, as well as investment in the next period, $pi^t$ and $ei^t$. In this

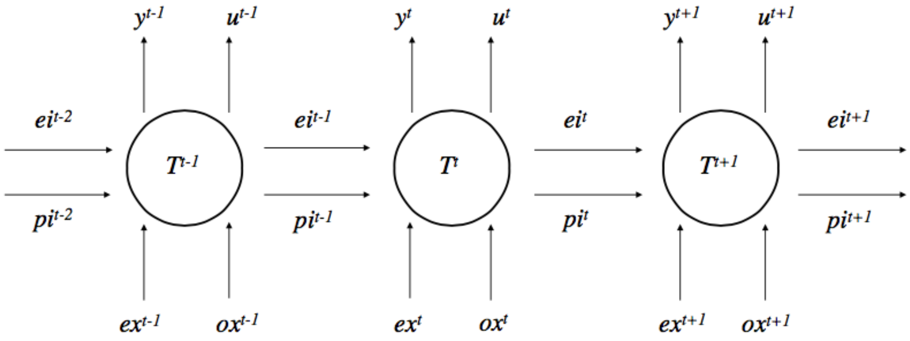

Figure 1: The Environmental Investment Technology Network

framework, future production, resource use and emissions depend on prior allocation of output between consumption (profits) and investment use. We assume the technology satisfies weak disposability of undesirable outputs, that for $(x^t,\ i^{t-1},\ y^t,\ u^t) \in T^t$, and $0 \leq \theta \leq 1$, $(x^t,\ i^{t-1},\ \theta y^t,\ \theta u^t) \in T^t$. This implies that both production and pollution outputs can scale proportionally, but that it may not be feasible to reduce pollution without also sacrificing some desirable production. We also assume that output satisfies the null joint property, that for $(x^t,\ i^{t-1},\ y^t,\ u^t) \in T^t$, if $u^t = 0$, then $y^t = 0$. It is not possible to produce good output without also producing some amount of pollution.

The corresponding DEA technology model takes the following form for each $k'^{th}$ observation $k' = 1$, ..., $K$ and time periods $t = 1, \dots, T$,

$$T^t = \{(y^t, u^t, x^t, pi^{t-1}, ei^{t-1}) : \tag{2}$$

$$
\begin{aligned}
y_m^t \leq & \sum_{k=1}^{K} z_k^t y_{km}^t, m = 1, \ldots, M, \\
u_j^t = & \sum_{k=1}^{K} z_k^t u_{kj}^t, j = 1, \ldots, J, \\
x_n^t \geq & \sum_{k=1}^{K} z_k^t x_{kn}^t, n = 1, \ldots, N, \\
pi^{t-1} \geq & \sum_{k=1}^{K} z_k^t pi_k^{t-1}, \\
ei^{t-1} \geq & \sum_{k=1}^{K} z_k^t ei_k^{t-q}, \\
z_k^t \geq & 0, \; k = 1, \ldots, K\},
\end{aligned}
$$

where the $z_k^t$ variables serve as endogenous weights to construct the technology as the convex cone of observed inputs and outputs in each time period. Here, we specify constant returns to scale for each subperiod, which in turn implies the network technology also satisfies constant returns to scale (Färe and Grosskopf, 1996). This DEA technology representation can also be modified to allow for variable or non-increasing returns to scale, while still maintaining weak disposability, by imposing additional structure to the intensity variables (Zhou et al., 2008b). The optimization of (2) provides a measure of best practice, both year by year and over time, that we can then use to evaluate performance at the firm level in terms of energy efficiency, environmental performance, and productivity change. We outline our use of the technology representation in (2) for index construction in the next section.

## 3 Network Technology Indexes

We construct our performance indexes from quantity indexes for production output, energy use and pollution emissions. Each quantity index uses Shephard (1970) subvector distance functions to compare relative performance across firms, based on the technology representation in (2). Beginning with productivity change for desirable output, we let

$$D_y^{\tau}(x^{\tau},\, i^{\tau-1},\, y^{\tau}, u^{\tau}) = inf\{\theta : (x^{\tau},\, i^{\tau-1},\, \frac{y^{\tau}}{\theta}, u^{\tau}) \in T^{\tau}\}, \tag{3}$$

where theta measures the feasible proportional increase in current production output, given current inputs, previous investment, and the production technology. We adapt our general network technology representation in (2) to estimate this output-oriented distance function as the solution to

$$\begin{aligned}(D_y^{t}(x^{t},\, i^{t-1},\, y^{t}, u^{t}))^{-1} = & \, max\, \theta \\ & \theta y_{k'm}^{t} \leq \sum_{k=1}^{K} z_k^t y_{km}^t,\; m = 1,\, ...,\, M, \\ & u_{k'j}^{t} = \sum_{k=1}^{K} z_k^t u_{kj}^t,\; j = 1,\, ...,\, J,\end{aligned} \tag{4}$$

$$
\begin{aligned}
& x^t_{k'n} \geq \sum_{k=1}^{K} z^t_k x^t_{kn},\ n = 1,\ ...,\ N, \\
& ei^{t-1}_{k'} \geq \sum_{k=1}^{K} z^t_k ei^{t-1}_k, \\
& pi^{t-1}_{k'} \geq \sum_{k=1}^{K} z^t_k pi^{t-1}_k, \\
& z^t_k \geq 0,\ k = 1,\ ...,\ K.
\end{aligned}
\tag{5}
$$

This gives rise to the widely applied Färe et al. (1994) geometric mean specification of the Malmquist productivity index, adapted to a network setting,

$$
\begin{aligned}
& M_y(\tau, \tau+1) = \\
& \left[ \left( \frac{D^{\tau}_y(x^{\tau+1},\ i^{\tau},\ y^{\tau+1}, u^{\tau+1})}{D^{\tau}_y(x^{\tau},\ i^{\tau-1},\ y^{\tau}, u^{\tau})} \right) \left( \frac{D^{\tau+1}_y(x^{\tau+1},\ i^{\tau},\ y^{\tau+1}, u^{\tau+1})}{D^{\tau+1}_y(x^{\tau},\ i^{\tau-1},\ y^{\tau}, u^{\tau})} \right) \right]^{\frac{1}{2}}.
\end{aligned}
\tag{6}
$$

We can then decompose overall productivity change into efficiency change and technology change, respectively, as

$$
EC_y(\tau, \tau+1) = \frac{D^{\tau+1}_y(x^{\tau+1},\ i^{\tau},\ y^{\tau+1}, u^{\tau+1})}{D^{\tau}_y(x^{\tau},\ i^{\tau-1},\ y^{\tau}, u^{\tau})}, \tag{7}
$$

and

$$TC_y(\tau,\tau+1) = \left[\left(\frac{D_y^{\tau}(x^{\tau+1},\, i^{\tau},\, y^{\tau+1}, u^{\tau+1})}{D_y^{\tau+1}(x^{\tau+1},\, i^{\tau},\, y^{\tau+1}, u^{\tau+1})}\right)\left(\frac{D_y^{\tau}(x^{\tau},\, i^{\tau-1},\, y^{\tau}, u^{\tau})}{D_y^{\tau+1}(x^{\tau},\, i^{\tau-1},\, y^{\tau}, u^{\tau})}\right)\right]^{\frac{1}{2}}. \quad (8)$$

To measure energy efficiency, we consider feasible contractions of energy use, given other inputs, investment and outputs using

$$D_{ex}^{\tau}(ex^{\tau},\, ox^{\tau},\, i^{\tau-1},\, y^{\tau}, u^{\tau}) = sup\{\lambda : (\frac{ex^{\tau}}{\lambda},\, ox^{\tau},\, i^{\tau-1},\, y^{\tau}, u^{\tau}) \in T^{\tau}\}, \quad (9)$$

where we focus on energy inputs separately from other production inputs. To estimate this feasible contraction of energy use, modeled here as the $N^{th}$ input, we adapt our technology to solve,

$$\begin{aligned} (D_{ex}(ex^t,\, ox^t,\, i^{t-1},\, y^t,))^{-1} = & \, min\, \lambda \qquad (10)\\ s.t. \quad & y_{k'm}^t \leq \sum_{k=1}^{K} z_k^t y_{km}^t,\ m = 1,\, ...,\, M,\\ & u_{k'j}^t = \sum_{k=1}^{K} z_k^t u_{kj}^t,\ j = 1,\, ...,\, J,\\ & x_{k'n}^t \geq \sum_{k=1}^{K} z_k^t x_{kn}^t,\ n = 1,\, ...,\, N-1,\\ & \lambda ex_{k'}^t \geq \sum_{k=1}^{K} z_k^t ex_k^t,\\ & ei_{k'}^{t-1} \geq \sum_{k=1}^{K} z_k^t ei_k^{t-1}, \end{aligned}$$

$$pi_{k'}^{t-1} \geq \sum_{k=1}^{K} z_k^t pi_k^{t-1},$$

$$z_k^t \geq 0,\, k = 1,\, ...,\, K,$$

$$(11)$$

We measure energy efficiency change, using the energy efficiency index (EEI),

$$EEI(\tau,\, \tau+1) = \frac{D_{ex}(ex^{\tau},\, ox^{\tau},\, i^{\tau-1},\, y^{\tau}, u^{\tau})}{D_{ex}(ex^{\tau+1},\, ox^{\tau+1},\, i^{\tau},\, y^{\tau+1}, u^{\tau+1})}, \tag{12}$$

where an EEI value greater than 1 indicates improvements to energy use over time. We note that the EEI here is equivalent to the efficiency change component of the dynamic energy performance index developed by Wu et al. (2012)

We incorporate pollution emissions into our network technology to measure environmental performance, by first estimating quantity indexes for both desirable and undesirable outputs. Our production quantity index for desirable outputs is written as

$$Q_y(\tau,\, \tau+1) = \frac{D_y^{\tau+1}(x^{\tau+1},\, i^{\tau},\, y^{\tau+1},\, u^{\tau+1})}{D_y^{\tau}(x^{\tau},\, i^{\tau-1},\, y^{\tau},\, u^{\tau})}. \tag{13}$$

For pollution emissions, we measure feasible contractions, given inputs, investment, and production output with

$$D_u^{\tau}(x^{\tau},\, i^{\tau-1},\, y^{\tau},\, u^{\tau}) = sup\{\delta : (x^{\tau},\, i^{\tau-1},\, y^{\tau},\, \frac{u^{\tau}}{\delta}) \in T^{\tau}\}, \tag{14}$$

which yields the corresponding pollution quantity index,

$$Q_u(\tau,\, \tau+1) = \frac{D_u^{\tau+1}(x^{\tau+1},\, i^{\tau},\, fy^{\tau+1},\, u^{\tau+1})}{D_u^{\tau}(x^{\tau},\, i^{\tau-1},\, y^{\tau},\, u^{\tau})}. \tag{15}$$

Again, employing a common reference technology, we estimate the numerator for the production quantity index as the solution to

$$(D_y^{t+1}(x^{t+1},\, i^t,\, y^{t+1},\, u^{t+1}))^{-1} = max\, \theta \tag{16}$$

$$\begin{aligned} s.t. \quad & \theta y_{k'm}^{t+1} \leq \sum_{k=1}^{K} z_k^{t+1} y_{km}^{t+1},\, m = 1,\, ...,\, M, \\ & x_{k'n}^{t+1} \geq \sum_{k=1}^{K} z_k^{t+1} x_{kn}^{t+1},\, n = 1,\, ...,\, N, \\ & u_{k'j}^{t+1} = \sum_{k=1}^{K} z_k^{t+1} u_{kj}^{t+1},\, j = 1,\, ...,\, J, \\ & ei_{k'}^{t} \geq \sum_{k=1}^{K} z_k^{t+1} ei_k^t, \\ & pi_{k'}^{t} \geq \sum_{k=1}^{K} z_k^{t+1} pi_k^t, \\ & z_k^{t+1} \geq 0,\, k = 1,\, ...,\, K, \end{aligned} \tag{17}$$

Similarly, we estimate the numerator for the pollution quantity index as the solution to

$$(D_u^{t+1}(x^{t+1},\, i^t,\, y^{t+1},\, u^{t+1}))^{-1} = min\, \delta \tag{18}$$

$$
\begin{aligned}
s.t.\quad & y_{k'm}^{t+1} \leq \sum_{k=1}^{K} z_k^{t+1} y_{km}^{t},\ m = 1,\ ...,\ M, \\
& x_{k'n}^{t+1} \geq \sum_{k=1}^{K} z_k^{t+1} x_{kn}^{t+1},\ n = 1,\ ...,\ N, \\
& \delta u_{k'j}^{t+1} = \sum_{k=1}^{K} z_k^{t+1} u_{kj}^{t+1},\ j = 1,\ ...,\ J, \\
& ei_{k'}^{t} \geq \sum_{k=1}^{K} z_k^{t+1} ei_k^{t}, \\
& pi_{k'}^{t} \geq \sum_{k=1}^{K} z_k^{t+1} pi_k^{t}, \\
& z_k^{t+1} \geq 0,\ k = 1,\ ...,\ K,
\end{aligned}
\tag{19}
$$

Following Färe et al. (2006; 2010), we then construct the environmental performance index (EPI) as the ratio of good to bad quantity indexes, as,

$$
EPI(y^{\tau},\ y^{\tau+1},\ u^{\tau},\ u^{\tau+1}) = \frac{Q_y(\tau,\ \tau+1)}{Q_u(\tau,\ \tau+1)}. \tag{20}
$$

The EPI relates change in desirable production output to change in pollution emissions, where an EPI value greater than 1 indicates a larger relative increase in goods to bads. We can use the underlying quantity indexes for goods and bads to determine the extent to which environmental performance improvements result from emissions reductions versus production increases. Restricting the focus to emissions, Zhou et al. (2010) demonstrate the use of input-oriented Malmquist indexes to decompose emissions performance into efficiency change and technology change. Other extensions of similar environmental technologies for performance index construction in this context include the use of non-radial directional distance functions (Chung et al., 1997; Zhou et al., 2012; Zhang et al., 2013; Wang et al., 2015) and the use of meta-frontier technologies (Chiu et al., 2012; Zhang et al., 2013; Wang et al., 2015).

# 4 Application to Swedish Manufacturing Firms

We apply our environmental investment network technology and associated performance index framework to an unbalanced panel of 66 firms from Sweden's Pulp and Paper manufacturing sector, for the years 2002 - 2008. Our data provide detailed production information at the plant level, including expenditures for standard production and energy inputs, as well as expenditures for environmental management practices, environmental investments and emissions of $CO_2$, $SO_2$, and $NO_X$. We summarize the production inputs by year in Table 1 and outputs in Table 2. Capital is calculated from gross investments using the perpetual inventory method (PIM) with a 0.087 depreciation rate and 1990 steady state year. Output is calculated as the ratio of total sales to a producer price index corresponding to firms in this sector. Capital and output are expressed in millions SEK, while environmental expenditures and investments are each expressed in thousands SEK. Labor is expressed in number of workers, energy in MWH, and emissions in tons. We note that because they are constructed from radial distance functions, our index values are independent of unit of measurement.

During our study period, average annual environmental expenditures range from 16,223,910 to 19,568,770 SEK, while average environmental investments range from 7,684,280 to 25,486,150 SEK. Average production values range from 179,424,800 to 206,408,600 SEK. Average $CO_2$ emissions range from 27,093 to 40,603 tons, while $SO_2$ and $NO_X$ range from 42.5 to 57.6 and 80.2 to 92.6 tons, respectively.

Even though we are not explicitly taking into account any policy measures and their effects in our estimations, there are plenty of reasons to suspect that they are playing an important role in shaping the behavior of firms (Brãnlund et al., 2014; Jaraite et al., 2014). Sweden has a long history of taxing energy and emissions. In 1990-1991 Sweden reformed its entire tax system, implementing taxes on energy, $CO_2$ and $SO_2$, as well as a fee on $NO_x$. The $CO_2$ tax gradually changed so that more weight was put on households and the industry paid only a part (about 20%) of the nominal tax rate (at present this translates to roughly 1,000 SEK/ton). Other more specific exemption rules apply to certain parts of the industry. In the period we are studying, 2002 - 2008, the major development in the policy arena is the introduction of the EU carbon permit trading system (EU ETS) in 2005. Studies show that the incentives for technological development induced by an EU price on carbon were not realized, most likely due to low permit prices (Lundgren et al., 2015). For the manufacturing industry within EU ETS,

Table 1: Production Inputs and Investments

| Year | Variable | Median | Mean | Std. Dev. | Min | Max |
|---|---|---|---|---|---|---|
| 2002 - 2008 | Labor | 478.00 | 644.00 | 620.16 | 42.00 | 3,938.00 |
| 309 Obs. | Energy | 369,113.40 | 824,521.40 | 1,156,597.00 | 1,202.45 | 6,319,466.00 |
|  | EnvExp | 9,200.00 | 18,082.05 | 23,941.54 | 80.00 | 146,660.00 |
|  | Capital | 642.20 | 1,484.56 | 1,726.57 | 9.47 | 6,979.91 |
|  | Env. Inv. | 41,950.80 | 260,288.60 | 455,961.42 | 0.00 | 2,548,965.50 |
| 2002 | Labor | 497.00 | 702.13 | 653.03 | 67.00 | 3,938.00 |
| 45 Obs. | Energy | 400,870.10 | 837,477.10 | 1,108,548.00 | 2,174.50 | 5,836,236.00 |
|  | EnvExp | 10,102.00 | 16,953.84 | 20,687.72 | 465.00 | 121,201.00 |
|  | Capital | 561.54 | 1,410.43 | 1,621.47 | 41.07 | 6,700.92 |
|  | Env. Inv. | 24,586.21 | 204,148.56 | 452,407.72 | 0.00 | 2,548,965.50 |
| 2003 | Labor | 502.50 | 670.44 | 636.19 | 57.00 | 3,823.00 |
| 46 Obs. | Energy | 374,507.40 | 791,316.70 | 1,151,796.00 | 1,347.44 | 6,157,801.00 |
|  | EnvExp | 8,864.00 | 16,223.91 | 22,674.69 | 223.00 | 127,811.00 |
|  | Capital | 568.36 | 1,378.62 | 1,659.01 | 23.46 | 6,716.47 |
|  | Env. Inv. | 33,452.17 | 245,297.37 | 496,018.80 | 0.00 | 2,344,735.50 |
| 2004 | Labor | 511.50 | 658.26 | 625.95 | 42.00 | 3,763.00 |
| 46 Obs. | Energy | 338,724.60 | 812,559.10 | 1,170,323.00 | 1,521.96 | 5,992,860.00 |
|  | EnvExp | 9,969.00 | 17,746.61 | 22,766.84 | 129.00 | 124,842.00 |
|  | Capital | 589.04 | 1,373.00 | 1,615.78 | 9.47 | 6,503.27 |
|  | Env. Inv. | 37,862.83 | 245,094.77 | 468,549.48 | 0.00 | 2,195,045.50 |
| 2005 | Labor | 505.00 | 660.37 | 640.05 | 48.00 | 3,688.00 |
| 43 Obs. | Energy | 369,113.40 | 829,330.00 | 1,193,091.00 | 1,409.16 | 6,319,466.00 |
|  | EnvExp | 8,088.00 | 17,785.14 | 24,463.82 | 80.00 | 134,173.00 |
|  | Capital | 731.05 | 1,502.66 | 1,663.16 | 10.14 | 6,370.19 |
|  | Env. Inv. | 64,810.87 | 270,931.05 | 468,940.73 | 0.00 | 2,026,164.50 |
| 2006 | Labor | 408.50 | 628.77 | 612.19 | 66.00 | 3,584.00 |
| 44 Obs. | Energy | 401,705.70 | 853,274.00 | 1,179,854.00 | 2,317.92 | 6,091,901.00 |
|  | EnvExp | 10,093.00 | 19,022.66 | 24,777.87 | 385.00 | 126,301.00 |
|  | Capital | 698.77 | 1,591.42 | 1,839.84 | 25.13 | 6,588.48 |
|  | Env. Inv. | 69,150.28 | 282,682.23 | 454,858.77 | 0.00 | 1,898,153.25 |
| 2007 | Labor | 393.00 | 583.02 | 592.06 | 50.00 | 3,595.00 |
| 43 Obs. | Energy | 361,652.00 | 817,974.10 | 1,169,423.00 | 1,273.76 | 6,058,650.00 |
|  | EnvExp | 7,200.00 | 19,568.77 | 25,469.92 | 427.00 | 123,605.00 |
|  | Capital | 557.45 | 1,564.56 | 1,882.31 | 28.01 | 6,789.30 |
|  | Env. Inv. | 61,129.45 | 262,283.97 | 420,129.53 | 0.00 | 1,774,605.88 |
| 2008 | Labor | 392.50 | 598.79 | 611.74 | 55.00 | 3,490.00 |
| 42 Obs. | Energy | 328,002.30 | 831,767.30 | 1,203,915.00 | 1,202.45 | 6,102,011.00 |
|  | EnvExp | 5,802.50 | 19,489.81 | 27,949.58 | 85.00 | 146,660.00 |
|  | Capital | 611.32 | 1,589.81 | 1,899.98 | 27.72 | 6,979.91 |
|  | Env. Inv. | 71,955.33 | 309,431.77 | 452,202.01 | 0.00 | 1,673,279.13 |

Table 2: Production Output Values and Emissions

| Year | Variable | Median | Mean | Std. Dev. | Min | Max |
|---|---|---:|---:|---:|---:|---:|
| 2002-2008 | Output | 120,679.70 | 191,158.50 | 210,878.40 | 5,333.55 | 1,228,211.00 |
| 309 Obs. | CO2 | 20,176.53 | 34,681.72 | 43,613.10 | 14.99 | 236,158.90 |
|  | SO2 | 22.50 | 50.73 | 67.87 | 0.00 | 353.19 |
|  | NOX | 32.53 | 87.87 | 115.32 | 0.02 | 515.88 |
| 2002 | Output | 123,694.00 | 179,424.80 | 190,013.90 | 9,782.56 | 1,050,955.00 |
| 45 Obs. | CO2 | 23,470.95 | 36,412.99 | 42,482.68 | 126.85 | 202,359.30 |
|  | SO2 | 32.72 | 57.64 | 71.54 | 0.04 | 345.68 |
|  | NOX | 41.80 | 92.62 | 113.80 | 0.09 | 507.35 |
| 2003 | Output | 112,257.60 | 184,992.40 | 205,664.40 | 5,616.71 | 1,137,316.00 |
| 46 Obs. | CO2 | 27,443.33 | 40,603.42 | 49,070.30 | 45.46 | 233,907.30 |
|  | SO2 | 26.96 | 55.45 | 73.19 | 0.00 | 353.19 |
|  | NOX | 42.82 | 89.76 | 119.48 | 0.04 | 515.88 |
| 2004 | Output | 118,401.00 | 194,955.40 | 219,045.80 | 5,333.55 | 1,202,286.00 |
| 46 Obs. | CO2 | 25,485.44 | 39,276.29 | 47,257.75 | 14.99 | 236,158.90 |
|  | SO2 | 39.70 | 55.61 | 71.71 | 0.00 | 296.73 |
|  | NOX | 33.43 | 91.66 | 123.30 | 0.02 | 443.50 |
| 2005 | Output | 134,929.60 | 206,408.60 | 227,636.00 | 5,335.50 | 1,228,211.00 |
| 43 Obs. | CO2 | 13,898.90 | 35,055.60 | 49,610.46 | 17.69 | 215,079.60 |
|  | SO2 | 10.58 | 49.29 | 73.46 | 0.00 | 318.59 |
|  | NOX | 17.74 | 85.51 | 120.65 | 0.02 | 511.84 |
| 2006 | Output | 124,459.20 | 205,328.90 | 225,125.50 | 14,020.95 | 1,220,450.00 |
| 44 Obs. | CO2 | 20,528.49 | 34,986.17 | 41,514.36 | 138.46 | 158,836.60 |
|  | SO2 | 19.45 | 50.37 | 65.26 | 0.00 | 267.16 |
|  | NOX | 32.31 | 88.93 | 115.99 | 0.09 | 463.66 |
| 2007 | Output | 117,487.90 | 182,584.00 | 211,165.40 | 5,877.11 | 1,145,948.00 |
| 43 Obs. | CO2 | 15,281.28 | 28,346.85 | 36,214.60 | 138.46 | 149,190.80 |
|  | SO2 | 15.20 | 42.45 | 58.74 | 0.03 | 256.94 |
|  | NOX | 20.38 | 80.20 | 108.00 | 0.09 | 461.97 |
| 2008 | Output | 118,771.50 | 184,645.70 | 208,631.40 | 5,656.28 | 1,087,075.00 |
| 42 Obs. | CO2 | 13,047.99 | 27,092.96 | 37,659.94 | 17.98 | 168,367.50 |
|  | SO2 | 19.10 | 43.14 | 61.77 | 0.00 | 275.46 |
|  | NOX | 20.88 | 85.69 | 112.10 | 0.02 | 459.47 |

the $CO_2$ tax was gradually phased-out from 2008, and completely removed from January 1, 2011. With respect to policy specifically aimed at energy use, Sweden introduced the Energy Efficiency Improvement Program (PFE) in January of 2005 as an instrument to spur energy intensive firms to energy efficiency improvements. Firms are given the opportunity to voluntarily join the program, and be exempted from the energy tax. The first period of the program was concluded in 2009, and followed by a new five-year period. The effects of this program are disputed, but the Energy Agency claims energy savings of 1.4 TWh annually (www.energymyndigheten.se). However, in a study on Swedish forest industry firms, Blomberg et al. (2012) suggest that voluntary energy efficiency programs of this kind are more likely to be successful if explicitly targeted at promoting technological development.

We first summarize the results at the industry level in Table 3, using the annual geometric means for each of our performance index measures, as well as the overall geometric means for the full study period. We include results for a non-network version of the technology model based solely on current-period investments for comparison. We refer to these as the contemporaneous results. To account for differences in firm size, we measure industry performance using weighted output shares, as in Färe et al. (2010). The network Malmquist results indicate an overall slight decrease in productivity for the study period, with a mean value of 0.995. Productivity losses for the period result from overall technology decline (0.989) versus relatively stable efficiency (1.006). Overall technological regress is due primarily to a marked decline in the 2006 - 2007 period (0.910), while this same period witnessed much greater efficiency gains (1.098). Mean values indicate modest technology gains in the 2004 - 2005 (1.046) and 2005-2006 periods (1.023), and relatively constant technology for the remaining periods. Although our results indicate little overall efficiency change, both the 2004 - 2005 and 2005 - 2006 periods exhibit efficiency losses (0.948 and 0.966, respectively), while the 2003-2004 and 2006-2007 each exhibit gains (1.025 and 1.098).

Our results indicate general improvements to energy efficiency for the study period, with an overall EEI value of 1.045. Year on year values exceed 1 in all but the 2005 - 2006 period (0.864), ranging from 1.014 for 2004 - 2005 to 1.139 for 2006 - 2007. Mean EPI values indicate little overall change in environmental performance (1.005), despite considerable variation from year to year. EPI values range from a low of 0.762 for 2004 - 2005 to a high of 1.176 for 2003 - 2004. We also find evidence of increasing improvements to environmental performance for the final 2006 - 2007 and 2007 - 2008 periods, with EPI values of 1.050 and 1.135, respectively. As with the Malmquist, we can decompose the EPI into measures of production and pollution performance to better understand the relative importance of each in the overall performance measure. For instance, the low performance in 2004 - 2005 results from simultaneous decreases in production and emissions efficiency, but we can see that in this case declines in emissions performance play more of a role. In contrast, the large improvement in the final period is due almost entirely to improvements in emissions efficiency, with a $Q_u$ value of 0.882, whereas production efficiency is relatively stable (1.001).

Comparing the network DEA results to results based on contemporaneous investment levels, we find that the contemporaneous results generally indicate higher levels of performance for the study period as a whole, although the pattern does not hold in all cases across annual index values. We might expect the contemporaneous performance results to be higher because they do not account for previous investment inputs in current output production. Indeed, the greatest differences exist for the Malmquist index results, where the contemporaneous values exceed the network results in almost every time period.

Table 3: Industry Geometric Means by Year

| | Year | Malm. | EffCh. | TechCh. | EEI | EPI | Qy | Qb |
|---|---|---|---|---|---|---|---|---|
| Network | | | | | | | | |
| | 2003-2008 | 0.995 | 1.006 | 0.989 | 1.045 | 1.001 | 1.006 | 1.004 |
| | 2003-2004 | 1.013 | 1.025 | 0.989 | 1.122 | 1.176 | 1.025 | 0.872 |
| | 2004-2005 | 0.991 | 0.948 | 1.046 | 1.014 | 0.762 | 0.943 | 1.239 |
| | 2005-2006 | 0.988 | 0.966 | 1.023 | 0.864 | 0.942 | 0.969 | 1.029 |
| | 2006-2007 | 0.998 | 1.098 | 0.910 | 1.139 | 1.050 | 1.096 | 1.043 |
| | 2007-2008 | 0.987 | 1.001 | 0.985 | 1.116 | 1.135 | 1.001 | 0.882 |
| Contemp. | | | | | | | | |
| | 2003-2008 | 1.014 | 1.008 | 1.006 | 1.047 | 1.015 | 1.009 | 0.994 |
| | 2003-2004 | 1.013 | 1.035 | 0.979 | 1.153 | 1.160 | 1.038 | 0.895 |
| | 2004-2005 | 1.018 | 0.953 | 1.069 | 1.009 | 0.885 | 0.955 | 1.079 |
| | 2005-2006 | 0.992 | 0.958 | 1.035 | 0.855 | 0.938 | 0.956 | 1.019 |
| | 2006-2007 | 1.035 | 1.103 | 0.939 | 1.219 | 1.082 | 1.103 | 1.019 |
| | 2007-2008 | 1.012 | 1.001 | 1.011 | 1.039 | 1.034 | 1.001 | 0.968 |

To allow for compounding effects of these annual fluctuations in performance, we graph the industry trends for each of our index values in Figures

2 and 3, using the cumulative geometric means. These highlight the relative gains and losses to each aspect of performance over time. In Figure 2, we see that overall declines to productivity build steadily over the study period, while efficiency and technology changes move in opposite directions. Declines to technology, particularly after 2005, outweigh corresponding efficiency gains, holding overall productivity below 1. Figure 3 illustrates the initial large decrease in environmental performance, compared to increasing energy efficiency and relatively constant productivity. Despite the large improvement in the final period, the overall trend for environmental performance stays below 1 for the remainder of the study period, while energy efficiency briefly declines and then rises after the 2005-2006 period. We also see some evidence that the trends for energy efficiency and environmental performance follow similar paths through time, suggesting a relationship between the two. This is somewhat expected, as reductions to energy use also decrease emissions from fuel sources.

To better understand the general performance at the plant level, we calculate the geometric means over time for each plant. We present these expanded plant level results in Tables 4 and 5. In Table 4, the plant level Malmquist values range from a low of 0.775 for plant 756 to a high of 1.140 for plant 49. For the former, productivity declines result from decreases to both efficiency and technology, while for the latter, productivity gains result entirely from technology improvements. Many of the plants exhibit relatively constant levels of efficiency, so that productivity change is due more to technology

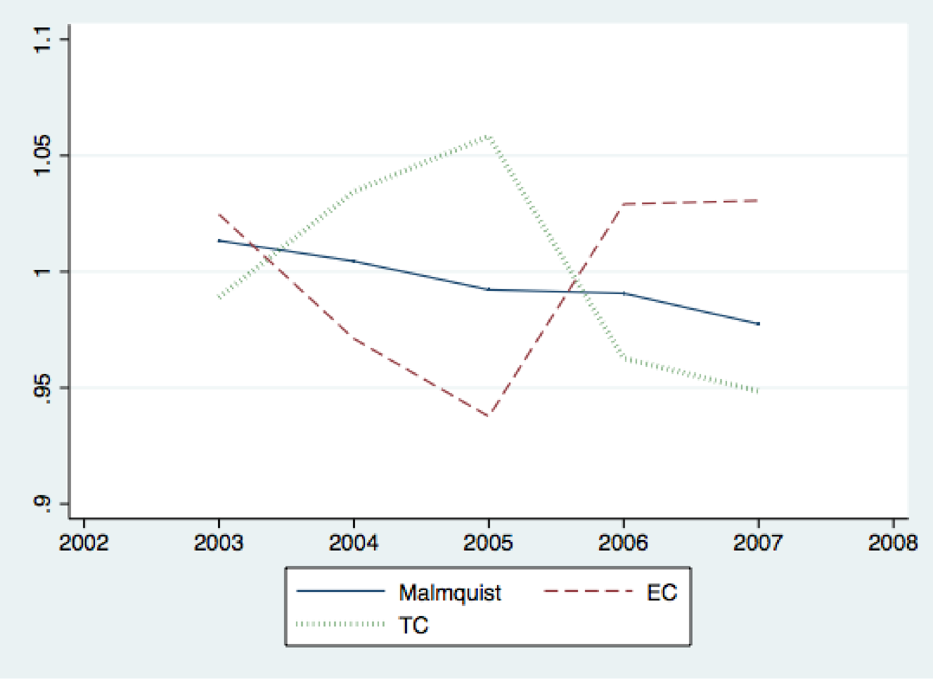

Figure 2: Industry Productivity Cumulative Trends

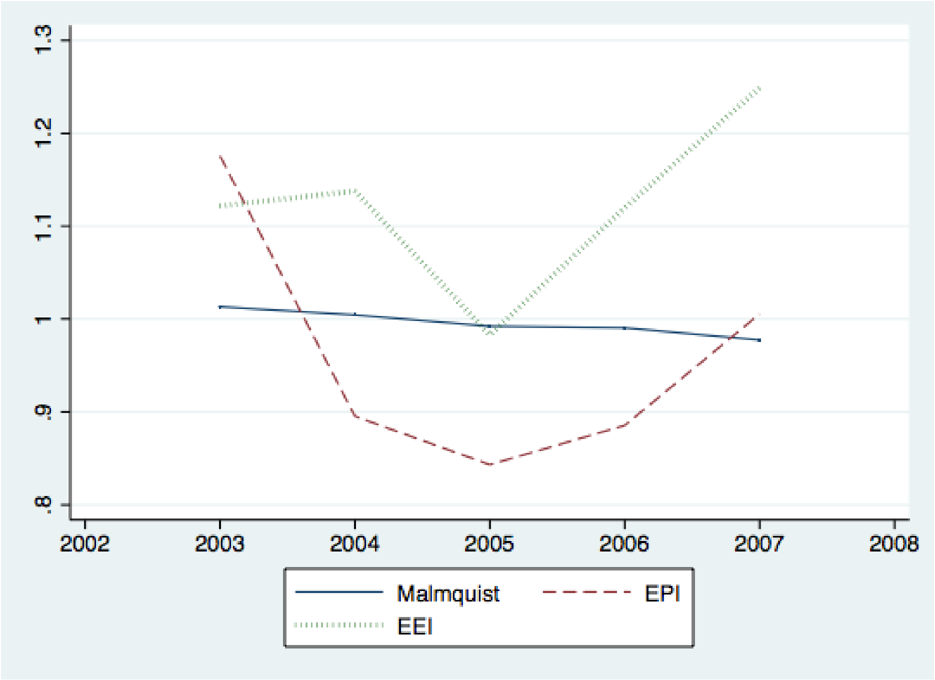

Figure 3: Industry Malmquist, EEI and EPI Cumulative Trends

change across firms.

The plant level EEI values in Table 5 range from a low of 0.748 to a high of 2.079, for firms 675 and 103, respectively. We note that firm 675 does have one of the higher Malmquist values (1.062), while firm 103 exhibits constant productivity for the study period. At the same time, plant 756 with the lowest productivity does manage to improve energy efficiency (1.036), while plant 49 with the highest productivity exhibits constant energy efficiency. As with production efficiency, energy efficiency is constant for many of the firms in our sample.

The EPI values range from a low of 0.340 for firm 537 to a high of 2.003 for firm 117. We note that the low EPI value for firm 537 appears to be due entirely to poor emissions performance (2.940), as this firm otherwise exhibits constant production efficiency over the study period. Conversely, the high EPI value for plant 117 is due to both an increase in production efficiency (1.060) and a decrease in the emissions quantity index (0.529). We note that plant 117 also has one of the highest EEI values (1.097), while maintaining relatively constant productivity (0.997). Variation in EPI values across firms results more from variation in the emissions quantity index than in production efficiency.

To better understand the relationship between these different aspects of performance, we plot the plant level values in Figures 4 - 6. We find some visual evidence of a positive relationship between productivity and environmental performance in Figure 4, suggesting that firms may not necessarily

Table 4: Plant Level Geometric Means: Productivity Change

| Plant | Malm. | EffCh. | TechCh. |
|---|---|---|---|
| 26 | 1.000 | 1.000 | 1.000 |
| 49 | 1.140 | 1.000 | 1.140 |
| 72 | 0.971 | 0.943 | 1.030 |
| 74 | 1.050 | 1.000 | 1.050 |
| 77 | 1.063 | 1.000 | 1.063 |
| 85 | 1.008 | 1.000 | 1.008 |
| 103 | 1.000 | 1.000 | 1.000 |
| 104 | 1.000 | 1.000 | 1.000 |
| 114 | 0.967 | 1.018 | 0.950 |
| 115 | 1.067 | 1.000 | 1.067 |
| 116 | 1.062 | 1.000 | 1.062 |
| 117 | 0.997 | 1.060 | 0.940 |
| 136 | 0.984 | 1.000 | 0.984 |
| 137 | 0.986 | 1.000 | 0.986 |
| 173 | 0.957 | 1.000 | 0.957 |
| 219 | 1.007 | 1.000 | 1.007 |
| 220 | 1.016 | 1.031 | 0.985 |
| 223 | 1.079 | 1.055 | 1.023 |
| 226 | 1.025 | 1.000 | 1.025 |
| 227 | 1.027 | 1.000 | 1.027 |
| 295 | 1.000 | 1.000 | 1.000 |
| 299 | 1.000 | 1.000 | 1.000 |
| 358 | 0.917 | 1.000 | 0.917 |
| 427 | 1.002 | 1.000 | 1.002 |
| 535 | 1.046 | 1.000 | 1.046 |
| 536 | 1.077 | 0.997 | 1.080 |
| 537 | 1.009 | 1.000 | 1.009 |
| 657 | 0.952 | 1.055 | 0.902 |
| 659 | 1.000 | 1.000 | 1.000 |
| 675 | 1.062 | 1.000 | 1.062 |
| 700 | 1.043 | 1.000 | 1.043 |
| 756 | 0.775 | 0.945 | 0.820 |
| 843 | 0.984 | 1.000 | 0.984 |
| 1304 | 1.000 | 1.000 | 1.000 |
| 1334 | 1.000 | 1.000 | 1.000 |
| 1442 | 1.000 | 1.000 | 1.000 |
| 1451 | 0.999 | 1.000 | 0.999 |
| 1485 | 1.000 | 1.000 | 1.000 |
| 1622 | 1.000 | 1.000 | 1.000 |
| 1623 | 1.000 | 1.000 | 1.000 |
| 2476 | 1.000 | 1.012 | 0.988 |
| 3003 | 0.996 | 1.000 | 0.996 |
| 3087 | 1.000 | 1.041 | 0.961 |
| 3129 | 1.050 | 1.000 | 1.050 |
| 3885 | 1.024 | 1.000 | 1.024 |
| 4142 | 1.000 | 1.000 | 1.000 |
| 5083 | 1.024 | 1.000 | 1.024 |
| 5270 | 0.981 | 1.000 | 0.981 |
| 5667 | 1.024 | 1.000 | 1.024 |
| 7368 | 1.008 | 1.000 | 1.008 |
| 9577 | 1.000 | 1.000 | 1.000 |
| 10708 | 1.000 | 1.000 | 1.000 |
| 11299 | 1.000 | 1.000 | 1.000 |
| 11748 | 1.000 | 1.000 | 1.000 |
| 15907 | 1.000 | 1.000 | 1.000 |

Table 5: Plant Level Geometric Means: Energy Efficiency and Environmental Performance

| Plant | EEI | EPI | Qy | Qb | Plant | EEI | EPI | Qy | Qb |
|---|---|---|---|---|---|---|---|---|---|
| 26 | 1.000 | 0.759 | 1.000 | 1.318 | 659 | 1.000 | 1.000 | 1.000 | 1.000 |
| 49 | 1.000 | 1.000 | 1.000 | 1.000 | 675 | 0.748 | 0.945 | 0.986 | 1.044 |
| 72 | 0.937 | 0.634 | 0.943 | 1.486 | 700 | 1.000 | 1.000 | 1.000 | 1.000 |
| 74 | 1.000 | 0.981 | 1.000 | 1.019 | 756 | 1.036 | 0.947 | 0.945 | 0.997 |
| 77 | 1.000 | 1.000 | 1.000 | 1.000 | 843 | 1.000 | 1.000 | 1.000 | 1.000 |
| 85 | 1.000 | 1.000 | 1.000 | 1.000 | 1304 | 1.000 | 1.000 | 1.000 | 1.000 |
| 103 | 2.079 | 1.207 | 1.000 | 0.829 | 1334 | 1.000 | 1.000 | 1.000 | 1.000 |
| 104 | 1.000 | 1.000 | 1.000 | 1.000 | 1442 | 1.000 | 0.775 | 1.000 | 1.291 |
| 114 | 0.982 | 1.024 | 1.018 | 0.994 | 1451 | 1.000 | 1.000 | 1.000 | 1.000 |
| 115 | 0.993 | 0.669 | 1.000 | 1.494 | 1485 | 1.054 | 1.076 | 1.000 | 0.929 |
| 116 | 1.000 | 0.537 | 1.000 | 1.862 | 1622 | 1.000 | 1.146 | 1.000 | 0.872 |
| 117 | 1.097 | 2.003 | 1.060 | 0.529 | 1623 | 1.000 | 1.000 | 1.000 | 1.000 |
| 136 | 1.000 | 1.000 | 1.000 | 1.000 | 2476 | 1.024 | 1.053 | 1.012 | 0.961 |
| 137 | 1.000 | 1.000 | 1.000 | 1.000 | 3003 | 1.000 | 1.000 | 1.000 | 1.000 |
| 173 | 1.000 | 1.000 | 1.000 | 1.000 | 3087 | 1.144 | 1.069 | 1.041 | 0.974 |
| 219 | 1.000 | 1.000 | 1.000 | 1.000 | 3129 | 1.000 | 1.000 | 1.000 | 1.000 |
| 220 | 1.054 | 1.109 | 1.031 | 0.930 | 3885 | 1.000 | 1.000 | 1.000 | 1.000 |
| 223 | 1.172 | 1.244 | 1.055 | 0.848 | 4142 | 1.000 | 1.000 | 1.000 | 1.000 |
| 226 | 1.000 | 1.000 | 1.000 | 1.000 | 5083 | 1.000 | 1.000 | 1.000 | 1.000 |
| 227 | 1.000 | 1.000 | 1.000 | 1.000 | 5270 | 1.000 | 1.000 | 1.000 | 1.000 |
| 295 | 1.000 | 1.000 | 1.000 | 1.000 | 5667 | 1.000 | 1.000 | 1.000 | 1.000 |
| 299 | 1.000 | 1.000 | 1.000 | 1.000 | 7368 | 1.000 | 1.000 | 1.000 | 1.000 |
| 358 | 1.000 | 0.695 | 1.000 | 1.439 | 9577 | 1.000 | 1.000 | 1.000 | 1.000 |
| 427 | 1.000 | 1.000 | 1.000 | 1.000 | 10708 | 1.000 | 1.000 | 1.000 | 1.000 |
| 535 | 0.987 | 0.637 | 1.000 | 1.570 | 11299 | 1.000 | 1.000 | 1.000 | 1.000 |
| 536 | 0.873 | 0.870 | 0.958 | 1.100 | 11748 | 1.000 | 1.000 | 1.000 | 1.000 |
| 537 | 1.000 | 0.340 | 1.000 | 2.940 | 15907 | 1.000 | 1.000 | 1.000 | 1.000 |
| 657 | 1.141 | 1.301 | 1.055 | 0.811 | | | | | |

tradeoff emissions performance for production performance. The Spearman's rank order correlation for the Malmquist and EPI is 0.318 and significant below the 0.001 level.

In Figure 5, a plot of the EEI and Malmquist values also provides little evidence of a relationship between energy efficiency and productivity. The Spearman's rank order coefficient in this case is 0.160, significant to just below the 0.030 level. That said, improvements to energy efficiency do not appear to entail significant losses to plant productivity, which is to some extent expected, given that energy inputs are included in the technology representation used to measure overall productivity.

Finally, we find some evidence of a positive relationship between energy efficiency and environmental performance in Figure 6, with a Spearman's rank order coefficient 0.390, significant below the 0.001 level. This also seems reasonable, given that improvements to energy efficiency from lower fuel use typically generate ancillary emissions reductions. This apparent relationship between the EPI and and EEI at the plant level is also consistent with the corresponding industry trends in Figure 3.

## 5 Conclusion

In this study, we develop a network technology representation to measure energy efficiency, environmental performance and productivity change, accounting for intertemporal investment decisions. We apply our approach

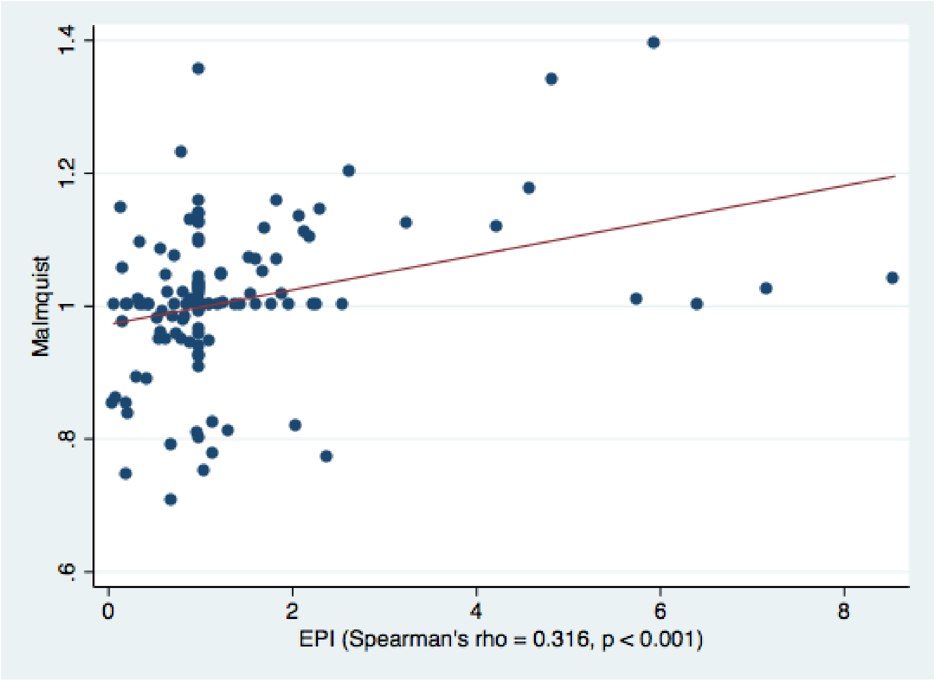

Figure 4: EPI and Malmquist Results at the Plant Level

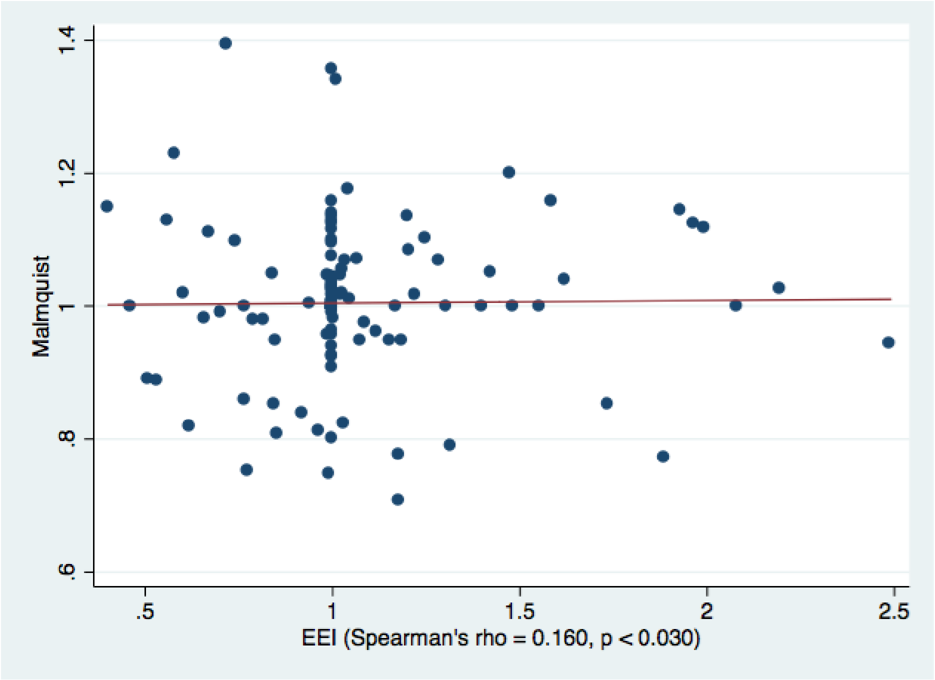

Figure 5: EEI and Malmquist Results at the Plant Level

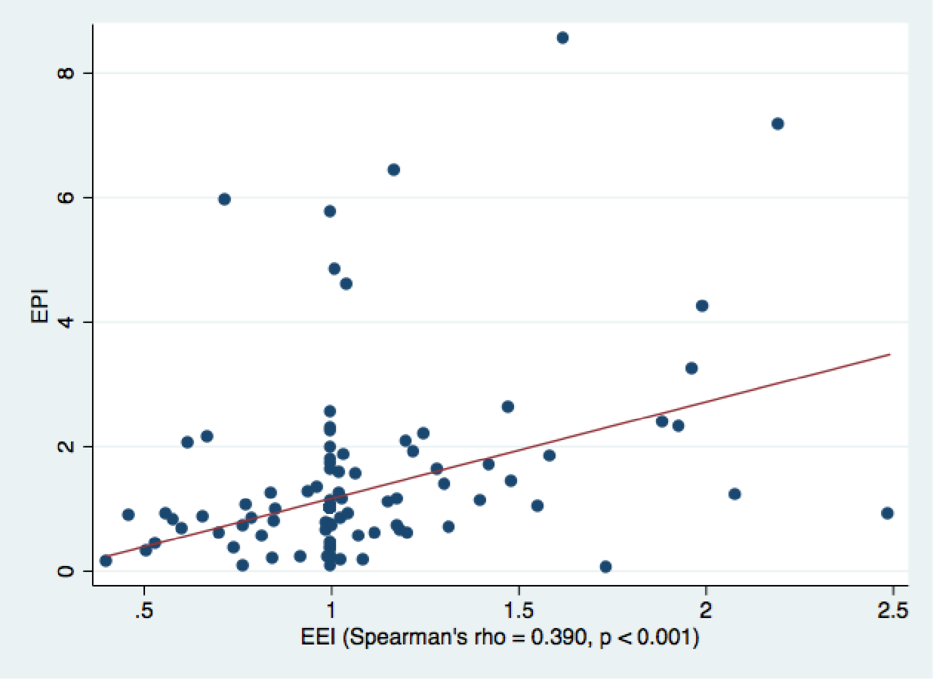

Figure 6: EEI and EPI Results at the Plant Level

to a panel of Swedish manufacturing firms operating in the pulp and paper sector for the years 2002 - 2008, to examine performance at both the industry and plant level. At the industry level, we find evidence of general improvements to both energy efficiency and declines to environmental performance, as well as a slight decrease in overall productivity. The performance measures vary more at the plant level, but we do find some evidence of positive relationships between energy efficiency and environmental performance, environmental performance and productivity, and energy efficiency and productivity.

Our empirical results add to the knowledge in two strands of literature: the Porter hypothesis and corporate social responsibility (CSR). The positive relationship between economic and environmental performance is in line with previous studies on CSR (see e.g., Crifo and Sinclair-Desagné, 2014). However, compared to most empirical CSR studies that are based on subjective scores and financial outcomes (see critical discussion in Paul and Siegel, 2006), our performance measures are grounded in sound production theory, and as such, they reflect actual performance rather than perceived performance. Furthermore, our study corroborates and complements more general recent findings in Lundgren and Marklund (2014) which for the 1990 - 2004 period find evidence that environmental performance and profitability are positively integrated in many industrial sectors in Sweden. In addition, our study adds new evidence for energy efficiency, finding that energy efficient firms do not necessarily sacrifice productivity.

It is important to qualify our empirical results by pointing out several limitations. First, while we are able to work with disaggregated plant-level data, we have a relatively small number of firms in each time period, which likely contributes to the large number of frontier observations. Related to this, we also work with a relatively short period of time (2002-2008). Ideally, we would like to incorporate investment decisions over longer time horizons. Finally, the investment data is self-reported, which may increase the potential for misclassification of environmental versus production-oriented investments. This is further complicated by the potential for dual use. For instance, an investment to reduce energy use in order to lower costs might be considered both a production-oriented and environmental investment. While fully distinguishing environmental and production-oriented investments may be difficult, this also highlights an advantage of using productivity theory in this context to model both types of investment jointly in energy use, production, and emissions.

To our knowledge, this is the first study to include intertemporal environmental investments in a network environmental technology framework. We believe this provides a useful way for both firm managers and regulators to account for investment decisions, in terms of improved energy efficiency and emissions reductions. One future extension of this research would be to also incorporate an abatement network, to more explicitly model the link between investment, abatement, and emissions. Related to this, we are interested in extending our current network to a dynamic optimization, to estimate optimal time paths for environmental investments for both environmental and production objectives. It would also be worthwhile to econometrically investigate the dynamic and causal relationships between firm performance and environmental investments. For instance, disentangling the extent to which environmental investment drives performance, and vice versa, would be useful from both a policy and managerial perspective.

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